SESAR 3 ER 1 Green-GEAR – D3.3 – ERR – Geometric Altimetry

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Abstract

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

The present document is the Exploratory Research Report (ERR) for the Geometric Altimetry Solution. It aims to define the vertical plane of Instrument Flight Paths geometrically, enabling route separation based on vertical path performance limits and continuous climb or descent through the Transition Layer. The document provides a description of the validation results.

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00.03	27/02/2025	release candidate	NATS	review comments integrated, for approval
01.00	28/02/2025	release	DLR	first submission to SJU

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

[1] Representatives of the participants to the project

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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

Three high level project objectives were developed into seven Use Cases through the Green GEAR Initial OSED for Geometric Altimetry [24]. These use cases cover the application of geometric altimetry for vertical navigation within a TMA environment and were assessed under both nominal and non-nominal conditions.

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

For completeness, use cases were also developed to assess geometric altimetry in the cruise phase.

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

The results showed that airspace designers can use geometrically-defined vertical paths to create greater flight efficiencies in the TMA than can be achieved using current day (barometric) principles. The cumulative results provided a net benefit overall for fuel & emissions at 2035 traffic levels; there was an average fuel disbenefit of 2kg per flight in the climb phase, offset by a larger average benefit of 24kg per flight in the descent and approach phases.

The benefits are realised primarily in high-density airspace, e.g. high or very high capacity TMAs. The decrease in fuel consumption is mostly a result of the optimised procedure-designed vertical profiles enabled by geometric altimetry. Optimised altitude constraints enabled by geometric altimetry can result in fuel savings, but enforcing a fixed climb gradient increases the fuel consumption for aircraft that would benefit from a higher gradient climb, which can outweigh the fuel savings. In addition, this can have knock-on detrimental impacts to speed and, consequently, noise and maintenance costs.

GeoAlt can enable the safe removal of the transition layer with no safety or human performance show-stoppers at this stage of project exploration. However, transitioning to geometric altimetry, particularly in a systemised airspace, requires comprehensive planning, robust support systems, and extensive training requirements.

Aircraft design considerations identified with no technical showstopper for Option 1. Aircraft design considerations identified with no technical showstopper for Option 2 in Descent and Approach. However, further R&I work would be required to establish technical feasibility for Climb.

The fuel and emissions impact of implementing geometric cruise showed a disbenefit. On average a small fuel disbenefit was demonstrated in the given short and medium length flight scenarios. Consequently, recommended follow-up includes R&I into the transition between GeoAlt in the TMA and standard Baro in cruise.

It is recommended to postpone the deployment of Geometric Altimetry solutions in all phases of flight until the necessary mitigations to GNSS jamming and spoofing threats have been implemented.

The initial maturity level was TRL 0 and the expected exit maturity level is TRL 2.

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2 Introduction

2.1 Purpose of the document

This document provides the Exploratory Research Report (ERR) for Geometric Altimetry to achieve TRL2 in service of SESAR Solution 0406, Vertical Guidance using Geometric Altimetry. It describes how the concept defined in the SESAR Green GEAR Initial OSED for Geometric Altimetry [24] was assessed in accordance with the Exploratory Research Report (ERP) [25].

The Initial OSED covers three project objectives:

- **OBJ 1.1**: Determination of whether Geometric Altimetry can safely deliver a net fuel efficiency benefit for an ATM network in the TMA
- **OBJ 1.2**: Determination of whether Geometric Altimetry can enable safe removal of Transition Layer
- **OBJ 1.3**: Use of Geometric Altimetry instead of barometric altimetry for required navigation performance (RNP) arrivals down to the intersection with the Final Approach segment.

The ERP defines four exercises:

1) TVAL.01.1- GreenGEAR-0406-TRL2 - Benefit assessment of a fully geometric TMA
2) TVAL.02.1- GreenGEAR-0406-TRL2 – Safety and Human Performance Assessment
3) TVAL.03.1- GreenGEAR-0406-TRL2 – Aircraft functions, architecture and cockpit systems.
4) TVAL.04.1- GreenGEAR-0406-TRL2 – Aircraft Performance & Procedures.

2.2 Intended readership

This document is aimed at the following stakeholders:

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

2.3 Background

This section presents the background on which the Green-GEAR project is building.

PJ.02 EARTH Solution 02-11 (2016-2020)

In SESAR 1, PJ.02-11 – Enhanced Terminal Area for efficient curved operations explored future CONOPS, including the use of geometric altitude during approach phase and the use of curved procedures.

PJ.02-11 reached V1 maturity by the end of SESAR 1 and gave recommendations on future Research and Innovation (R&I) activities linked to Advanced curved TMA operation. The Real Time Simulations that took place in PJ.02-11 addressed primarily airborne aspects and ground aspects were discussed during Expert Group meetings. The potential in using GNSS based Advanced curved TMA operation was recognised for both arriving and departing aircraft. However, it was identified that future Research and Innovation work needed to cater for ATC aspects as well, for both the new arrival and departure concepts to mature.

PJ.02-W2 AART Solution 04.3 (2020-2023)

PJ.02-W2-04.1/2/3 was the continuation of PJ.02-11.

The Airport Airside and Runway Throughput project worked on the concept of Advanced Curved Operation in the TMA, which was linked to three SESAR Solutions, one of which was Advanced Curved Approach Operation in the TMA with the use of geometric altitude.

SESAR 2020 VLD2 ALBATROSS (2020-2023)

ALBATROSS had the aim to demonstrate how the technical and operational R&D achievements of the past years translate into fuel efficiency improvements in real operations. The Demonstration activity covered all flight phases and addressed both operational and technological aspects of aviation and Air Traffic Management (ATM).

Among the concepts demonstrated in real conditions was exercise EXE-03 where a demonstration and study were conducted to evaluate the benefits of closed-path PBN-to-ILS procedures with and without a pilot support system for energy management, compared to radar vectoring procedures to the same runway. The specific feature of EXE-03 was that the closed-path trajectory was already assigned by ATC to the pilots at the beginning of the descent when passing the IAF (Initial Approach Fix) of the STAR (Standard Arrival Route), avoiding tactical lateral instructions during the approach. Lateral tactical ATC instructions prevent optimised CDAs, as the distance-to-go (DTG) is crucial information to estimate the aircraft’s energy state and hence decide on the energy dissipation strategy. The conclusions stressed the necessity to deploy PBN-to-xLS procedures (including RNP or LPV approaches) to as many flights as possible. Green-GEAR works especially on the vertical component of PBN-to-xLS, whose increased predictability is expected to contribute significantly to reducing the need for ATCO intervention.

SESAR 2020 PJ37-W3 ITARO (2021-2023)

ITARO project demonstrated on a larger scale several solutions in the airport environment, including procedures to enable more efficient and integrated runway throughput and terminal operations; a collaborative framework for managing delay constraints on arrivals; and improved arrival and departure operations.

Among those, a flight trial EXE-003 was conducted to increase the maturity level of Interval Management (IM) operations on RNP routes/procedures and continuous descent operations (i.e. fixed profile descents) in high density TMA environments by performing flight trials with an aircraft equipped with the RNP, VNAV and Flight-deck Interval Management (FIM) capability.

EXE-003 conducted arrival operations with frequent speed adjustments on business jet flights following closed PBN STARs with fixed descent angle of 2° or 2.5°.

The consolidated pilot feedback on the IM speed guidance aspect of the concept was that sometimes speed brakes were necessary to create sufficient deceleration, suggesting that the use of speed brakes for low-drag airliners may be needed to decelerate on RNAV routes with a fixed vertical angle.

It showed that a balance is to be found between by the procedure designer: a shallower vertical profile will require less speed brakes, but also gives less fuel/noise benefits.

That said, the use of speed brakes did not raise pilot acceptance issues, therefore the corresponding HP validation objective was assessed as OK.

2.4 Structure of the document

This Exploratory Research Report (ERR) describes the assessment results of using geometric altimetry for vertical navigation.

Section 2 (this section) provides the context for the project concept.

Section 3 provides the context for the assessment as key parameters from the Exploratory Research Plan, including the assessment objectives, assumptions and split by research exercise.

Section 4 sets out the assessments' results, starting with a summary table of the results per objective in Section 4.1, detailed results per objective in Section 4.2, and confidence in the results in Section 4.3.

Section 5 sets out the consolidated conclusions derived from the various exercise results and the recommendations for further Research and Innovation.

The Appendices provide the assessment details, grouped per exercise:

Appendix A - Benefit assessment of a fully geometric TMA; Exercise #01, led by NATS

Appendix B - Safety and Human Performance Assessment; Exercise #02, led by NATS

Appendix C - Aircraft functions, architecture and cockpit systems; Exercise #03, led by Airbus

Appendix D - Aircraft Performance & Procedures; Exercise #04, led by DLR

2.5 Glossary of terms

Term	Definition	Source of the definition
Final Approach	That segment of an instrument approach procedure in which alignment and descent for landing are accomplished Below the Transition Layer	ICAO PANS OPS [27]
Geometric Altitude/ GeoAlt	Defining routes and procedures using geometric height. Aircraft navigation systems constructing vertical paths based on geometric height and navigating to geometric height.	Project Definition

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Term	Definition	Source of the definition
Geometric constraints at waypoints	Flight procedures continue to constrain vertical flight profiles through the use of altitude constraints, but the constraints become geometric altitudes instead of barometric. Defined as concept Option 1.	Project Definition
Geometric Path / Geo Path	Paradigm change in flight procedures, now being vertically defined by published geometric paths with vertical containment assumptions. Defined as concept Option 2, with two sub-options: • Sub-option 2.1 - without V-RNP: navigation and guidance capability with vertical containment performance demonstrated at aircraft certification / ops approval level but without RNP-like onboard monitoring and alerting. • Sub-option 2.2 - with V-RNP: navigation and guidance capability with vertical containment performance supported by RNP-like onboard monitoring and alerting.	Project Definition
Initial Approach	That segment of an instrument approach procedure between the initial approach fix and the intermediate fix or, where applicable, the Final Approach fix or point. Typically, below the Transition Layer	ICAO PANS OPS [27]
Instrument Approach Procedure / IAP	A series of predetermined manoeuvres by reference to flight instruments with specified protection from obstacles from the initial approach fix, or where applicable, from the beginning of a defined arrival route to a point from which a landing can be completed and thereafter, if a landing is not completed, to a position at which holding or en-route obstacle clearance criteria apply.	ICAO PANS OPS [27]
Instrument Flight Procedures	Instrument flight procedures (IFP) are used by aircraft flying in accordance with instrument flight rules and are designed to facilitate safe and efficient aircraft operations. It is a published procedure used by aircraft flying in accordance with the instrument flight rules	ICAO [29] and IFATCA [30]

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Term	Definition	Source of the definition
	which is designed to achieve and maintain an acceptable level of safety in operations and includes one or more of the following: an instrument approach procedure, a standard instrument departure (SID), a planned departure route and a standard instrument arrival (STAR).	
Standard Instrument Departure / SID	A designated instrument flight rule (IFR) departure route linking the aerodrome or a specified runway of the aerodrome with a specified significant point, normally on a designated ATS route, at which the en-route phase of a flight commences. Typically, below or crossing the Transition Layer	ICAO PANS OPS [27]
Standard instrument arrival / STAR	A designated instrument flight rule (IFR) arrival route linking a significant point, normally on an ATS route, with a point from which a published instrument approach procedure can be commenced. Typically, above or crossing the Transition Layer	ICAO PANS OPS [27]
Transition Layer	The airspace between the transition altitude and the transition level, where the Transition Altitude is the altitude at or below which the vertical position of an aircraft is controlled by reference to altitudes and the Transition Level is the lowest flight level available for use above the transition altitude.	ICAO PANS OPS [27]
Vertical RNP / V-RNP	There is currently no RTCA/EUROCAE definition or standard for vertical RNP. However, for the purposes of this concept, Vertical RNP is considered to be the equivalent in the vertical plane to RNP in the lateral plane.	PBN Manual [27]

Table 1: glossary of terms

2.6 List of acronyms

Term	Definition
ADIRS	Air Data Inertial Reference System
ADS-B	Automatic Dependent Surveillance – Broadcast
AGL	above ground level
AIAA	American Institute of Aeronautics and Astronautics
AIXM	Aeronautical Information Exchange Model
AirTOp	Air Traffic Optimisation [simulation software]
AR	Authorisation Required
ATC	Air Traffic Control
ATCO	Air Traffic Controller / ATC Officer
ATM	Air Traffic Management
AUC	Airspace user cost efficiency [performance indicator]
AVES	Air Vehicle Simulator
BADA	Base of Aircraft Data
CAP	capacity [performance indicator]
CBA	cost-benefit analysis
CDA	Continuous Descent Approach
CONOPS	Concept of Operations
D<no.>	Deliverable <no.>
DES	Digital European Sky
DISA	Delta ISA
DMP	Data Management Plan
DTG	Distance-to-Go
ENV	environment [performance indicator]

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Term	Definition
ER	Exploratory Research
ERP	Exploratory Research Plan
ERR	Exploratory Research Report
EU	European Union
EUROCAE	European Organisation for Civil Aviation Equipment
EXE	Exercise
FCU	Flight Control Unit
FEFF	fuel efficiency [performance indicator]
FMS	Flight Management System
FTS	Fast-Time Simulation
GeoAlt	Vertical Guidance using Geometric Altimetry
GLS	GNSS Landing System
GNSS	Global Navigation Satellite System
Green-GEAR	Green operations with Geometric altitude, Advanced separation & Route charging Solutions
HC	High Complexity
HE	Horizon Europe
HFOM	Horizontal Figure of Merit
HIL	Horizontal Integrity Limit
HP	Human Performance
HP	Human performance [performance indicator]
ICAO	International Civil Aviation Organisation
IAF	Initial Approach Fix
IAP	Instrument Approach Procedure

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Term	Definition
ID	Identifier
IFATCA	International Federation of Air Traffic Controllers' Associations
IFP	Instrument Flight Procedure
ILS	Instrument Landing System
ISA	International Standard Atmosphere
JU	Joint Undertaking
KPA	Key Performance Area
KPI	Key Performance Indication
LPV	Localiser Performance with Vertical guidance
M<no.>	project month <no.>
MLS	Microwave Landing System
MMR	Multi-Mode Receiver
MSL	Mean Sea Level
NavDB	Navigation Database
ND	Navigation Display
NEST	Network Strategic Monitoring Tool
OBJ<no.>	objective <no.>
OPS	Operations
OSED	Operational Service and Environment Description
PANS	Procedures for Air Navigation Services
PBN	Performance Based Navigation
PFD	Primary Flight Display
Q<no.>	(calendar) quarter <no.>

Term	Definition
QNH	[barometric reference pressure setting to achieve MSL altitude indication in vicinity of airfield]
R&I	Research & Innovation
RNP	Required Navigation Performance
RTCA	Radio Technical Commission for Aeronautics
SAF	safety [performance indicator]
SBAS	Satellite-Based Augmentation System
SEN	sensitive (limited under the conditions of the Grant Agreement)
SESAR	Single European Sky ATM Research
SID	Standard Instrument Departure
S3JU	SESAR 3 Joint Undertaking
SJU	SESAR Joint Undertaking
SME	Subject Matter Expert
SOL	Solution
SRM	Safety Reference Material
STAR	Standard Terminal Arrival Route
STATFOR	[EUROCONTROL] Statistics and Forecasts Service
STELLAR	SESAR Tool Enabling collaborative ATM Research
Suc	Success
T<no.>	task <no.>
TA	Transversal Area
TAWS	Terrain Avoidance and Warning System
TCAS	Traffic Alert and Collision Avoidance System
TMA	Terminal Manoeuvring Area

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Term	Definition
ToC	Top of Climb
ToD	Top of Descent
TRL	Technology Readiness Level
UK	United Kingdom [of Great Britain and Northern Ireland]
UKRI	UK Research and Innovation
V<no.>	version <no.>
VD	Vertical Display
VFOM	Vertical Figure of Merit
VIL	Vertical Integrity Limit
V-RNP	Vertical Required Navigation Performance
WA	Working Area
WP<no.>	Work package <no.>
xFOM	[generic abbreviation for different Figure of Merit, e.g. HFOM and VFOM]
xIL	[generic abbreviation for different Integrity Limit, e.g. HIL and VIL]
xLS	[generic abbreviation for different precision approach and landing systems, e.g. ILS, MLS, GLS]

Table 2: list of acronyms

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3 Context of the exploratory research report

3.1 Project / SESAR solution 0406: a summary

SESAR solution ID	SESAR solution title	SESAR solution definition	Justification (why the solution matters?)
0406	Vertical Guidance using Geometric Altimetry	The vertical plane of Instrument Flight Paths can be defined geometrically, enabling route separation based on vertical path performance limits and continuous climb or descent through the Transition Layer	Variation in localised pressure creates fuel, environmental and workload inefficiencies due to current reliance on barometric altimetry.

Table 3: Geometric Altitude scope

The project explored several conceptual options relating to SESAR Solution 0406. First is the target end state, where a fully geometric environment encompasses all aircraft in all flight phases reporting geometric height and using geometric altimetry for vertical navigation. Two options for this end state were considered with climbing and descending traffic:

- Option 1: Flight procedures continue to constrain vertical flight profiles through the use of altitude constraints, but the constraints become geometric altitudes instead of barometric.
- Option 2: Paradigm change in flight procedures, now being vertically defined by published geometric paths with vertical containment assumptions, with two sub-options:
  - Sub-option 2.1 - without V-RNP: navigation and guidance capability with vertical containment performance demonstrated at aircraft certification / ops approval level but without RNP-like onboard monitoring and alerting.
  - Sub-option 2.2 - with V-RNP: navigation and guidance capability with vertical containment performance supported by RNP-like onboard monitoring and alerting.

Options 1 and 2 were assessed qualitatively from various perspectives:

- Aircraft systems and operations,
- ATC operations
- Safety
- Human factors.

Option 2 was also assessed quantitatively in terms of:

- TMA network fuel burn, emissions and capacity
- Individual flight in descent fuel burn and emissions
- Individual flight in climb burn and emissions

Secondly, transition states, where there is a mixed capability, with some aircraft operating geometric altimetry and others remaining barometric, were considered in the qualitative assessments.

In addition to the two end state options considered for climbing and descending traffic, the project also assessed cruise operations using a fixed geometric altitude. The cruise phase was assessed qualitatively in terms of aircraft systems and operations, and quantitatively in terms of individual flight fuel burn and emissions.

3.2 Summary of the exploratory research plan

3.2.1 Exploratory research plan purpose

The research was conducted through four exercises:

1) Benefit assessment of a fully geometric TMA
2) ATC Safety and Human Performance Assessment
3) Aircraft functions, architecture and cockpit systems.
4) Aircraft Performance & Procedures.

The purpose of Exercise 1 was primarily to determine whether it was feasible and beneficial to design airspace based on instrument flight procedures using geometric altimetry to define waypoint constraints and/or vertical paths. Assessed at network/TMA level benefits. The assessment was led by NATS, who used its in-house airspace design tool, 'DesignAir', to design a solution scenario for geometric procedures: SIDs (standard instrument departures), STARs (standard instrument arrivals) and IAPs (instrument approach procedures) based on a set of design principles (see Appendix A.1). A reference scenario was also constructed as the equivalent fully barometric TMA, optimised using PBN procedures with altitude or Flight Level constraints applied for procedural separation.

The AirTOp tool was used to run Fast-Time Simulations (FTS) of the two designs (geometric and barometric) using historic peak traffic loading as an input. The difference between the outputs from the geometric design and barometric design indicated the GeoAlt solution's relative benefits.

Exercise 2 was led by NATS. Safety and HP assessment was carried out through a workshop focus group paper exercise to identify the key features for ATC in a fully geometric environment. During the workshop, ATC experts were asked to consider the use of a Geo-only environment as well as a mixed mode of operation between Geo and Baro. During a previous internal stakeholder workshop, the workshop covered nominal conditions and fallback due to GNSS loss or spoofing, which were identified as the major risk with geometric operations.

Exercise 3 was led by Airbus, who assessed the impact of the GeoAlt concept of operations on aircraft functions, architecture and cockpit systems, focused on large commercial aircraft (Airbus families). The assessment has been conducted with a team of experts in ATM, Cockpit Operations, Flight Management System (FMS) and Navigation systems (other than FMS), also supported by Flight Performance specialists. The assessment has covered technical and operational feasibility considerations regarding FMS and Flight Performance, Navigation Systems, Management of Jamming & Spoofing Threats, Compatibility with Surveillance Functions and Cockpit Systems and Flight Crew Operation.

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Exercise 4 was led by DLR. The validation exercise was performed by means of validated aircraft simulations. One major simulation tool to be used in the validation exercise was the simulation model of the A320 D-ATRA, which already existed at DLR but needed to be enhanced for the specific validation exercise in the project. With this simulation model, most accurate re-simulations of real flights were performed as well as more generic simulations for a more theoretical investigation of the physical effects.

A new fast-time-simulation will be developed within this validation exercise, which allows to re-simulate a large number of real flights with a simpler but faster simulation model.

Figure 1, below, illustrates how exercises 1-4 relate to one another.

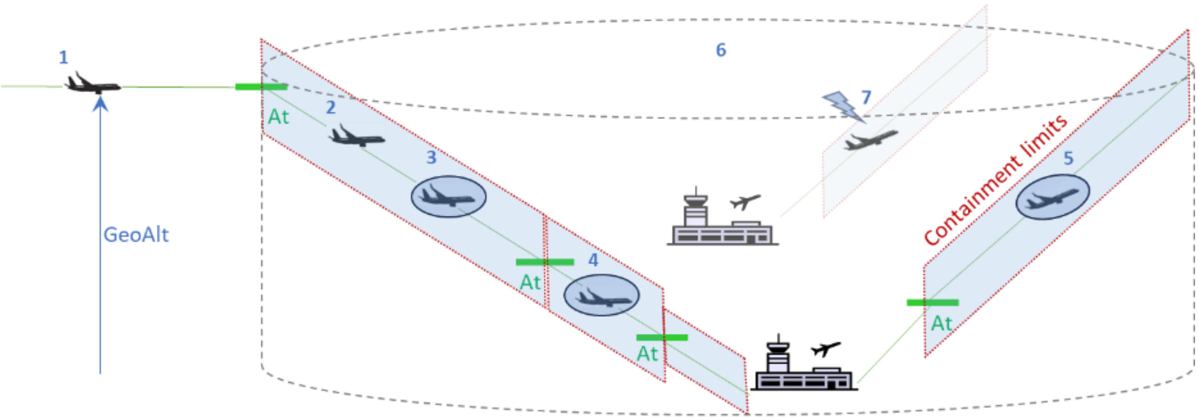

Figure 1: Illustration of the validation exercises for the GeoAlt solution

Where,

1. Ex.3 - Qualitative assessment of geometric cruise on aircraft functions, architecture and cockpit systems. Ex.4 – Quantitative assessment of geometric cruise versus barometric cruise through aircraft simulations.
2. Ex.4 - Quantitative assessment of geometric descent through aircraft simulations.
3. Ex.3 - Qualitative assessment of geometric descent on aircraft functions, architecture and cockpit systems.
4. Ex.3 - Qualitative assessment of geometric Initial Approach on aircraft functions, architecture and cockpit systems.
5. Ex.3 - Qualitative assessment of geometric climb on aircraft functions, architecture and cockpit systems.
6. A fully geometric TMA compared to a fully barometric TMA
    a. Ex.1 - Quantitative assessment through fast-time ATC simulations
    b. Ex.2 - Qualitative Safety and Human Performance assessment
7. Ex.2 - Qualitative Safety and Human Performance assessment of fallbacks due GNSS loss or spoofing.

3.2.2 Summary of validation objectives and success criteria

The validation objectives and success criteria are as described in the Exploratory Research Plan (ERP) [25].

The validation objectives stated here cover the three project objectives relating to this solution (see section 2.1), plus additional objectives derived through the project's concept development.

[OBJ]

Identifier	OBJ-GreenGEAR-0406-TRL2-ERP-FUE1
Objective	Determine whether GeoAlt can safely deliver a net fuel efficiency benefit for an ATM network in the TMA.
Title	ATM Network Fuel Efficiency
Category	Performance
Key environment conditions	Nominal conditions, traffic sample 2035, TMA high complexity
TRL	TRL2

[OBJ Trace]

Relationship	Linked Element Type	Identifier
<COVERS>	<SESAR Solution>	0406
<COVERS>	<Enabler>	TBC
<COVERS>	<Sub-Operating Environment>	TMA HC

[OBJ Suc]

Identifier	Success Criterion
CRT-GreenGEAR-0406-TRL2-ERP-FUE1.001	There is a net fuel efficiency benefit for geometric procedures compared to barometric procedures

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[OBJ]

Identifier	OBJ-GreenGEAR-0406-TRL2-ERP-ENV1
Objective	Determine whether GeoAlt can safely deliver a net CO_2 emissions benefit for an ATM network in the TMA.
Title	ATM Network CO_2 emissions
Category	Performance
Key environment conditions	Nominal conditions, traffic sample 2035, TMA high complexity
TRL	TRL2

[OBJ Trace]

Relationship	Linked Element Type	Identifier
<COVERS>	<SESAR Solution>	0406
<COVERS>	<Enabler>	TBC
<COVERS>	<Sub-Operating Environment>	TMA HC

[OBJ Suc]

Identifier	Success Criterion
CRT-GreenGEAR-0406-TRL2-ERP-ENV1.001	There is a net CO_2 emissions benefit for geometric procedures compared to barometric procedures

[OBJ]

Identifier	OBJ-GreenGEAR-0406-TRL2-ERP-CAP
Objective	Determine whether GeoAlt can safely deliver a net capacity benefit for an ATM network in the TMA.
Title	ATM Network Capacity
Category	Performance
Key environment conditions	Nominal conditions, traffic sample 2035, TMA high complexity
TRL	TRL2

[OBJ Trace]

Relationship	Linked Element Type	Identifier
<COVERS>	<SESAR Solution>	0406
<COVERS>	<Enabler>	TBC
<COVERS>	<Sub-Operating Environment>	TMA HC

[OBJ Suc]

Identifier	Success Criterion
CRT-GreenGEAR-0406-TRL2-ERP-CAP.001	There is a net capacity benefit for geometric procedures compared to barometric procedures

[OBJ]

Identifier	OBJ-GreenGEAR-0406-TRL2-ERP-SAF1
Objective	Determine whether Geometric Altimetry can enable safe removal of Transition Layer
Title	Safety
Category	Performance
Key environment conditions	Nominal conditions, abnormal conditions and failure modes; traffic sample 2035, TMA high complexity
TRL	TRL2

[OBJ Trace]

Relationship	Linked Element Type	Identifier
<COVERS>	<SESAR Solution>	0406
<COVERS>	<Enabler>	TBC
<COVERS>	<Sub-Operating Environment>	TMA HC

[OBJ Suc]

Identifier	Success Criterion
CRT-GreenGEAR-0406-TRL2-ERP-SAF1.001	The geometric solution demonstrates no critical safety showstoppers.

[OBJ]

Identifier	OBJ-GreenGEAR-0406-TRL2-ERP-HP1
Objective	To assess the preliminary Human Performance aspects under the Geometric Altimetry solution for any showstoppers.
Title	Human Performance
Category	Human Performance
Key environment conditions	Nominal conditions, abnormal conditions and failure modes; traffic sample 2035, TMA high complexity
TRL	TRL2

[OBJ Trace]

Relationship	Linked Element Type	Identifier
<COVERS>	<SESAR Solution>	0406
<COVERS>	<Enabler>	TBC
<COVERS>	<Sub-Operating Environment>	TMA HC

[OBJ Suc]

Identifier	Success Criterion
CRT-GreenGEAR-0406-TRL2-ERP-HP1.001	The geometric solution demonstrates no critical human performance showstoppers.

[OBJ]

Identifier	OBJ-GreenGEAR-0406-TRL2-ERP-FEA1
Objective	Determine whether the use of GeoAlt for RNP arrivals down to the intersection with the Final Approach segment is technically feasible at the airborne implementation level
Title	Feasibility in Initial Approach
Category	Technical feasibility
Key environment conditions	Nominal conditions, traffic sample 2035, TMA high complexity
TRL	TRL2

[OBJ Trace]

Relationship	Linked Element Type	Identifier
<COVERS>	<SESAR Solution>	0406
<COVERS>	<Enabler>	TBC
<COVERS>	<Sub-Operating Environment>	TMA HC

[OBJ Suc]

Identifier	Success Criterion
CRT-GreenGEAR-0406-TRL2-ERP-FEA1.001	No technical showstopper is identified at airborne implementation level. This actually has two dimensions: 1. Technical feasibility: the necessary evolutions on aircraft architecture and systems to support the new operational concept are identified, and their associated technological maturity risk and qualitative development cost estimation are deemed reasonable. 2. Operational feasibility: potential impacts on aircraft operation and performance when conducting the new operational concept with the foreseen technical solution are identified and deemed acceptable from airspace users' perspective (both regarding flight crew operation and airline business considerations).

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[OBJ]

Identifier	OBJ-GreenGEAR-0406-TRL2-ERP-FEA2
Objective	Determine whether the GeoAlt solution for Climbs and Descents is technically feasible at the airborne implementation level
Title	Feasibility in Climb and Descent
Category	Technical feasibility
Key environment conditions	Nominal conditions, traffic sample 2035, TMA high complexity
TRL	TRL2

[OBJ Trace]

Relationship	Linked Element Type	Identifier
<COVERS>	<SESAR Solution>	0406
<COVERS>	<Enabler>	TBC
<COVERS>	<Sub-Operating Environment>	TMA HC

[OBJ Suc]

Identifier	Success Criterion
CRT-GreenGEAR-0406-TRL2-ERP-FEA2.001	No technical showstopper is identified at airborne implementation level. This actually has two dimensions: 1. Technical feasibility: the necessary evolutions on aircraft architecture and systems to support the new operational concept are identified, and their associated technological maturity risk and qualitative development cost estimation are deemed reasonable. 2. Operational feasibility: potential impacts on aircraft operation and performance when conducting the new operational concept with the foreseen technical solution are identified and deemed acceptable from airspace users' perspective (both regarding flight crew operation and airline business considerations).

[OBJ]

Identifier	OBJ-GreenGEAR-0406-TRL2-ERP-FUE2
Objective	Determine the impact to fuel for the individual flight in descent
Title	Fuel Efficiency for Individual Flight in Descent
Category	Performance
Key environment conditions	Nominal conditions, traffic sample 2035, TMA high complexity
TRL	TRL2

[OBJ Trace]

Relationship	Linked Element Type	Identifier
<COVERS>	<SESAR Solution>	0406
<COVERS>	<Enabler>	TBC
<COVERS>	<Sub-Operating Environment>	TMA HC

[OBJ Suc]

Identifier	Success Criterion
CRT-GreenGEAR-0406-TRL2-ERP-FEU2.001	The introduction of geometric altimetry does not increase the fuel consumption on average

[OBJ]

Identifier	OBJ-GreenGEAR-0406-TRL2-ERP-ENV2
Objective	Determine the impact to CO_2 emissions for the individual flight in descent
Title	CO_2 emissions for Individual Flight in Descent
Category	Performance
Key environment conditions	Nominal conditions, traffic sample 2035, TMA high complexity
TRL	TRL2

[OBJ Trace]

Relationship	Linked Element Type	Identifier
<COVERS>	<SESAR Solution>	0406
<COVERS>	<Enabler>	TBC
<COVERS>	<Sub-Operating Environment>	TMA HC

[OBJ Suc]

Identifier	Success Criterion
CRT-GreenGEAR-0406-TRL2-ERP-ENV2.001	The introduction of geometric altimetry does not increase the CO_2 emissions on average

[OBJ]

Identifier	OBJ-GreenGEAR-0406-TRL2-ERP-FUE3
Objective	Determine the impact to fuel for the individual flight in cruise
Title	Fuel Efficiency for Individual Flight in Cruise
Category	Performance
Key environment conditions	Nominal conditions, traffic sample 2035, TMA high complexity
TRL	TRL2

[OBJ Trace]

Relationship	Linked Element Type	Identifier
<COVERS>	<SESAR Solution>	0406
<COVERS>	<Enabler>	TBC
<COVERS>	<Sub-Operating Environment>	TMA HC

[OBJ Suc]

Identifier	Success Criterion
CRT-GreenGEAR-0406-TRL2-ERP-FUE3.001	The introduction of geometric altimetry does not increase the fuel consumption on average

[OBJ]

Identifier	OBJ-GreenGEAR-0406-TRL2-ERP-ENV3
Objective	Determine the impact to CO_2 emissions for the individual flight in cruise
Title	CO_2 emissions for Individual Flight in Cruise
Category	Performance
Key environment conditions	Nominal conditions, traffic sample 2035, TMA high complexity
TRL	TRL2

[OBJ Trace]

Relationship	Linked Element Type	Identifier
<COVERS>	<SESAR Solution>	0406
<COVERS>	<Enabler>	TBC
<COVERS>	<Sub-Operating Environment>	TMA HC

[OBJ Suc]

Identifier	Success Criterion
CRT-GreenGEAR-0406-TRL2-ERP-ENV3.001	The introduction of geometric altimetry does not increase the CO_2 emissions on average

3.2.3 Validation assumptions

Assumption ID	Assumption title	Assumption description	Justification	Impact Assessment
ASS-GreenGEAR-0406-TRL2-ERP-001	GNSS Environment	The GNSS environment for the solution scenario will be similar as in current operations. Refer to OSED Operational Characteristics.	Project focus is on operational fallback procedures. Changes in GNSS technology to resolve jamming and spoofing is out of scope of Green GEAR's GeoAlt Solution.*	The exercises will not identify new airborne enablers regarding improved GNSS performance.
ASS-GreenGEAR-0406-TRL2-ERP-002	Transition Stages	Introduction of GeoAlt would be implemented in a segregated way by flight phase so assessment of geometric operations can be validated in isolation.	Managing a mix of aircraft flying to different datums is seen as impractical for ATC to safely manage	The exercises will not consider all potential implementation options

Table 4: validation assumptions overview

* Research into technical resilience to GNSS Jamming and Spoofing continues outside of the project. With respect to the evolution of EGNOS to cope with that, the ongoing actions are:

1. For spoofing: several projects analysing SBAS authentication solutions and the way to implement it.
2. For jamming: EGNOS v3 will implement dual frequency so it will be robust to jamming in one frequency (L1 or L5). But it will be easy for hackers to jam both L1 and L5 at the same time, so no easy solution for jamming in the future. It is in fact one of the weaknesses of GNSS (it is very easy and cheap to jam the frequencies) and the only protection is the law.

3.2.4 Validation exercises list

The following table presents the layout of the four validation exercises of the Solution, which remain the same as described in the Exploratory Research Plan (ERP) [25]. Exercises 1 and 4 performed quantitative assessments, whereas exercises 2 and 3 performed qualitative assessments.

Full details of the Use Cases referenced can be found in the Initial OSED for Geometric Altimetry [24].

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[EXE]

Identifier	TVAL.01.1- GreenGEAR-0406-TRL2
Title	Benefit assessment of a fully geometric TMA
Description	Fast-time simulation of a fully geometric TMA compared with a fully barometric TMA to determine the relative benefits and disbenefits of geometrically-defined instrument flight procedures at a network level.
KPA/TA addressed	Operational Efficiency, Environment, Capacity
Addressed expected performance contribution(s)	Reduction in fuel burn and related CO2 emissions Increase in TMA airspace capacity
Maturity level	TRL2
Use cases	Use Case 4 - Fully Geometric TMA, including Departure, Climb, Descent, Initial Approach and Final Approach
Validation technique	Fast Time Simulation
Validation platform	AirTOp
Validation location	Southampton, UK
Start date	01/08/2024
End date	29/11/2024
Validation coordinator	NATS
Status	<completed>
Dependencies	None

[EXE Trace]

Linked Element Type	Identifier
<SESAR Solution>	0406
<Project>	Green GEAR
<Sub-Operating Environment>	TMA HC
<Validation Objective>	OBJ-GreenGEAR-0406-TRL2-ERP-FUE1 OBJ-GreenGEAR-0406-TRL2-ERP-ENV1 OBJ-GreenGEAR-0406-TRL2-ERP-CAP

[EXE]

Identifier	TVAL.02.1-GreenGEAR-0406-TRL2
Title	Safety and Human Performance assessment
Description	Safety and Human Performance assessment carried out through workshops as a paper exercise to identify the key features for ATC in a fully geometric environment. Assessment will cover both nominal conditions and fallback due to GNSS loss or spoofing, which are seen as the major risk with geometric operations.
KPA/TA addressed	Safety, Human Performance
Addressed expected performance contribution(s)	No safety blockers that can't be mitigated No Human Performance blockers that can't be mitigated
Maturity level	TRL2
Use cases	Use Case 4 - Fully Geometric TMA, including Departure, Climb, Descent, Initial Approach and Final Approach Use Case 5 – Single aircraft loss of GNSS Use Case 6 – Single aircraft subject to GNSS Spoofing Use Case 7 – Complete loss of GNSS
Validation technique	Expert Focus Group
Validation platform	n/a
Validation location	Southampton, UK
Start date	01/08/2024
End date	29/11/2024
Validation coordinator	NATS
Status	<completed>
Dependencies	None

[EXE Trace]

Linked Element Type	Identifier
<SESAR Solution>	0406
<Project>	Green GEAR
<Sub-Operating Environment>	TMA HC
<Validation Objective>	OBJ-GreenGEAR-0406-TRL2-ERP-SAF1 OBJ-GreenGEAR-0406-TRL2-ERP-HP1

[EXE]

Identifier	TVAL.03.1-GreenGEAR-0406-TRL2
Title	Aircraft functions, architecture and cockpit systems
Description	Assessment using expert judgement to address the impact of the GeoAlt concept of operations as described in the Initial OSED on aircraft functions, architecture and cockpit systems, focused on large commercial aircraft (Airbus families).
KPA/TA addressed	Transversal
Addressed expected performance contribution(s)	Technical feasibility
Maturity level	TRL1
Use cases	Use Case 1 – Geometric Initial Approach and Final Approach Use Case 2 – Geometric Descent Use Case 3 – Geometric Cruise Use Case 4 - Fully Geometric TMA, including Departure, Climb, Descent, Initial Approach and Final Approach Use Case 5 – Single aircraft loss of GNSS Use Case 6 – Single aircraft subject to GNSS Spoofing Use Case 7 – Complete loss of GNSS
Validation technique	Expert Focus Group
Validation platform	N/A
Validation location	Toulouse, France
Start date	02/04/2024
End date	20/12/2024
Validation coordinator	Airbus
Status	<completed>
Dependencies	None

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[EXE Trace]

Linked Element Type	Identifier
<SESAR Solution>	0406
<Project>	Green GEAR
<Sub-Operating Environment>	TMA All, En-Route All
<Validation Objective>	OBJ-GreenGEAR-0406-TRL2-ERP-FEA1 OBJ-GreenGEAR-0406-TRL2-ERP-FEA2

[EXE]

Identifier	TVAL.04.1-GreenGEAR-406-TRL1
Title	Aircraft Performance & Procedures
Description	Simulation study for the assessment of the effects from the use of geometric altimetry instead of barometric altimetry on aircraft performance and flying procedures. The objective is to evaluate the effect on fuel consumption and other aircraft-performance-related parameters.
KPA/TA addressed	Operational Efficiency, Environment
Addressed expected performance contribution(s)	Reduction in fuel burn and related CO_2 emissions Increase in airspace capacity
Maturity level	TRL1
Use cases	Use Case 2 – Geometric Descent Use Case 3 – Geometric Cruise
Validation technique	Analytical Modelling
Validation platform	N/A
Validation location	Braunschweig, Germany
Start date	02/01/2024
End date	19/12/2024
Validation coordinator	DLR
Status	<completed>
Dependencies	None

[EXE Trace]

Linked Element Type	Identifier
<SESAR Solution>	0406
<Project>	Green GEAR
<Sub-Operating Environment>	TMA HC and Enroute
<Validation Objective>	OBJ-GreenGEAR-0406-TRL2-ERP-FUE2 OBJ-GreenGEAR-0406-TRL2-ERP-ENV2 OBJ-GreenGEAR-0406-TRL2-ERP-FUE3 OBJ-GreenGEAR-0406-TRL2-ERP-ENV3

Table 5: validation exercise layout

3.3 Deviations

3.3.1 Deviations with respect to the S3JU project handbook

There are no deviations with respect to the S3JU project handbook.

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

There were three deviations from the Exploratory Research Plan (ERP).

For exercise #01, the benefit assessment of a fully geometric TMA, assumption ASS-GreenGEAR-0406-TRL2-ERP-005, was changed:

- Route crossing or overlapping whilst one or both are not in level flight= 1,500 ft [*instead of 1,520ft as defined in the ERP*]

The change was made for simplification of airspace design and analysis at this low maturity stage, rounding the separation to the nearest 100ft. 1,500ft was used as part of the airspace design principles for the test case airspace design.

For exercise #03, the aircraft functions, architecture and cockpit systems were assessed for the cruise phase in addition to the climb, descent and approach phases. This provides completeness of the technical feasibility assessment alongside the quantified assessments in Exercises #01 and #04. The results are included in Section 4.2.10.

For exercise #04, the aircraft performance & procedures were assessed for the climb phase in addition to the descent phase. This provides completeness of the aircraft-level quantified assessment alongside the ATC/airspace quantified assessment in Exercise #01. The results are included in Section 4.2.3.

4 Validation results

4.1 Summary of project / SESAR Solution 0406 validation results

Project / SESAR solution validation objective ID and title	Project / SESAR solution success criterion ID and criterion	Project / SESAR solution validation results	Validation objective status
OBJ-GreenGEAR-0406-TRL2-ERP-FUE1 Determine the fuel and environmental impact of a fully geometric high complexity TMA, compared to an optimised TMA based on barometric operations.	**CRT-GreenGEAR-0406-TRL2-ERP-FUE1.001** There is a net fuel efficiency benefit for geometric procedures compared to barometric procedures	Arrival and departure flows showed a decrease in fuel burn and a forecast reduction in fuel by 2035. Fuel reduction of 23kg per flight, combined Climb, Descent and Approach phases, at 2035 traffic levels.	OK
OBJ-GreenGEAR-0406-TRL2-ERP-ENV1 Determine the fuel and environmental impact of a fully geometric high complexity TMA, compared to an optimised TMA based on barometric operations.	**CRT-GreenGEAR-0406-TRL2-ERP-ENV1.001** There is a net CO_2 emissions benefit for geometric procedures compared to barometric procedures.	Arrival and departure flows showed a decrease in CO_2e and a forecast reduction in CO_2e by 2035. CO_2e reduction of 71kg per flight, combined Climb, Descent and Approach phases, at 2035 traffic levels.	OK
OBJ-GreenGEAR-0406-TRL2-ERP-FUE2 Determine the impact to fuel for the individual flight in descent	**CRT-GreenGEAR-0406-TRL2-ERP-FEU2.001** The introduction of geometric altimetry does not increase the fuel consumption on average	<u>Descent:</u> The descent analysis showed a decrease in fuel consumption of several percent, which is mostly a result of the optimised vertical profile (enabled by geometric altimetry) and not a result of the geometric altimetry directly.	Partially OK

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Project / SESAR solution validation objective ID and title	Project / SESAR solution success criterion ID and criterion	Project / SESAR solution validation results	Validation objective status
		Climb: The climb analysis showed that optimised altitude constraints (enabled by geometric altimetry) can result in fuel savings, but enforcing a fixed climb gradient increases the fuel consumption and this can outweigh the fuel savings and therefore result in an overall negative benefit.	
OBJ-GreenGEAR-0406-TRL2-ERP-ENV2 Determine the impact to CO_2 emissions for the individual flight in descent	**CRT-GreenGEAR-0406-TRL2-ERP-ENV2.001** The introduction of geometric altimetry does not increase the CO_2 emissions on average	Descent: The descent analysis showed a decrease in CO_2 emissions of several percent, which is mostly a result of the optimised vertical profile (enabled by geometric altimetry) and not a result of the geometric altimetry directly. Climb: The climb analysis showed that optimised altitude constraints (enabled by geometric altimetry) can result in a reduction of CO_2 emissions, but enforcing a fixed climb gradient increases the CO_2 emissions and this can outweigh the reduction of CO_2 emissions and therefore result in an overall negative benefit.	Partially OK
OBJ-GreenGEAR-0406-TRL2-ERP-CAP Determine the capacity impact of a fully geometric high complexity TMA, compared to an optimised TMA based on barometric	**CRT-GreenGEAR-0406-TRL2-ERP-CAP.001** There is a net capacity benefit for geometric procedures compared to barometric procedures	On average, across all hours of the day, there are 36 hourly sector entries in the Reference compared to 33 in the Solution Scenario. However, there has been a marginal increase in occupancy times in the Solution Scenario.	NOK

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Project / SESAR solution validation objective ID and title	Project / SESAR solution success criterion ID and criterion	Project / SESAR solution validation results	Validation objective status
OBJ-GreenGEAR-0406-TRL2-ERP-SAF1 Determine whether GeoAlt can enable safe removal of Transition Layer	**CRT-GreenGEAR-0406-TRL2-ERP-SAF1.001** There are no safety showstoppers identified for removal of the Transition Layer	The workshop concluded that GeoAlt can enable the safe removal of the transition layer with no show stoppers. However, for a more systemised airspace several aspects would need to be researched further. This would include managing the shift in controller's roles from active to monitoring, ensuring robust technological tools for aspects such as conformance monitoring and conflict detection, and developing clear procedures for handling emergencies and fallback scenarios involving both barometric and geometric. Additionally, during transition periods with mixed mode operations, attention must be given to providing clear indicators, updated phraseology and thorough training.	OK
OBJ-GreenGEAR-0406-TRL2-ERP-HP1 To assess the preliminary Human Performance aspects under the Geometric Altimetry solution for any showstoppers.	**CRT-GreenGEAR-0406-TRL2-ERP-HP1.001** The geometric solution demonstrates no critical human performance showstoppers.	The workshop findings indicate no insurmountable human performance show stoppers. However, transitioning to geometric altimetry, particularly in a systemised airspace, requires comprehensive planning, robust support systems, and extensive training. While geometric altimetry has the potential to enhance safety and efficiency, careful management of risks such as situation awareness impacts, communication errors, and system vulnerabilities is crucial is ensure operational safety and performance.	OK

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Project / SESAR solution validation objective ID and title	Project / SESAR solution success criterion ID and criterion	Project / SESAR solution validation results	Validation objective status
OBJ-GreenGEAR-0406-TRL2-ERP-FEA1 Feasibility in Initial Approach	**CRT-GreenGEAR-0406-TRL2-ERP-FEA1.001** No technical showstopper is identified at airborne implementation level. This actually has two dimensions: Technical feasibility: the necessary evolutions on aircraft architecture and systems to support the new operational concept are identified, and their associated technological maturity risk and qualitative development cost estimation are deemed reasonable. Operational feasibility: potential impacts on aircraft operation and performance when conducting the new operational concept with the foreseen technical solution are identified and deemed acceptable from airspace users' perspective (both regarding flight crew operation and airline business considerations).	**Solution Option 1:** Technically feasible but open points regarding management of jamming & spoofing threats and FMS predictions. **Solution Option 2:** Technically feasible but open points regarding management of jamming & spoofing threats, FMS predictions, and speed management on constant FPA segments.	Partially OK
OBJ-GreenGEAR-0406-TRL2-ERP-FEA2 Feasibility in Climb and Descent	**CRT-GreenGEAR-0406-TRL2-ERP-FEA2.001** No technical showstopper is identified at airborne implementation level. This actually has two dimensions: Technical feasibility: the necessary evolutions on aircraft architecture and systems to support the new operational concept are identified, and their associated technological maturity risk and qualitative development cost estimation are deemed reasonable. Operational feasibility: potential impacts on aircraft operation and performance when conducting the	**Solution Option 1:** Climb and Descent: Technically feasible but open points regarding management of jamming & spoofing threats and FMS predictions. **Solution Option 2:** Descent: Technically feasible but open points regarding management of jamming & spoofing threats, FMS predictions, and speed management on constant FPA segments.	Partially OK

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Project / SESAR solution validation objective ID and title	Project / SESAR solution success criterion ID and criterion	Project / SESAR solution validation results	Validation objective status
	new operational concept with the foreseen technical solution are identified and deemed acceptable from airspace users' perspective (both regarding flight crew operation and airline business considerations).	Climb: In addition to open points regarding operational feasibility, not possible to conclude on technical feasibility due to major FMS impacts. Further R&D work with FMS suppliers required.	
OBJ-GreenGEAR-0406-TRL2-ERP-FUE3 Determine the impact to fuel for the individual flight in cruise	**CRT-GreenGEAR-0406-TRL2-ERP-FUE3.001** The introduction of geometric altimetry does not increase the fuel consumption on average	Long-term average increase in fuel consumption of about 6 kg (0.2 % of trip fuel) for evaluated short-/medium-range flights	NOK
OBJ-GreenGEAR-0406-TRL2-ERP-ENV3 Determine the impact to CO_2 emissions for the individual flight in cruise	**CRT-GreenGEAR-0406-TRL2-ERP-ENV3.001** The introduction of geometric altimetry does not increase the CO_2 emissions on average	Long-term average increase in CO2 emissions relative to increase of fuel consumption for evaluated short-/medium-range flights	NOK

Table 6: summary of validation exercises results

4.2 Detailed analysis of project / SESAR solution validation results per validation objective

4.2.1 OBJ-GreenGEAR-0406-TRL2-ERP-FUE1 results

Overall, a significant fuel benefit was indicated based on the difference in vertical profile and lateral track distance between Reference and Solution Scenarios. This demonstrates that airspace designers can use geometrically-defined vertical paths to create greater flight efficiencies at a TMA, or network, level, than can be achieved using current day (barometric) principles.

For STARs and IAPS, 5% (3°) descent gradients were used throughout with aircraft modelled to strictly adhere to the gradient.

For SIDs, below 3000ft, the climb rates were kept the same as in the barometric model; this is to allow aircraft to achieve minimum speed and climbs to get airborne from the runway and comply with local noise profile restrictions. Between 3000ft and the end of the SID (up to 17,000ft maximum), a constant 7% climb rate is modelled. Above the end of the SID, typical aircraft performance climb rates are used as per the barometric model.

Using geometric altimetry in the TMA as described above, the cumulative results of this project analysis provided a net benefit overall for fuel & emissions at 2035 traffic levels:

- Climb: c.2 kg fuel disbenefit per flight
- Descent and Approach: c.24k g fuel benefit per flight
- TOTAL (net): c.23kg[2] fuel benefit per flight

See also the results from Exercise #04 (Section 4.2.3), which show similar outcomes: significant potential fuel benefit for Geometric Path in descent but minimal to negative fuel benefit for Geometric Path in climb.

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

Table 7: Combined summary of arrival and departure total fuel/CO2e in UK FIR.

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

Table 8: Overall Green Gear Total fuel benefit in UK FIR

The size of the benefit only shows a potential scale of benefit as there were limitations with the modelling capability because speed profiles could not be adjusted according to the climb or descent rate. Therefore, the calculated fuel differences between Reference and Solution Scenarios are based on the difference in the vertical profiles and lateral track distance.

Fuel and CO2e analysis has been carried out on the proposed Green Gear model. The fuel and CO2e calculations for this analysis have been based solely on the affected routes and the traffic utilising those routes. Any routes that have not changed as part of the Green Gear model and remain as current day operations have not been included.

Routes have been cut to the UK FIR boundary, and all calculations are based on the segments of the routes between UK FIR boundary and runway or vice versa for arrivals and departures respectively.

[2] These summary fuel figures are rounded to the nearest integer value, hence the value of 23kg as opposed to 22kg for the total.

The details of the analysis results are given in Appendix A. The illustrations of the Reference and Solution Scenarios can be found in Appendix A.3.

4.2.2 OBJ-GreenGEAR-0406-TRL2-ERP-ENV1 results

Overall a significant CO_2 emissions benefit was indicated.

The environmental results were derived as a direct factor of the fuel results because the analysis only considered a measure of the CO_2 equivalent emissions (CO2e) directly generated from the fuel burn: fuel x 3.15. Therefore, the results for ENV1 are captured under section 4.2.1.

4.2.3 OBJ-GreenGEAR-0406-TRL2-ERP-FUE2 results

In the results of the descent analysis, several different effects are visible. The change of the altimetry type influences the fuel savings by a very small amount and can be positive or negative depending on the QNH. In an optimised descent scenario, the differences would not cancel out each other in a long-term scenario with varying weather conditions, but a noticeable advantage for the geometric altimetry would remain. For the shown example scenario, the change from the baseline descent profile to the solution descent profile results in fuel savings of approximately 23 kg, which is about 6.6% of the fuel consumption for this scenario. Even though these fuel savings are mostly not a direct result of the geometric altimetry, if the optimised descent profile in the solution scenario is considered to be enabled by the usage of geometric altimetry, then the change of the altimetry type indirectly enables these fuel savings. Also, the usage of geometric altimetry reduces the variance of the fuel consumption and therefore improves the predictability.

In the climb scenario, the influence of the altimetry type on the fuel savings is similar to the influence in the descent scenario: it can be positive or negative depending on the QNH. For the shown example scenario, the change from the baseline climb profile to the solution climb profile results in fuel savings of approximately 2 kg, which is only about 0.25% of the fuel consumption for this scenario and therefore much lower than the benefit in the descent scenario. The reasons for the only very low fuel savings are the two counteracting effects in the optimisation of the climb profile: the removal of the level-off segment in the solution scenario has a positive influence on the fuel savings while forcing the aircraft to fly a fixed climb gradient has a negative influence on the fuel savings. In total, a small positive benefit remains. Even though these fuel savings are not a direct result of the geometric altimetry, if the optimised climb profile in the solution scenario is considered to be enabled by the usage of geometric altimetry, then the change of the altimetry type indirectly enables these fuel savings. In contrast to the descent scenario, the usage of geometric altimetry in the climb scenario increases the variance of the fuel consumption and therefore decreases the predictability.

For the TMA analysis, it can be concluded that geometric altimetry has a direct positive effect on the fuel consumption because, in contrast to barometric altimetry, the flight level constraints are at fixed geometric altitudes and are therefore not moved away from the optimal profile when the QNH is changing. This direct effect, however, only exists when flying an optimised profile. Also, geometric altimetry has an indirect positive effect on the fuel consumption by enabling an optimisation of the climb and descent profiles. The optimisation of the climb profile in the solution scenario results in small fuel savings but leaves potential for further improvement while the optimisation of the descent profile

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in the solution scenario already results in significant fuel savings of about 6.6% of the fuel consumption from the top of descent until the ILS intercept.

See also the results from Exercise #01 (Section 4.2.1).

4.2.4 OBJ-GreenGEAR-0406-TRL2-ERP-ENV2 results

The results on fuel consumption for the descent / climb phase as outlined in the previous section can be directly transferred into CO_2 emissions. It can be concluded that geometric altimetry has a direct positive effect on CO_2 emissions during descent and climb.

4.2.5 OBJ-GreenGEAR-0406-TRL2-ERP-CAP1 results

Overall, no capacity increase was indicated through the proxy metrics analysed. However, there was no conclusive significant detriment to capacity either.

SECTOR ENTRIES

The average sector entries per hour varies by sector due to different traffic flows entering or not entering a sector in the Reference scenario and Solution scenario. This is because climb and descent rate changes cause some traffic flows to climb above while others remain below certain sector. Overall, the trend between the models is similar with no difference to traffic levels spread across the day. For the 2035 traffic sample, across all hours of the day there are on average 36 hourly sector entries in the reference scenario compared to 33 hourly sector entries in the solution scenario.

SECTOR OCCUPANCY

In terms of sector occupancy, on average flights spend an extra 7 seconds longer across all the sectors in the solution scenario compared to the reference scenario in 2035. This is due to the less steep 7% climb profiles than statistically observed at 8% on the SIDs. This is more noticeable in the EGTTLAM, EGTTJAC and EGTTSAB sectors where the aircraft are spending longer climbing in these sectors. Overall, there has been a marginal increase in occupancy times between the reference and solution scenarios.

TRAFFIC INTERACTIONS

The analysis has indicated that the overall number of interactions between aircraft in the Solution Scenario has increased by 27% compared to the Reference Scenario for the 2035 traffic sample. This is mainly due to increased interactions between Heathrow arrivals levelling off at higher levels for the BNN hold interacting with Stansted NUGO and Heathrow WOBUN departures in the EGTTBNN sector. It was determined that these interactions were caused by shortcomings of the airspace design rather than the concept itself; these would be caught and resolved through standard iterative airspace design processes.

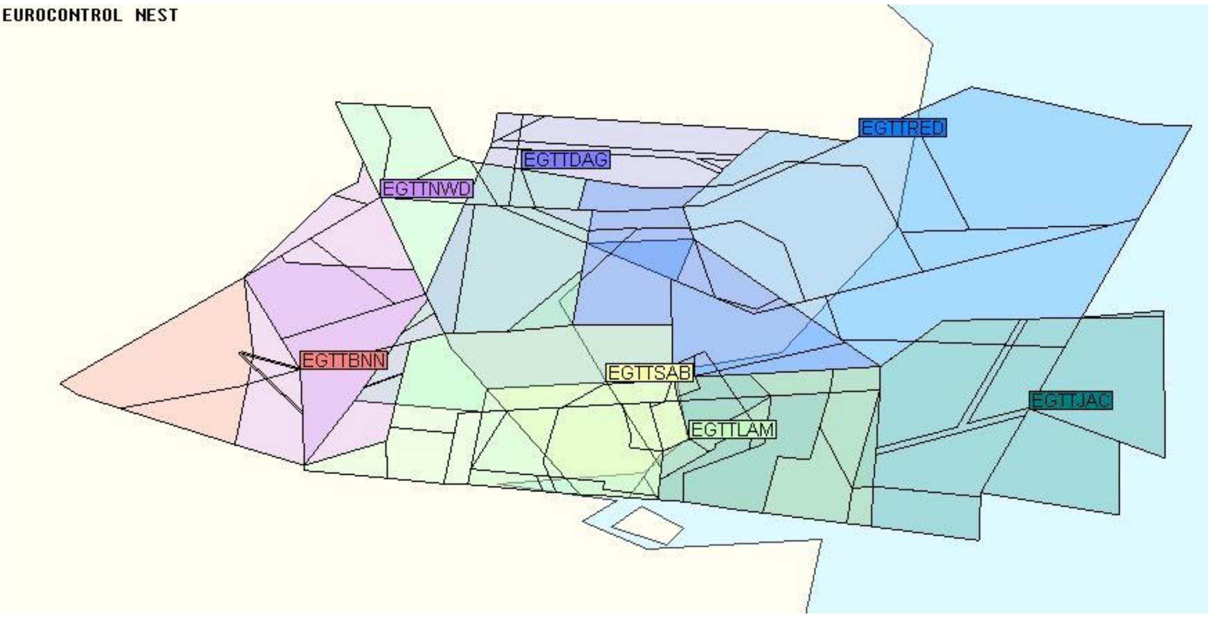

Figure 2: A map of the London ATC sectors assessed under Exercise #01.

4.2.6 OBJ-GreenGEAR-0406-TRL2-ERP-SAF1 results

To address the primary objective on whether GeoAlt could enable the safe removal of the transition later (**OBJ 1.1.**), controllers indicated that removing the transition layer in a fully geometric environment would be feasible and pose minimal hazards to the operation, in the context of the current day operation prior to airspace systemisation. This positive feedback suggests that removing the transition layer, from a controller point of view, would simplify altitude management without introducing significant operational challenges. Removing the transition layer associated with pressure datum changes between QNH and standard pressure eliminates the need for pilots to adjust altimetry mid-flight or the potential for the wrong QNH given. No major safety hazards were identified with the move to GeoAlt and the removal of the transition layer, additional consideration and analysis will be required for the transition to a systemised airspace on top of the transition to GeoAlt.

4.2.7 OBJ-GreenGEAR-0406-TRL2-ERP-HP1 results

To address the validation objective of assessing human performance, no critical showstoppers were identified, primarily, for the scenario (Appendix B.1 Summary of Validation Scenarios) which would introduce geometric operations by changing barometric height constraints at waypoints for geometric, i.e. without a significant change to ATC MOPS. Controllers felt that transitioning to this configuration would require minimal adjustments to existing procedures.

By contrast, the majority of human performance impacts were associated with the airspace scenarios (Appendix B.1 Summary of Validation Scenarios), where a shift to geometric altimetry is coupled with a more systemised airspace that is more tightly defined in both the vertical and lateral planes, incorporating fixed vertical and lateral geometric paths. While an increase in a more systemised airspace, whether using barometric or geometric altimetry, entails changes such as a shift in controller roles to a system monitoring role, the introduction of GeoAlt presents additional consideration, for example it would require controllers to adjust to a new way of interpreting altitude information. However, this report focuses specifically on the implications of GeoAlt within a systemised airspace, rather than examining systemisation within barometric altimetry. Transitionary factors, particularly in mixed mode operations, require significant attention as the controllers emphasised the importance of clear visual indicators and consistent phraseology to distinguish between barometric and geometric operations, especially when in failure scenarios. Training will play a critical role in ensuring controllers and pilots are equipped to manage new procedures effectively.

Overall, while GeoAlt presents opportunities and benefits to the operation, a careful phased approach to its implementation will be essential to address any human performance issues as well as establishing the appropriate airspace design. Whilst no significant HP issues were identified, it should be noted that this was an early theoretical assessment that encompassed of several use cases and airspace environments. A switch from barometric to geometric constraints without changing the airspace was considered to be relatively simple and may results in managing less complex and easier interactions. However, with the development of an airspace change to a more optimised airspace, this in turn impacts the severity of the effect on roles, technology, communication and training for the controller. This highlighted the need to adjust the transitionary steps of geometric altimetry to the following:

1) Geo Initial Approach

2) Lateral Path + Geo Alt constraints (no airspace change)

3) Geo TMA (Approach, Descent & Climbs), potentially through a set of smaller changes, e.g. airport per airport, i.e. could be a mix of Geo Alt constraints and Geo Vertical Path.

4) Airspace block (Cruise, Approach, Descent & Climbs)

With the progression to a more systemised airspace, every step of this transitionary period would require an in-depth human performance and safety assessment, to further investigate the impact. Such a transition would, in the end, involve significant changes in controller roles and responsibilities, require advancements in technology, updates to communication and teamwork, as well as extensive training requirements, as such influencing the impact on human performance. While further investigation into these specific details of these changes may uncover potential challenges, the controllers did not identify any major showstoppers during the workshop that would halt the progression of the project from an ATC human performance perspective at this stage when working under the assumptions outlined. However, further established mitigations and protocols will be required for fallback scenarios, emergencies and failures and outlined in Appendix B Validation Exercise Report #02.

4.2.8 OBJ-GreenGEAR-0406-TRL2-ERP-FEA1 results

Results for this validation objective (Feasibility in Initial Approach) are covered by results for the next validation objective (Feasibility in Climb and Descent).

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4.2.9 OBJ-GreenGEAR-0406-TRL2-ERP-FEA2 results

Results for this validation objective (Feasibility in Climb and Descent) also cover results for the previous validation objective (Feasibility in Initial approach).

These results come from exercise #03 (airborne impact assessment conducted by Airbus), and are structured in two subsections:

- Technical Feasibility
- Operational Feasibility

Each of those subsections provides assessment outcomes for both Solution Options, that is:

Solution Option 1: use of geometric instead of barometric altimetry, while keeping current instrument flight procedures philosophy for vertical navigation based on altitude constraints at waypoints while letting the aircraft freely define its vertical path respecting those constraints.

Solution Option 2: Extends Solution 1 by introducing, in addition to the use of geometric altitude, a new airspace design philosophy based on departure and arrival procedures imposing constant flight path angle segments with vertical containment expectations (i.e. V-RNP).

4.2.9.1 Technical Feasibility

For Solution Option 1, some design considerations have been identified with no technical showstopper so far for Climb, Descent and Approach.

For Solution Option 2, some design considerations have been identified with no technical showstopper so far for Descent and Approach, while further R&D work would be required to establish technical feasibility for Climb.

The identified design considerations for both Solution Options are summarised hereafter.

Outcomes common to both Solution Options

Navigation Systems (other than FMS)

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

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

Design considerations addressing this topic are provided in Appendix C (validation exercise #03 report), with no technical showstopper identified so far.

Flight Management System (FMS) Predictions

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

Note: Air-Ground exchange of ADS-C EPP data, as well as ground display and alerting of trajectory information, are mandated in Europe by CP1 from end 2027. However, such mandate is only applicable for forward fit. Few aircraft exchange ADS-C EPP data with ATC today.

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

A simple solution could use conservative assumptions to meet safety objectives regarding fuel, such as considering a worst-case geo-baro offset based on statistical data. A worst-case offset from fuel consumption perspective would bring a lower bound of the baro altitude at a given geo altitude, which would also impact other performance computations such as speed, time, vertical profile, etc.

However, such conservative approach would degrade the accuracy of FMS predictions, leading to a negative impact on predictability, which may also degrade fuel efficiency if airline flight planning requires loading of additional fuel. Flight crew tasks and ATC operations relying on FMS predictions may potentially be also impacted.

The impact of such a simple solution would be too high if geometric reference is used all along the flight, especially due to the cumulated error on fuel and time predictions, but it could be interesting for future R&D work to assess if the impact might remain within acceptable limits when the use of geometric reference is limited to Climb, Descent and Approach.

A more advanced solution to tackle this challenge could rely on upgrading both FMS and OCC flight planning tools to use meteorological data with pressure forecast grids at different geometric altitudes, as currently done with wind and temperature at different barometric altitudes/FLs. In addition to the FMS and OCC systems impact, it could be interesting for future R&D work to assess the potential impact on MET services to have the forecast data (pressure, wind and temperature) referenced to geometric altitudes.

For the use of geometric altimetry limited to Climb, Descent and Approach, an alternative solution could be based on making the FMS and the OCC flight planning tools able to compute the pressure altitude at an expected geometric altitude by themselves, using the necessary static geographical information (e.g. offset between baro and geo altitudes in ISA conditions) and the dynamic local atmospheric conditions (e.g. QNH and temperature at departure and destination airports).

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

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Compatibility with Surveillance Functions

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

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

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

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

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

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

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

Manual vs Automatic altitude reference switching

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

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

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

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

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

Outcomes specific to Solution Option 2

FMS climb profile computation

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

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

Cockpit HMI for V-RNP onboard monitoring and alerting

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

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

4.2.9.2 Operational Feasibility

Outcomes common to both Solution Options

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

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

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

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

Outcomes specific to Solution Option 2

This Solution Option has significant operational drawbacks requiring further R&D work to consolidate the impact assessment for Descent & Approach and to conclude on feasibility for Climb.

Regarding **Descent & Approach**, the main operational drawbacks that have been identified for Solution Option 2 are related to speed management, with respect to two aspects:

Aircraft deceleration along a fixed vertical angle path is not the most operationally efficient, since in some cases the aircraft may need to start deceleration very soon and with a low deceleration rate, both of which are operationally unpractical for flight crew and ATC for speed management purposes.

There is a huge diversity of aircraft deceleration performance, which means that, under the same weather conditions on the same vertical path, some aircraft may have an adequate deceleration rate in clean configuration while others may not be able to decelerate without speed brakes or early flaps / landing gear extension, with the associated impact on noise and maintenance costs.

The proposed way forward for Solution Option 2 in descent and initial approach phases would be to:

- Limit the use of fixed vertical paths to complex airspace seeking to systemise traffic separation, while still allowing the use of optimised FMS profile anywhere else.

- Consider the diversity of aircraft deceleration performance when designing the vertical profile of arrival and initial approach procedures to prevent speed management issues.

Regarding **Climb**, the main operational drawbacks identified for Solution Option 2 are summarised below:

Climb phase is currently driven by a flight performance paradigm where the aircraft climbs at its best rate while following speed targets, with no notion of vertical path to be flown other than some altitude constraints not to be exceeded. Moving towards a new paradigm where a defined vertical path would need to be flown during climb, involves a significant change in flight crew operation, and rises some concerns regarding the potential interference between the new paradigm and the still necessary aircraft performance considerations to ensure flyability and flight efficiency.

There is a huge variety of aircraft climb performance so, in order to ensure flyability by all the expected diversity of aircraft in the expected range of weather conditions, the flight path angle considered for procedure design would have to be significantly lower than current climb rates of most aircraft, thus heavily penalising flight efficiency.

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Moreover, during the initial climb phase where the aircraft has to accelerate from take-off speed to the 250kt speed limit (or to its optimal climb speed if lower than 250kt), such speed change induces a significant local reduction of the aircraft flight path angle. Such acceleration phase can be delayed by the pilot during flight preparation by adapting the acceleration initiation altitude ("ACCEL" FMS parameter with default value 1500ft AGL), but it should remain at a reasonable altitude AGL to let the aircraft fly in clean configuration as soon as possible.

Furthermore, aircraft climb performance decreases with altitude due to the dependence of engine thrust and aerodynamics on air density, so fixed vertical angle departure procedures cannot provide optimised climb profiles. In order to be flyable, the designed vertical angle would need to fit the lower climb performance at the end (higher altitude) part of the departure procedure, thus reducing flight efficiency along the most part of the procedure.

The proposed way forward for Solution Option 2 in Climb phase would be to avoid using fixed vertical angle paths in this phase if possible. Otherwise, consider the following recommendations:

- Limit fixed vertical angle paths to the smallest extent possible, while still allowing free climb profile anywhere else.
- Consider the diversity of aircraft climb performance, for example by publishing two alternative departure procedures with different vertical profile, one for high climb performance traffic and other for low climb performance traffic. Further R&D work would be required to assess if such a discrete number of authorised climb profiles would satisfy the operational needs.
- Avoid using fixed vertical angle paths at low altitudes where aircraft would normally be accelerating from take-off speed to climb speed, unless such paths could be discontinued soon enough (e.g., no later than 5000ft AGL) to allow for a timely switch to clean configuration.
- Progressively decrease the required vertical angle along subsequent segments of the departure procedure. Further R&D work would be needed to assess the potential challenges associated to the transitions between segments with different vertical angle.

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4.2.10 Additional feasibility results from Exercise #03, relating to the Cruise phase

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

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

In today's operations, pilots can contribute to flight optimisation by requesting, when possible, a cruise flight level as close as possible to the optimum flight level computed by the FMS. The optimum altitude ("OPT ALT") is generally a few thousand feet below the maximum recommended altitude ("REC MAX"), which is considered as the upper limit for safe operation.

The REC MAX is computed by the FMS, not only based on the aircraft maximum certified altitude, but also on performance considerations that depend on flight and weather conditions. It is defined as the lowest of:

- Maximum altitude at maximum cruise thrust in level flight
- Maximum altitude at maximum climb thrust with 300 ft/min vertical speed
- Maximum certified altitude
- 1.3 g buffet limited altitude.

It must be highlighted that the REC MAX can be several thousand feet below the aircraft maximum certified altitude for a flight operating close to its Maximum Take-off Weight (MTOW) or in hot weather conditions (DISA>>0).

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

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

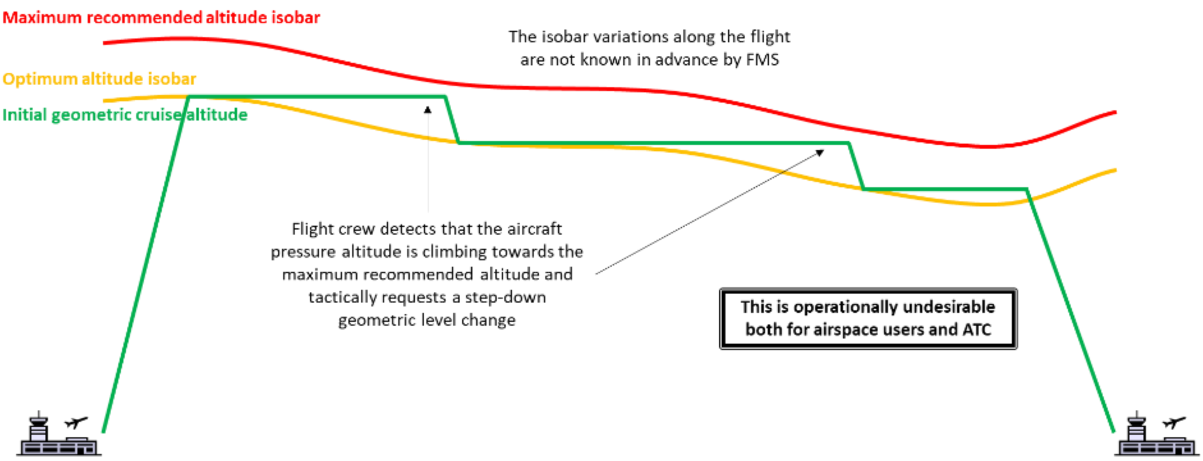

Figure 3: Geometric navigation in cruise – flight envelope and cruise altitude optimisation challenge (a)

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

However, the marginal (if any) potential benefits of using geometric altitude in cruise cannot counterbalance either the costs of developing the associated enablers, or the remaining operational hurdles of the increased number of level changes.

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

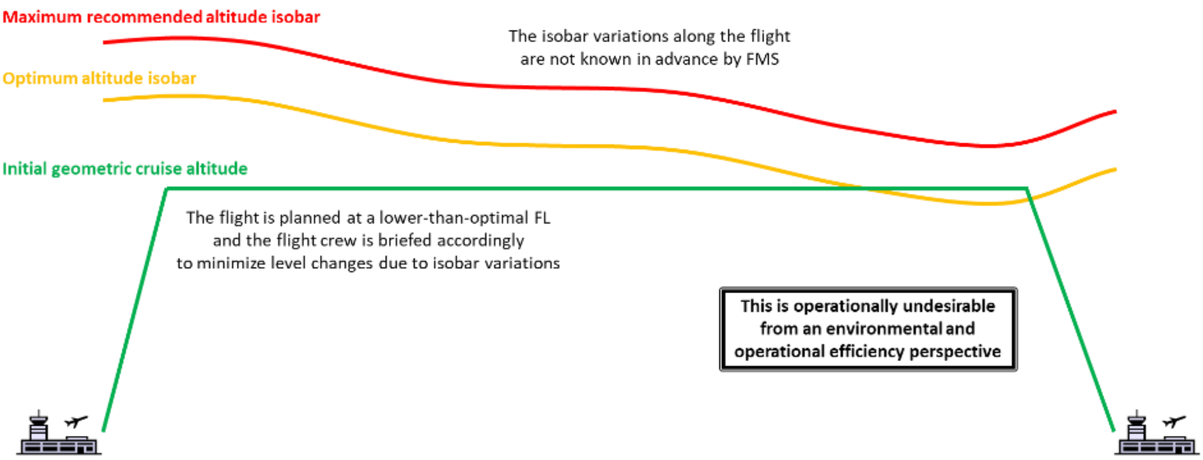

Figure 4: Geometric navigation in cruise – flight envelope and cruise altitude optimisation challenge (b)

It has been concluded that this operational challenge is significant enough to constitute a showstopper for the use of geometric altitude in cruise phase.

4.2.11 OBJ-GreenGEAR-0406-TRL2-ERP-FUE3 results

For cruise flight one can conclude that the use of geometric altimetry instead of barometric leads in average to a slight increase of the fuel consumption of about 0.2% of the trip fuel. The maximum increase in consumed fuel observed in the simulation is about 90 kg. However, it can be expected that in some extreme cases these values might also be even higher. The flight time is only affected in a negligible way.

In case that geometric altimetry is used in cruise flight, it must be assured that the maximum barometric altitude of the aircraft, which is aerodynamically the more relevant parameter for the service ceiling, is not exceeded. If so, a step descent has to be performed in order to stay within the admissible flight enveloped defined by barometric altitudes.

Because of the observed slightly increased fuel consumption by using geometric altimetry in cruise flight, it is recommended not to use geometric altimetry in cruise flight, but to stick with barometric altimetry instead. In case that geometric altimetry would be used during climb and/or descent flight phases but not during cruise, a proper transition between geometric and barometric altimetry is mandatory.

4.2.12 OBJ-GreenGEAR-0406-TRL2-ERP-ENV3 results

The results on fuel consumption for cruise flight as outlined in the previous section can be directly transferred into CO2 emissions. It can be concluded that on average geometric altimetry has a negative effect on CO2 emissions during cruise.

4.3 Confidence in validation results

4.3.1 Limitations of validation results

The quantitative assessment of fuel and CO_2 impacts was only assessed for concept Option 2 (refer to Section 3.1). Concept Option 1 was only assessed in qualitative terms.

For the net fuel efficiency benefit for an ATM network in the TMA (OBJ-GreenGEAR-0406-TRL2-ERP-FUE1), there were limitations with the modelling capability because speed profiles could not be adjusted according to the climb or descent rate

4.3.1.1 Quality of validation results

The fuel (OBJ-GreenGEAR-0406-TRL2-ERP-FUE1) and CO_2 impacts (OBJ-GreenGEAR-0406-TRL2-ERP-ENV1) for the ATM network in the TMA represent potential benefits only and would be subject to change/reduction depending on a number of factors:

- Aircraft speed profiles in climb or descent
- Variations in meteorological conditions
- The function of technical solutions to enable aircraft to navigate and maintain a fixed geometric path in descent within specified tolerances.
- The function of technical solutions to enable aircraft to construct, navigate and maintain a fixed geometric path in climb within specified tolerances.

The fuel and CO_2 benefits for the individual aircraft in climb represent conservative benefits because the geometric profile was forced into a shallow climb after the end of the SID to meet a common point with the barometric profile at 20,000ft (refer to Section 4.2.3).

The airspace capacity impacts (OBJ-GreenGEAR-0406-TRL2-ERP-CAP1) provide indications only that capacity is likely to be largely unaffected. The quantitative assessment was carried through fast-time simulations only, where both scenarios (reference and solution) were fed with the same traffic sample. No capture of the human/workload element was possible.

The evaluation of fuel (OBJ-GreenGEAR-0406-TRL2-ERP-FUE3) and CO2 (OBJ-GreenGEAR-0406-TRL2-ERP-ENV3) impacts for cruise flight was not able to consider the flight-specific maximum recommended altitude REC MAX (refer to section 4.2.10). For the evaluation of flight performance in cruise only a maximum altitude of 40,000 ft was applied. This means that the evaluation performed for cruise was not able to detect all cases where the performance limit of the aircraft would have been exceeded in case that the REC MAX is below 40,000 ft.

4.3.1.2 Significance of validation results

The results obtained for fuel/CO_2e from the Exercise #01 FTS are based on a BADA 4.2 model. The model is stable and returns the exact fuel rate for the same input parameters. However, during FTS the trajectories are recorded at a 4s resolution, and trimmed to the UK FIR, leading to a minor digitisation of the dataset. This can lead to variances between a baseline (barometric model in this report) and scenario (Geometric) due to the resolution and trimming.

The amount of variation in kg is a dependent on the aircraft type being modelled and the phase of flight.

In addition, the change in vertical level or speed over 4s, while minor for each step, can impact the fuel rate by up to ±0.05kg. This is the max size of the digitisation error per step. However, aggregated over the duration of the flight profile this can become significant, with longer flights having a potentially much higher uncertainty.

The significance is that the standard deviation is many times lower than the claimed changes to fuel. Therefore, inaccuracies potentially introduced due to digitisation and trimming of the FTS results does not impact the conclusions.

This uncertainty analysis only covers the sources within the FTS processing. In comparing FTS results to actual real-world fuel and CO_2e values there are other sources of variation. In essence, the FTS makes assumptions about the following parameters that would influence the real fuel/CO_2e.

- Aircraft mass is assumed to be either nominal for departures, or low for arrivals. In actuality, there would be a wide variation. This impacts both the BADA 4.2 fuel rates and would be a dependent variable in the IAS/TAS/ROCD of the aircraft.
- FTS assumes standard pressure and temperature with no local variation or wind influencing the flights.
- There are no divergences (from any source) from the flight planned path.

The first two of these are very hard to model due to the number of permutations involved. However, as a simulated comparison we can exclude the influence of all three as we assume that all parameters or external influences would interact with each flight in exactly the same manner between baseline and scenario. This leads us to have confidence in the direction of benefit/disbenefit from FTS analysis, though the achieved benefits can vary significantly between analysis and reality.

Typically, our internal estimation of the impact this has on the FTS is to consider fuel changes (scenario minus baseline) only to be accurate within ±5kg per aircraft. This can scale significantly if applied to traffic flows with a high volume of traffic. However, other than the change to EGGW departures, this uncertainty estimate would not lead the fuel impact of this report to be questioned. It should be noted that this should only be applied to individual flows not combined totals. As an overall low impact change could be a composite of a large benefit and large disbenefit, with each benefit/disbenefit itself being accurate.

	Error margin FTS to actual per aircraft (kg)	Error margin FTS to actual Annual Total Departures (T)	Error margin FTS to actual Annual Total Arrivals (T)
EGLL	5	220	699
EGSS	5	479	485
EGGW	5	4	321
EGLC	5	77	-

Table 9: Estimated error to benefits comparing FTS to actuals

A statistical evaluation was only performed for the cruise evaluation. Here, the number of considered flights was found to be large enough to be statistically significant. As for the TMA (climb and descent) a case study was performed, statistical significance is not applicable there. Nevertheless, the results of the TMA evaluation appear plausible and are considered significant enough to represent the situation in the TMA well enough and to give a good indication of the general effects.

The evaluation of aircraft performance in cruise has only been performed using short- and medium range flights of A320 aircraft. Hence, the results are only applicable to that kind of flights and aircraft type. However, the results are considered representative for other aircraft types and long-range flights regarding their general trend. The quantitative results, however, cannot directly be transferred to long-range flights. Also, for the re-simulation of flights (cruise evaluation) no re-planning of the single flights (e.g. to address isobar variations along cruise) could be performed. Therefore, no effects from a variation in the overall flight planning due to the use of geometric altimetry could be considered.

5 Conclusions and recommendations

5.1 Conclusions

5.1.1 Conclusions on project/ SESAR solution maturity

This ERR addresses some of the maturity criteria for Solution 0406. The FRD, ECO-EVAL and Final OSED will address other of the maturity criteria, once completed.

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 been addressed in exercises #02 and partially #03, and which have been successful by failing to identify significant human performance and safety specific showstoppers at this stage;
- Impact on the most significant KPAs such as capacity and cost/fuel efficiency, which have been addressed in exercises #01 and #04 and have demonstrated a net fuel benefit without more than negligible impact on capacity;
- Interaction with other SESAR Solutions; this has partially been performed by studying the viability of using geometric altimetry also outside the TMA, as could be an enabler for Solution 0407, Separation Minima, in exercises #03 and #04. These exercises have concluded that from a standalone point of view there are operational and performance disbenefits of using geometric altimetry in cruise; whether they could be outweighed by the KPA improvements of the said Solution needs to be determined with the results from its ECO-EVAL which is pending.
- Identification of relevant R&D needs and recommendations for further work; these have been developed and are documented later in this chapter.

The example chosen for the work presented in this ERR is a high-capacity TMA that has particular problems with level-offs in climb, which are required for traffic separation, and this particular issue may not be relevant in other high-capacity TMAs and certainly not at lowly-frequented airports. However, it is not a requirement of the Geometric Altimetry Solution that is it introduced all over Europe, or even the globe, at the same time. The analysis presented in this ERR shows that there are operational contexts where the Solution could be beneficial.

The major open point from the Validation activities documented here is the safety and security threat stemming from jamming (which may be intentional or accidental) and spoofing (which is usually intentional[3]). Methods to deal with that are being developed by activities in line with joint EUROCAE /

[3] 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.

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. Under the interpretation that the TRL2 maturity criteria require identification and discussion but not solution of these safety and security problems, this situation would not prevent TRL2 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.

5.1.2 Conclusions on concept clarification

5.1.2.1 Concept Conclusions relating to the TMA

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

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

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

However, it has been shown that the detrimental effects of forcing aircraft to maintain a constant climb or descent rate cannot be ignored. In the case of the climb phase alone, it may not be possible to achieve a net benefit. As well as having a detrimental effect on fuel, compared to an unrestricted climb or descent, it also has knock-on impacts to speed and, consequently, noise. For example, in the descent, if the aircraft is not provided with a sufficiently shallow descent, it may not be able to reduce speed for the Approach without the use of speed brakes, which are less fuel efficient and create noise, as well as increased maintenance costs. Therefore, the design of the descent could be broken into two parts: a nominal FPA with constant speed, followed by a shallower FPA (still not a level-off) allowing for a nominal deceleration rate. This solution would fit with the Airbus’ philosophy for the next generation of CDA function. However, it would not allow the full benefit of an FMS-computed double slope profile adapted to each aircraft performance and the current flight and weather conditions. Additionally, these procedures would be most efficient as Descend Via, i.e. without tactical speed instructions applied by ATC, which could adversely impact the aircraft’s energy management.

In the climb phase, forcing an aircraft to climb at a fixed gradient may not allow it to accelerate to meet its speed schedule, which could have both a fuel and time impact, or even not be flyable at all since aircraft climb performance decreases with altitude. A conservative (low) climb gradient would ensure flyability but would also degrade fuel efficiency.

Aircraft are currently designed to prioritise their speed schedule over the vertical constraints in the climb phase, only adapting their vertical speed/pitch to reach and maintain the current speed target or to level-off when reaching the current altitude target (either the maximum authorised altitude from a published altitude constraint, or manually set by the pilot on the FCU). Other than that, the FMS does not automatically adapt speed or flight path angle based on altitude constraints, it just informs the flight crew if the altitude constraints are predicted to be achieved or missed, and the pilot would need to take manual action if deemed necessary (e.g. reducing IAS to increase climb angle, etc).

More importantly, there is a huge variety of aircraft climb performance so, in order to ensure flyability by all, the expected diversity of aircraft in the expected range of weather conditions, to create a viable solution for Option 2 (Section 3.1) in the climb phase, a couple of methods could be employed:

(a) Design climb gradients achievable by the lowest common denominator
(b) Design multiple SIDs based on the predicted range of climb performance, e.g. High and Low

The lowest common denominator would need to factor in meteorological conditions as well as individual aircraft performance. The limitation of (a) is that it may reduce the efficiency by more than the benefit gained by the efficiency of using geometric airspace design.

The limitation of (b) is that it necessitates an increase in the number of SIDs that have to be fit into the volume of airspace under consideration. In high or very high TMAs, where this solution is primarily targeted, this could have an adverse effect on overall TMA efficiency.

Alongside procedural design considerations, a change in the function of the navigation system would be required so that vertical profile is prioritised over speed (IAS). It would be the most beneficial method from an airspace design perspective but would mark a paradigm shift in aircraft navigation logic that would be the most difficult to implement and, as mentioned above, would have to balance against the detrimental fuel, time and maintenance impact. Significant navigation system change would also be needed to force aircraft to adhere to fixed vertical profiles.

The application of Option 1 (Section 3.1) is far easier from a technical feasibility perspective but limits the efficiency of the airspace design.

Therefore, a composite solution is recommended for the TMA/airspace design:

- For the Approach phase, use Geo constraints at waypoints (Option 1) in order to gain safety and efficiency benefits with the interface between Initial and Final Approach, or use Geo Path (Option 2) in complex airspace where necessary to systemise traffic separation as well as gain the interface benefits.
- If Geo Path is used in Approach, allow for deceleration segments where necessary; consider the diversity of aircraft deceleration performance when designing the vertical profile of initial approach procedures to prevent speed management issues.
- For the Descent phase, use Geo constraints at waypoints (Option 1) in order to gain safety and efficiency benefits by eliminating the Transition Layer effects, or use Geo Path (Option 2) in

complex airspace where necessary to systemise traffic separation as well as gain the Transition Layer avoidance benefits.

- If Geo Path is used in Descent, allow for deceleration segments where necessary; consider the diversity of aircraft deceleration performance when designing the vertical profile of arrival procedures to prevent speed management issues.
- Where possible in the airspace design or arrivals (i.e. without significant detriment to the overall design efficiency), rely on Geo constraints at waypoints only (Option 1), allowing the use of optimised FMS profile in descent and Approach.
- For the Climb phase, rely on Geo constraints at waypoints only (Option 1). The switch from baro to geo enables geo vs geo separation between the arrivals and departures, which is far easier and safer for the controller to manage.

The use of Geo Path (Option 2) for Climb has been demonstrated to be practical and potentially beneficial from an airspace design perspective. However, achieving a beneficial design is difficult and the level of change to the aircraft systems is significant. Therefore, it should only be considered for highly congested airspace, and as part of a composite solution together with Geo Path in Descent and Approach. If this option were to be progressed, the following limitations would have to apply:

- Geo Path (Option 2) in Climb only where necessary for deconfliction; limit fixed vertical angle paths to the smallest extent possible. Where possible, avoid using fixed vertical angle paths at low altitudes where aircraft would normally be accelerating from take-off speed to climb speed.
- Where fixed angle paths are required, consider the diversity of aircraft climb performance under all reasonable meteorological conditions, for example by publishing two alternative departure procedures with different vertical profile, one for high climb performance traffic and other for low climb performance traffic.
- Geo Path in Climb to allow for tapering climb profile where necessary: progressively decrease the required vertical angle along subsequent segments of the departure procedure.
- Where possible in the airspace design (i.e. without significant detriment to the overall design efficiency), still rely on Geo constraints at waypoints (Option 1), allowing the use of optimised FMS profile in descent and allowing free climb profile.

5.1.2.2 Concept Conclusions relating to Cruise

The use of geometric altimetry has been found not operationally suitable for Cruise phase, due to significant challenges inherent to the dependency of aircraft performance on barometric conditions, particularly regarding flight envelope (e.g. maximum operating altitude) and cruise altitude optimisation.

Indeed, geometric-based cruise would lead to an increased number of cruise level changes (not only step-up but also step-down) following isobar variations in order to keep the aircraft within its flight envelope and as close as possible to its optimum cruise altitude. Such operational complexity would be undesirable from Airspace Users and ATC perspective.

To prevent such increased complexity, an alternative solution would be to plan the flights at lower than optimal cruise altitude to minimise the need for safety-related step-down level changes, and

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briefing flight crews to limit optimisation-related level changes. This would bring a negative impact on environment, operational efficiency and potentially also capacity due to reduced use of the upper flight levels.

Implementation of geometric cruise was found to be detrimental when considered in isolation.

Geometric cruise could potentially be considered as part of a broader rollout alongside a geometric TMA if there is a demonstrable benefit when the whole system is considered. For example, the cumulative results of this project's analysis indicate a net fuel and emissions benefit could be possible overall because the TMA benefits could outweigh the geometric cruise disbenefits, notwithstanding the limitations on cruise analysis (Refer to Section 4.3.1.1). Also it may enable other concepts such as RVSM 2 (see Solution 0407), which could provide capacity benefits.

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

5.1.2.3 Concept Conclusions on broader considerations

Management of Jamming & Spoofing Threats

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

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

- A reversion to barometric altitude will be required on-board the aircraft (automatic or manual) upon detection but more likely preferable before entering the interference area.
- A reversion to barometric based airspace and management of all aircraft affected in the area by air traffic controllers such as clearance and RVSM constraints must be performed.
- A robust jamming and spoofing detection tool (on the ground and/or on-board) must be operational in order to ensure aircraft can timely and concurrently revert to barometric altitude approximately at the same locations.
- The management of the transition between an airspace managed in barometric altitude and a geometric altitude: This is already needed under normal conditions but this situation might occur very often in some regions near conflict zones, which could lead to decide to not switch to geometric altitude at all in some airspaces.
- Standardised and agreed upon phraseology and SQUAWK notices.

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5.1.3 Conclusions on technical aspects

For Solution Option 1, this exercise has identified some design considerations with no technical showstopper identified so far for Climb, Descent and Approach.

For Solution Option 2, this exercise has identified some design considerations with no technical showstopper identified so far for Descent and Approach, while further R&D work would be required to establish technical feasibility for Climb.

The identified design considerations for both Solution Options are summarised hereafter.

Conclusions common to both Solution Options

Navigation Systems (other than FMS)

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

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

Design considerations addressing this topic are provided in Appendix C (validation exercise #03 report), with no technical showstopper identified so far.

Flight Management System (FMS) Predictions

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

Note: Air-Ground exchange of ADS-C EPP data, as well as ground display and alerting of trajectory information, are mandated in Europe by CP1 from end 2027. However, such mandate is only applicable for forward fit. Few aircraft exchange ADS-C EPP data with ATC today.

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

A simple solution could use conservative assumptions to meet safety objectives regarding fuel, such as considering a worst-case geo-baro offset based on statistical data. A worst-case offset from fuel consumption perspective would bring a lower bound of the baro altitude at a given geo altitude, which would also impact other performance computations such as speed, time, vertical profile, etc.

However, such conservative approach would degrade the accuracy of FMS predictions, leading to a negative impact on predictability, which may also degrade fuel efficiency if airline flight planning

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requires loading of additional fuel. Flight crew tasks and ATC operations relying on FMS predictions may potentially be also impacted.

The impact of such a simple solution would be too high if geometric reference is used all along the flight, especially due to the cumulated error on fuel and time predictions, but it could be interesting for future R&D work to assess if the impact might remain within acceptable limits when the use of geometric reference is limited to Climb, Descent and Approach.

A more advanced solution to tackle this challenge could rely on upgrading both FMS and OCC flight planning tools to use meteorological data with pressure forecast grids at different geometric altitudes, as currently done with wind and temperature at different barometric altitudes/FLs. In addition to the FMS and OCC systems impact, it could be interesting for future R&D work to assess the potential impact on MET services to have the forecast data (pressure, wind and temperature) referenced to geometric altitudes.

For the use of geometric altimetry limited to Climb, Descent and Approach, an alternative solution could be based on making the FMS and the OCC flight planning tools able to compute the pressure altitude at an expected geometric altitude by themselves, using the necessary static geographical information (e.g. offset between baro and geo altitudes in ISA conditions) and the dynamic local atmospheric conditions (e.g. QNH and temperature at departure and destination airports).

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

Compatibility with Surveillance Functions

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

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

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

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

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

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

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

Manual vs Automatic altitude reference switching

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

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

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

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

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

<u>Conclusions specific to Solution Option 2</u>

FMS climb profile computation

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

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

Cockpit HMI for V-RNP onboard monitoring and alerting

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

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

5.1.4 Conclusions on performance assessments

The concept of using Instrument Flight Procedures to define the vertical geometric path that the aircraft FMS has to follow, provides the potential for significant fuel and environmental benefits when considered TMA-wide. This is primarily through enabling the airspace designer to reduce the impact of procedural conflicts on climb and descent profiles, leading to a greater number and/or greater duration of continuous climbs and continuous descents. This was also demonstrated at the individual aircraft level. However, the result of constraining aircraft to fly a specific vertical profile, dictated by the instrument flight procedure increases fuel burn compared to enabling open climb in-between waypoint constraints. Therefore, there is a balance to be struck depending on the level of airspace systemisation required.

The potential fuel benefits in descent are primarily due to the removal of uncertainty due to local pressure variations. A greater amount of usable airspace is provided by reduction in the uncertainty buffers that have to be built in due to the pressure variation / the Transition Layer and the position of the aircraft in-between waypoints. Benefits subject to airspace design.

The potential fuel benefits in climb are primarily due to the minimisation of climb interruptions, such as level offs, which leads to flights able to reach their cruising height sooner. Benefits subject to airspace design.

For the TMA analysis, it can be concluded that geometric altimetry has a direct positive effect on the fuel consumption because, in contrast to barometric altimetry, the flight level constraints are at fixed geometric altitudes and are therefore not moved away from the optimal profile when the QNH is changing. This direct effect, however, only exists when flying an optimised profile. Also, geometric altimetry has an indirect positive effect on the fuel consumption by enabling an optimisation of the climb and descent profiles. The optimisation of the climb profile in the solution scenario results in small fuel savings but leaves potential for further improvement while the optimisation of the descent profile in the solution scenario already results in significant fuel savings of about 6.6% of the fuel consumption from the top of descent until the ILS intercept.

For cruise flight one can conclude that the use of geometric altimetry instead of barometric leads in average to a slight increase of the fuel consumption of about 0.2% of the trip fuel. The maximum increase in consumed fuel observed in the simulation is about 90 kg. However, it can be expected that in some extreme cases these values might also be even higher. It must be emphasised that the numbers shown here for cruise have only been assessed for Europe-wide short-/medium-range flights of a single aircraft type. It can be expected that for long-range flights the quantitative average fuel disbenefit is higher (even if the relative, percental disbenefit might be of similar magnitude).

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5.2 Recommendations

5.2.1 Recommendations for next R&I phase

The Green GEAR project has indicated that it is possible to design TMA airspace using procedures and/or waypoints based on geometric height. It has also identified a range or operational and technical hurdles to be addressed and concluded that there are no absolute showstoppers. However, there are significant technical challenges, particularly for Option 2.

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

1) Higher fidelity assessment of Option 2 (a V-RNP type solution), e.g.
   - Human-in-the-loop assessment of managing vertically-defined Geo paths.
   - Procedure development
   - Development and assessment of ground system- conformance monitoring capability to Geo path.
   - A/G comms of baro and geo in parallel, and/or
   - Display and management of baro and geo at CWPs

2) Quantitative analysis of Option 1 and/or transition states, e.g.:
   - Straight switch of Baro to Geo (no airspace change)
   - Geometric path in descent and Approach with Geo constraints (only) in climb
   - Geo below TL and Baro (FL) above

3) Consolidate outcomes for Descent & Approach, particularly regarding speed management challenges for Solution Option 2

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

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

6) Assess if a discrete number of authorised climb profiles (e.g. High/Medium/Low) for Solution Option 2 would satisfy the operational needs.

7) Assess the potential challenges associated to the transitions between segments with different vertical angle in the climb for Solution Option 2.

8) Ground support to aircraft technical capability development for Solution Option 1 or Option 2

9) Assess whether it could be a good idea to have a GeoAlt -> baro STD transition somewhere, instead of today's baro QNH -> baro STD. As part of this consider, Manual vs Automatic altitude reference switching, e.g. to include changes to the interface between baro in cruise and geo in descent or airspace border interfaces between baro to geo.

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

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5.2.2 Recommendations for future R&I activities

As identified in Section 5.1.2.3, GNSS availability and reliability is key to the viability of this concept. Therefore, it is recommended that future R&I activities are progressed in relation to the following standards that are in development.

- Standards for the Management of GNSS Jamming & spoofing threats is being developed in ED-259B[31]/DO-401A for 2026
- A Dual Constellation Multi-Frequency SBAS MOPS (Minimum Operational Performance Standards) is expected to be delivered in future iterations, ED-259C/DO-401B, circa 2029.

Additional recommendations relating to GeoAlt, but not directly relating to Green GEAR outcomes:

- GeoAlt for High Altitude Operations (HAO), for example as an early introduction to GeoAlt in cruise for all operations.

- Alternative clearance rules for procedure design. Clearance above obstacles or terrain is currently provided by blanket values for enroute/STAR, initial and intermediate segments with final segments and SIDS being protected with sloping surfaces (other than LNAV only). Clearance between one instrument procedure and another, or between airspace boundaries (i.e. separation with something which is not a physical obstacle) is not something considered during procedure design per se. However, procedure designers may need to refer to other documents/standards when required. New design criteria would need to be created to take account of vertical track keeping when using GeoAlt; these standards could be developed outside of ICAO PANS-OPS. For example, RNP-AR was developed as a standalone design manual [32] and PBN route spacing guidance in the UK was designed as a distinct CAA Publication [33].

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.

Validation

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

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

System engineering

Safety

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

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

Human performance

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

Environment assessment

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

Security

Programme management

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

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

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

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

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

6.2 Reference documents

[24] SESAR 3 ER 1, “Green GEAR Initial OSED – Geometric Altimetry”, Deliverable D3.1, ed. 01.01, 28th June 2024.

[25] SESAR 3 ER 1, “Green GEAR ERP – Geometric Altimetry”, Deliverable D3.2, ed. 01.00, 22nd November 2024.

[26] EUROCAE ED-75 / RTCA DO-236, Minimum Aviation System Performance Standards (MASPS), Required Navigation Performance for Area Navigation

[27] ICAO Doc 8168, Procedures for Air Navigation Services.

[28] ICAO Doc 9613, PBN Manual, Edition 4

[29] https://www.icao.int/safety/OPS/OPS-Section/Pages/flightprocedure.aspx.

[30] https://ifatca.wiki/kb/instrument-flight-procedures/.

[31] ED-259 - Minimum Operational Performance Standards for Galileo - Global Positioning System - Satellite-Based Augmentation System Airborne Equipment

[32] ICAO Doc 9905, Required Navigation Performance Authorisation Required (RNP AR) Procedure Design Manual

[33] CAP1385, PBN Enhanced Route Spacing Guidance, Edition 2, December 2022

Appendix A Validation exercise #01 report

A.1 Summary of the validation exercise #01 plan

Exercise #01 completed in accordance with the ERP SESAR solution 406 (D3.2 – Geometric Altimetry). A summary of the plan is as follows.

A.1.1 Validation exercise description and scope

Exercise #01 is Exercise **TVAL.01.1- GreenGEAR-0406-TRL2** in the ERP [25]; it covers **Use Case 4**, **Fully Geometric TMA, including Departure, Climb, Descent, Initial Approach and Final Approach** in the Initial OSED [24].

Exercise #01 assessed the potential benefits of a fully geometric TMA from an ATC airspace/route design perspective. NATS used its in-house airspace design tool, 'DesignAir', to design sets of procedures - SIDs, STARs and IAPs – for both the solution and reference scenarios.

The validation objectives were to determine whether GeoAlt can safely deliver (a) a net fuel efficiency benefit and (b) a net capacity benefit in the TMA.

Fast-Time Simulations (FTS) of the two designs (geometric and barometric) were run using historic traffic samples derived from real-world UK data as an input to AirTOp® (Air Traffic Optimisation), to accurately model enroute and TMA airspace.

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

SESAR solution validation objective	SESAR solution success criteria	Coverage and comments on the coverage of SESAR solution validation objective in exercise #01	Exercise validation objective	Exercise success criteria
OBJ-GreenGEAR-0406-TRL2-ERP-FUE1 Determine whether GeoAlt can safely deliver a net fuel efficiency benefit for an ATM network in the TMA.	CRT-GreenGEAR-0406-TRL2-ERP-FUE1.001 There is a net fuel efficiency benefit for geometric procedures compared to barometric procedures	Partially covered as assessment limited to high complexity TMA environment	Determine the fuel and environmental impact of a fully geometric high complexity TMA, compared to an optimised TMA based on barometric operations.	There is a net fuel efficiency benefit for geometric procedures compared to barometric procedures

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SESAR solution validation objective	SESAR solution success criteria	Coverage and comments on the coverage of SESAR solution validation objective in exercise #01	Exercise validation objective	Exercise success criteria
OBJ-GreenGEAR-0406-TRL2-ERP-ENV1 Determine whether GeoAlt can safely deliver a net CO_2 emissions benefit for an ATM network in the TMA.	CRT-GreenGEAR-0406-TRL2-ERP-ENV1.001 There is a net CO_2 emissions benefit for geometric procedures compared to barometric procedures	Partially covered as assessment limited to high complexity TMA environment	Determine the fuel and environmental impact of a fully geometric high complexity TMA, compared to an optimised TMA based on barometric operations.	There is a net CO_2 emissions benefit for geometric procedures compared to barometric procedures
OBJ-GreenGEAR-0406-TRL2-ERP-CAP Determine whether GeoAlt can safely deliver a net capacity benefit for an ATM network in the TMA.	CRT-GreenGEAR-0406-TRL2-ERP-CAP.001 There is a net capacity benefit for geometric procedures compared to barometric procedures	Partially covered as assessment limited to high complexity TMA environment	Determine the capacity impact of a fully geometric high complexity TMA, compared to an optimised TMA based on barometric operations.	There is a net capacity benefit for geometric procedures compared to barometric procedures

Table 10: Validation Objectives addressed in validation exercise #01

A.1.3 Summary of validation exercise #01 validation scenarios

The Reference Scenario contained an optimised route structure, utilising current day restrictions: barometric altimetry with Altitude and Flight Level constraints at waypoints.

The test case airspace design for the reference scenario was constructed based on the following design principles:

- RNAV1 and RNP1 STARs SIDs and Initial Approach Procedures
- Altitude or Flight Level constraints applied where necessary for procedural separation only

The Solution Scenario contained an optimised route structure, using the GeoAlt concept: with fixed climb/descent gradients based on geometric point-to-point vertical paths. The solution scenario focused on an idealised end state where there are procedurally-defined geometric lateral and vertical paths meaning that Instrument Flight Procedures (IFPs) are defined in 3 dimensions.

The test case airspace designs were constructed based on the following design principles:

1. Design limited to London TMA routes transiting through, or near, the region of Brookmans Park 'BPK' (northern London TMA), where there is interaction of SIDs and STARs.

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2. Routes are designed from runway to enroute airspace or enroute airspace to runway.
3. PBN Instrument Flight Procedures only; no ATS routes.
4. All SID end points connect to the existing ATS route structure.
5. All STAR start points connect to the existing ATS route structure.
6. CAP1385 route spacing applies; even though applicable in UK only, expect the principle of data-driven design to increase
7. SIDs are able to extend to enroute airspace, i.e. may pass through the Transition Layer. (Current UK CAA guidance does not allow this in the London TMA)
8. Minimum radar separation applies as 3 nm, 1000 ft
9. Procedural separation is to be fully achieved by the route design, i.e. height constraints or vertical profiles are defined accordingly.
10. Climb Via and Descent Via clearances can be applied to every SID, STAR and IAP.
11. Speed constraints only applied on SIDs where there is a turn > 45 degrees.

Specific airspace design principles for the solution scenario were also applied:

12. Vertical route separation rules are based on
    a. Routes crossing or overlapping whilst in level flight= 1,000 ft
    b. Route crossing or overlapping whilst one or both are not in level flight= 1,500 ft
13. 5% and 7% climb geometric gradients assumed optimum achievable for all aircraft types under all wind conditions
14. 3° (5%) geometric descent gradient assumed optimum achievable for all aircraft types under all wind conditions
15. If holding at stack required, follow gradient to the holding level then level-off to enter stack. Will have to descend through the levels and leave at the default At level.

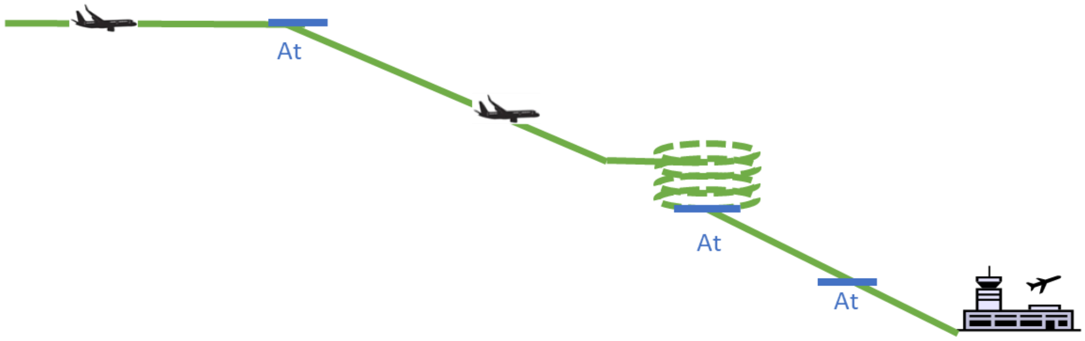

Figure 5: Illustration of the geometric vertical profile is affected by stack holding

16. Fly-by turns will create some variation in track distance flown which may affect vertical profile. Therefore, would be better to us RF Turns instead of, e.g., series of TF legs
17. STARs use AT level constraints at start and end (based on 5% gradient) with not intermediate level constraints. Sector-to-sector standing agreements removed.

Additional airspace Design Principles were derived as part of the iterative design process through DesignAir and AirTOP. To distinguish from the original design principles in the ERP [25], the additional ones are listed as: 11, 13, 14, 15, 16 & 17.

Current day UK airspace was imported into AirTOp to configure the reference scenario. The Green GEAR design (solution scenario) was exported from DesignAir. Peak summer and winter traffic days were imported into AirTOp and aligned with the Green GEAR network structure. Traffic that fell outside of the scope of the Green GEAR design was removed from the simulations (e.g. where flight profiles and routes were unchanged). Vertical limitations and speed restrictions were added to adhere to the Green GEAR design.

Procedural models were used to determine fuel, CO2e emission and track differences between the Green GEAR GeoAlt design and the Reference scenario. These models did not simulate any holding, vectoring or arrival sequencing. The models were run 10 times each, with randomised flight departure times. The results were used to determine the environmental impact of the GeoAlt design.

Network models, that simulated holding, vectoring, and arrival sequencing, were run 20 times each, with randomised flight departure times. The results were used to determine the additional impact of network congestion.

Both the procedural and network models (Reference scenario and Solution scenario) were run for 2 sample days (7th July and 6th October), for the 2 years (2023 and 2035) on a westerly runway configuration only. Traffic was grown in 2035 based on the STATFOR MTF forecast (Feb 2024) UK growth rate. The output from the 2 samples days was than annualised based on the anticipated traffic counts across the winter and summer seasons.

Comparisons of the performances of the two designs under historic peak traffic loading has been undertaken against the validation objectives to determine whether GeoAlt can safely deliver (a) a net fuel efficiency benefit and (b) a net capacity benefit in the TMA.

Traffic Samples

The traffic samples used in these simulations were taken from a 2023 summer day (7th July) and a 2023 winter day (6th October). These days were selected as busy traffic days.

There were 78 aircraft types in the imported traffic samples. The complexity of creating 78 new aircraft variants was too much of a risk to the integrity of the simulation output, and as such it was deemed appropriate to group the aircraft into representative types. This resulted in 8 common aircraft type groupings. Once grouped, new aircraft type variants were created with 7% climb rate profiles to enable them to fly the Green GEAR departure routes. The aircraft counts, by type, for each of the airports is shown below.

	EGLL		EGLC		EGSS		EGGW	
	Arrivals	Departures	Arrivals	Departures	Arrivals	Departures	Arrivals	Departures
A320	382	386	4	4	47	48	148	141
B738	15	17	2	2	242	234	26	25
B789	128	148	0	0	2	2	0	0
B77W	117	119	0	0	7	7	0	0
C56X	0	0	1	3	9	10	23	28
E190	4	4	62	63	3	3	6	4
A388	27	27	0	0	0	0	0	0
B763	14	14	0	0	7	7	2	2
Other	9	9	10	10	11	7	21	16

Table 11: Aircraft Type counts for 2023-07-07 (summer day)

	EGLL		EGLC		EGSS		EGGW	
	Arrivals	Departures	Arrivals	Departures	Arrivals	Departures	Arrivals	Departures
A320	372	377	3	3	41	44	141	134
B738	16	17	3	3	241	232	25	27
B789	113	138	0	0	1	1	0	0
B77W	127	127	0	0	8	8	0	0
C56X	0	0	0	2	1	7	22	20
E190	5	5	71	72	2	2	2	2
A388	34	35	0	0	0	0	0	0
B763	17	17	0	0	4	4	2	2
Other	8	9	9	8	10	13	18	20

Table 12: Aircraft Type counts for 2023-10-06 (winter day)

Traffic Growth to 2035

Each of the arrival and departure flows were measured as a percentage of the total flights for each of the airports. The daily averages were then multiplied by the 2023 recorded traffic levels for the summer and winter days for the individual traffic flows to provide an annual total benefit for 2023 traffic.

Traffic was grown to 2035 levels, using the STATFOR MTF forecast (Feb 2024) UK growth rate. The traffic at each airport was grown as a whole and the arrival and departure flows calculated as a percentage of the grown total. The forecast UK growth rate at each airport for 2035, was 23%, or a scale factor of 1.23.

EGLL traffic was not grown (as part of the 2035 analysis) as additional assumptions on future application and effectiveness of ATC tools is out of scope of this assessment. Without these, any additional traffic to EGLL, oversaturates the RMA and adversely impacts the model. As a consequence, the overall traffic growth was 10% or 1.10.

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	EGLL		EGLC		EGSS		EGGW	
	Arrivals	Departures	Arrivals	Departures	Arrivals	Departures	Arrivals	Departures
A320	382	386	4	5	56	61	177	177
B738	15	16	3	2	289	287	28	32
B789	136	138	0	0	8	8	0	0
B77W	109	129	0	0	3	4	0	0
C56X	0	0	5	2	12	10	30	28
E190	4	4	77	80	4	6	6	10
A388	27	27	0	0	0	0	0	0
B763	14	14	0	0	8	8	2	3
Other	9	10	10	18	14	8	28	24

Table 13: Aircraft Type counts for 2035-07-07 (summer day)

	EGLL		EGLC		EGSS		EGGW	
	Arrivals	Departures	Arrivals	Departures	Arrivals	Departures	Arrivals	Departures
A320	372	377	3	4	48	56	164	184
B738	16	17	4	3	297	281	30	33
B789	145	145	0	0	9	10	0	0
B77W	104	129	0	0	1	1	0	0
C56X	0	0	2	2	8	7	28	24
E190	5	5	87	87	2	3	4	4
A388	25	26	0	0	0	0	0	0
B763	17	17	0	0	7	7	2	2
Other	8	9	12	13	13	19	15	21

Table 14: Aircraft Type counts for 2035-10-06 (winter day)

A.1.4 Summary of validation exercise #01 validation assumptions

The validation assumptions for exercise #01 in addition to those identified in section 3.2.3, are given in Table 15.

Assumption ID	Assumption title	Assumption description	Justification	Impact assessment
ASS-GreenGEAR-0406-TRL2-ERP-003	Aircraft Performance	It is assumed that all aircraft have equipage with geometric vertical navigation. .	To enable benefit analysis of the fully geometric end state	Benefits analysis captures a specific option end state only

Assumption ID	Assumption title	Assumption description	Justification	Impact assessment
ASS-GreenGEAR-0406-TRL2-ERP-004	Aircraft Equipage with V-RNP	Aircraft navigation systems have been developed to comply with a vertical tolerance applied to Instrument Flight Procedures (IFPs)	To enable benefit analysis of the fully geometric end state	Benefits analysis captures a specific option end state only
ASS-GreenGEAR-0406-TRL2-ERP-005	Airspace layout using Vertical Route Separation	Vertical route separation rules for the geometric test case airspace design will be based on: • Routes crossing or overlapping whilst in level flight= 1,000 ft • Route crossing or overlapping whilst one or both are not in level flight= 1,500ft	To enable benefit analysis of the fully geometric end state. The separation is based on 2x the largest Vertical Path Performance Limits defined in ED-75/DO-236.	The benefits of geometric route design are based on a research assumption that is not formally defined but is simply an extrapolation of the lateral PBN logic.
ASS-GreenGEAR-0406-TRL2-ERP-006	GeoAlt Regulation	The use of geometric altimetry for vertical navigation within the TMA has been mandated	To enable benefit analysis of the fully geometric end state.	Benefits analysis captures a specific option end state only
ASS-GreenGEAR-0406-TRL2-ERP-007	Traffic Characteristics	Traffic will be based on London arrivals and departures	Use of historic traffic data for London TMA is the most representative traffic for the test case	Not all aircraft types will be assessed.

Table 15: validation exercise #01 assumptions overview

A.2 Deviation from the planned activities

There were no deviations from the Exploratory Research Plan (ERP) [25], except for the following.

Assumption ASS-GreenGEAR-0406-TRL2-ERP-005, was changed:

- Route crossing or overlapping whilst one or both are not in level flight= 1,500 ft [*instead of 1,520ft as defined in the ERP*]

The change was made for simplification of airspace design and analysis at this low maturity stage, rounding the separation to the nearest 100ft.

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A.3 Validation exercise #01 results

A.3.1 Summary of validation exercise #01 results

Exercise #01 validation objective ID	Exercise #01 validation objective title	Exercise #01 success criterion ID	Exercise #01 success criterion	Sub-operating environment	Exercise #01 validation results	Exercise #01 validation objective status
OBJ-GreenGEAR-0406-TRL2-ERP-FUE1	Determine the fuel and environmental impact of a fully geometric high complexity TMA, compared to an optimised TMA based on barometric operations.	CRT-GreenGEAR-0406-TRL2-ERP-FUE1.001	There is a net fuel efficiency benefit for geometric procedures compared to barometric procedures	TMA HC	Arrival and departure flows showed a decrease in fuel burn and a forecast reduction in fuel by 2035. Annualised fuel reduction at 2035 traffic levels of.	OK
OBJ-GreenGEAR-0406-TRL2-ERP-ENV1	Determine the fuel and environmental impact of a fully geometric high complexity TMA, compared to an optimised TMA based on barometric operations.	CRT-GreenGEAR-0406-TRL2-ERP-ENV1.001	There is a net CO_2 emissions benefit for geometric procedures compared to barometric procedures.	TMA HC	Arrival and departure flows showed a decrease in CO2e and a forecast reduction in CO2e by 2035. Annualised CO2e reduction at 2035 traffic levels of.	OK

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Exercise #01 validation objective ID	Exercise #01 validation objective title	Exercise #01 success criterion ID	Exercise #01 success criterion	Sub-operating environment	Exercise #01 validation results	Exercise #01 validation objective status
OBJ-GreenGEAR-0406-TRL2-ERP-CAP	Determine the capacity impact of a fully geometric high complexity TMA, compared to an optimised TMA based on barometric	CRT-GreenGEAR-0406-TRL2-ERP-CAP.001	There is a net capacity benefit for geometric procedures compared to barometric procedures	TMA HC	On average, across all hours of the day, there are 36 hourly sector entries in the Reference compared to 33 in the Solution Scenario. However, there has been a marginal increase in occupancy times in the Solution Scenario.	NOK

Table 16: validation exercise #01 results

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

The first challenge was to design a geometric airspace using the design principles given in Section 0. The solution scenario enabled continuous climbs and continuous descents to be designed in, with fewer level-offs required in climb or descent; also, some lateral track distances could be shortened. The profile improvements were enabled due to the reduction in the uncertainty buffers typically built in due to pressure variation / Transition Layer and the position of the aircraft in-between waypoints.

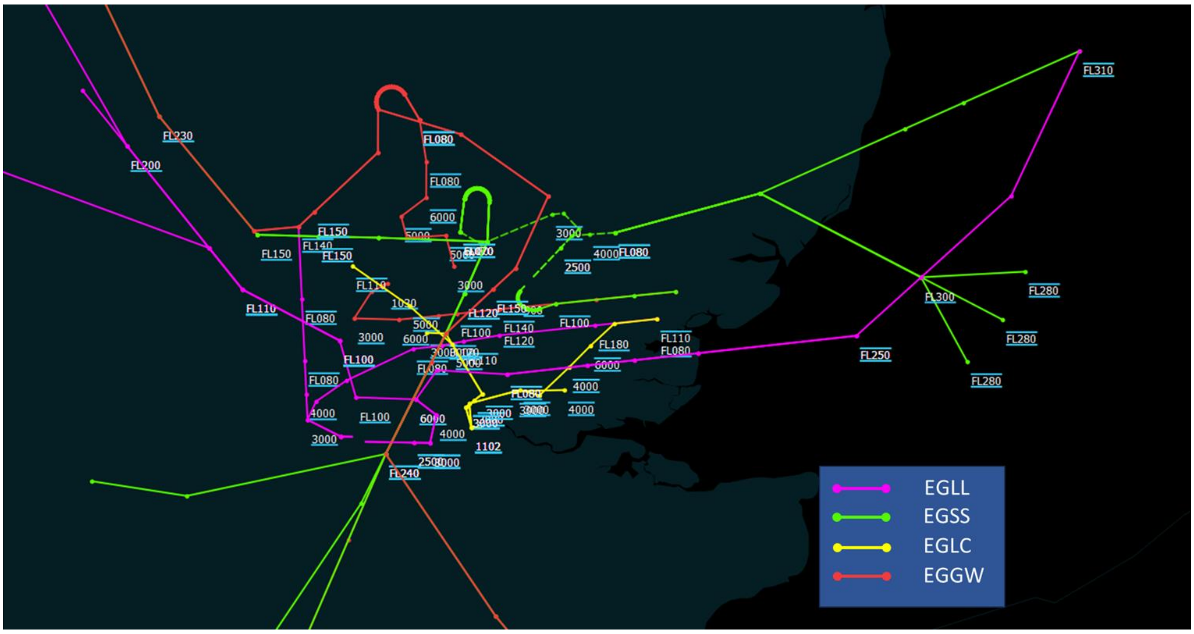

Figure 6: Reference Scenario - barometric altimetry with Altitude and Flight Level constraints at waypoints

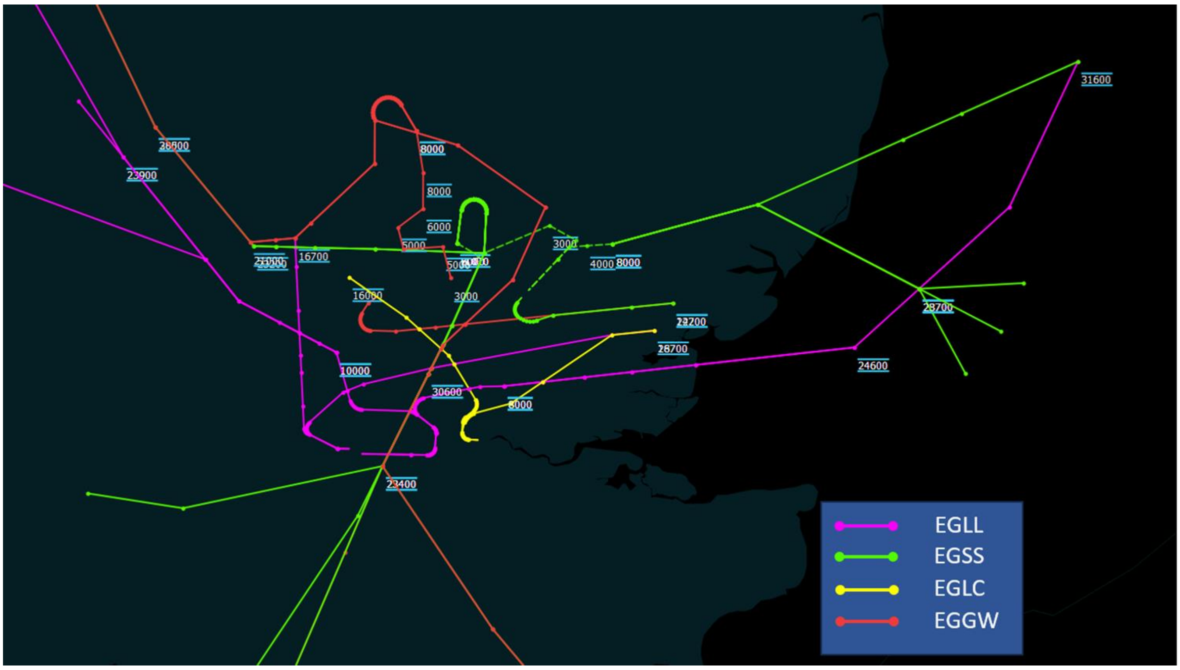

Figure 7: Solution Scenario - fixed climb/descent gradients based on geometric point-to-point vertical paths

A.3.2.1 OBJ-GreenGEAR-0406-TRL2-ERP-FUE1 Results

Overall a significant fuel benefit was indicated. However, the size of the benefit only shows a potential scale of benefit as there were limitations with the modelling capability because speed profiles could

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not be adjusted according to the climb or descent rate. Therefore, the calculated fuel differences between Reference and Solution Scenarios are based on the difference in the vertical profiles and lateral track distance.

Fuel and CO2e analysis has been carried out on the proposed Green Gear model. The fuel and CO2e calculations for this analysis have been based solely on the affected routes and the traffic utilising those routes. Any routes that have not changed as part of the Green Gear model and remain as current day operations have not been included.

Routes have been cut to the UK FIR boundary, and all calculations are based on the segments of the routes between UK FIR boundary and runway or vice versa for arrivals and departures respectively.

DESCENT & APPROACH

Comparison of the descent results under Exercises #01 (this section) and #04 (see Appendix C) showed a reasonable correlation.

	2023 Arrivals		
	Fuel Burn (T)	CO2e (T)	%
EGLL	-1,394	-4,391	-0.9%
EGSS	-2,243	-7,065	-2.8%
EGGW	-1,196	-3,767	-2.1%
EGLC	-	-	-
Total	-4,833	-15,224	-1.6%
Per flight (kg)	-23.15	-72.91	-1.6%

Table 17: 2023 Fuel/CO_2e impacts on arrivals with the % change relative to overall fuel in UK FIR.

	2035 Arrivals		
	Fuel Burn (T)	CO2e (T)	%
EGLL	-1,447	-4,558	-1.0%
EGSS	-2,460	-7,749	-2.5%
EGGW	-2,042	-6,432	-2.7%
EGLC	-	-	-
Total	-5,949	-18,739	-1.8%
Per flight (kg)	-24.20	-76.22	-1.8%

Table 18: 2035 Fuel/CO_2e impacts on arrivals with the % change relative to overall fuel in UK FIR.

Arrivals (avg. per flight)

- The difference between the Reference and Solution Scenarios for EGLL LAM arrivals was not significant enough to provide any benefit. EGLL arrivals via BNN averaged approximately 1% per flight fuel burn reduction.

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- EGSS arrivals showed the greatest reduction with a 3% per flight benefit for both ABBOT and LOREL arrivals.
- EGGW arrivals showed an average 2% per flight reduction.

CLIMB

Comparison of the original climb results under Exercises #01 (Appendix A) and #04 (Appendix C)) showed a discrepancy between the results. This was investigated between project partners and found to be due to differences in the modelling assumptions and limitations imposed to simplify the analysis at this low maturity phase.

There was a difference in common end point between the barometric and geometric climbs. The analysis under Exercise #01 assumed the 7% climb gradient continued past the end of the SID to cruise (e.g. 36,000ft). Whereas analysis under Exercise #04 assumed a shallow climb gradient for the solution scenario after the SID end point (e.g. 17,000ft) to a common end point at 20,000ft.

In Exercise #01, a constant climb gradient was used for practicality reasons, i.e. to simplify the test case airspace design. However, it is clear that a climb gradient of 7% could not be maintained by the majority of aircraft all the way to cruise height, making the results overly optimistic.

In Exercise #04, an end point of 20,000ft was used for practicality reasons. The fixed end point was to ensure that the scenario always ends at the same energy level even when using barometric altimetry with different QNH values. However, Exercise #01 determined that a significant benefit is obtained by reaching cruise height earlier, making the Exercise #04 results overly pessimistic.

Therefore, an additional piece of analysis was conducted in January to bridge the two outcomes. This involved measuring the fuel impact all the way to a common point at cruise height, but with a standard tapering gradient after the end of the SID instead of a fixed gradient. Figure 8 shows how the climb profiles were created for the additional analysis compared the original solution scenario (Appendix A) and reference scenario. The green line represents a more practical vertical climb profile for the solution scenario than the red. It can be seen that avoidance of a level-off in the climb enables the flight to reach its cruise height earlier.

In response to the results from Exercise #03: *limit fixed vertical angle paths to the smallest extent possible* (refer to Section 4.2.9), it was determined that SIDs designed with an end point higher than 17,000ft could be capped at 17,000ft, part way along the SID, without causing procedural conflict, meaning that the forced 7% gradients in the geometric design never extended higher than 17,000ft. This further increases the achievability of the results. Other SIDs ended at much lower heights.

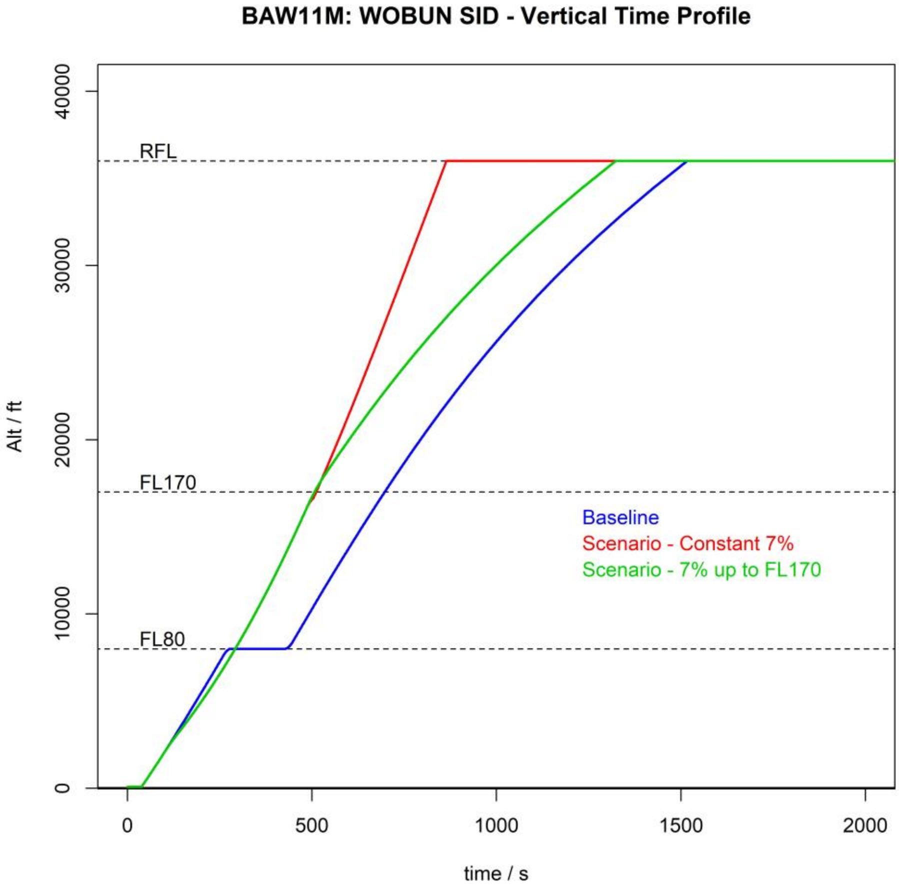

Figure 8: An example of the relative vertical climb profiles of the Reference Scenario ('Baseline'), Solution Scenario ('Scenario – Constant 7%') and additional analysis ('Scenario – 7% up to FL170')

The revised annual departure fuel burn benefits between barometric and geometric designs are summarised in Table 19. Benefits are highlighted in green, penalties (i.e. more fuel consumed) are highlighted in red.

	2023 DEPARTURES		
	Fuel Burn (T)	CO2e (T)	%
EGLL	-3,870	-12,191	-2.6%
EGSS	4,126	12,998	2.5%
EGGW	-7	-22	-0.7%
EGLC	-580	-1,827	-2.9%
Total	-331	-1,042	-0.1%
Per flight (kg)	-2.12	-6.68	-0.1%

Table 19: Annual 2023 Fuel/CO_2e impacts on departures with the % change relative to overall fuel in UK FIR.

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For the 2023 traffic sample there is a 6.68kg CO2e benefit per aircraft, changing to a 5.23kg CO2e disbenefit per aircraft in 2035, because the forecast traffic growth between 2023 and 2035 created a multiplier effect for the less efficient geometric SIDs. EGSS traffic is grown. EGLL traffic is assumed to remain static, i.e. a third Heathrow runway is not assumed.

	2035 DEPARTURES		
	Fuel Burn (T)	CO2e (T)	%
EGLL	-3,870	-12,191	-2.6%
EGSS	4,905	15,451	2.4%
EGGW	-9	-28	-0.6%
EGLC	-724	-2,280	-2.4%
Total	302	952	0.1%
Per flight (kg)	1.66	5.23	0.1%

Table 20: Annual 2035 Fuel/CO_2e impacts on departures with the % change relative to overall fuel in UK FIR.

NOTE: A negative value represents a fuel burn benefit when comparing the geometric scenario to the barometric scenario. For this analysis a conversion factor of 1 : 3.15 has been used per kg fuel to kg CO_2e.

The fuel flow rates are calculated from a BADA 4.2 model. The climb rate and true airspeed of the profile are inputs into the full BADA equations to derive the thrust and therefore fuel consumption of the aircraft. The assumed mass of the aircraft is the BADA nominal mass value which varies for each aircraft type. Only the rate of climb and procedures are altered between barometric and geometric models. The net result is a fuel flow rate that is impacted by the rate of climb and phase of flight (climb, level, descent).

The barometric model uses climb rates and IAS values based on observed mean performance for each aircraft type within the UK FIR. The departure procedures (SIDS) in the barometric often require periods of level flight in order to design in separation of traffic flows.

In comparison, the geometric model has a composite of climb rate assumptions. Below 3000ft, the climb rates are the same as in the barometric model. This is to allow aircraft to achieve minimum speed and climbs to get airborne from the runway and comply with local noise profile restrictions. Above 3000ft up to the end flight level of the SID[4], or up to FL170, whichever is lower, a constant 7% climb rate is modelled. There occasionally is small amount of divergence from 7% climb rate due to calculation conversions between IAS and TAS. Above the end of the SID or FL170, typical aircraft performance climb rates are used as per the barometric model. The size of the benefit only shows a

[4] For Stansted departures (PAAVO, NUGBO, UTAVA) this is FL130, for all other departures we assume the FL170 limit as the effective end of the 7% climb gradient. Even though some SIDs (EGLL BINNY) end higher at FL280.

potential scale of benefit as there were limitations with the modelling capability because speed profiles could not be adjusted according to the climb or descent rate.

As can be seen in Table 19 (2023 results) and Table 20 (2035 results), some of the geometric SIDs provide a benefit and others a disbenefit. There is a large variability in benefits, on a case by case basis, depending on the geometric gradient compared to the barometric and the duration of level segments at a low altitude. The following figures illustrate these differences.

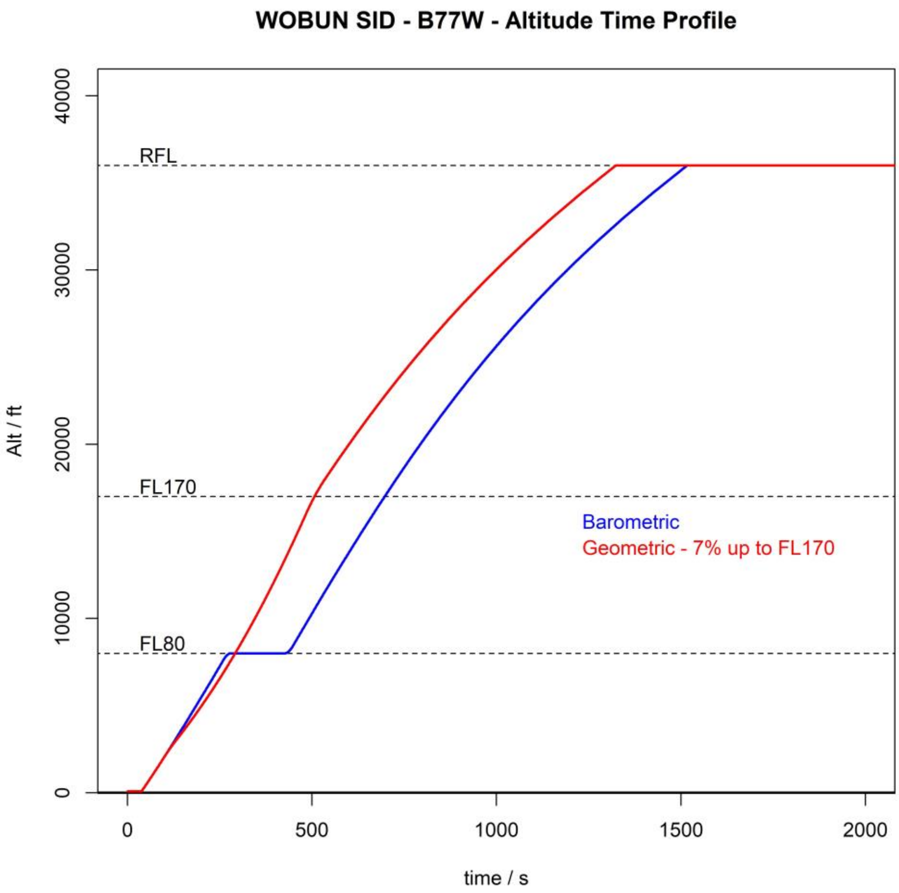

Figure 9: EGLL WOBUN SID profile for a B77W from FTS.

WOBUN SID – B77W – The barometric design has a level-off limitation at FL80. The initial climb rate performance of an B77W exceeds 7%. However, the Geometric design no longer requires a level off and has a slightly higher performance above FL100. The net effect is an earlier cruise at RFL instead of a more fuel inefficient level-off at low altitudes.

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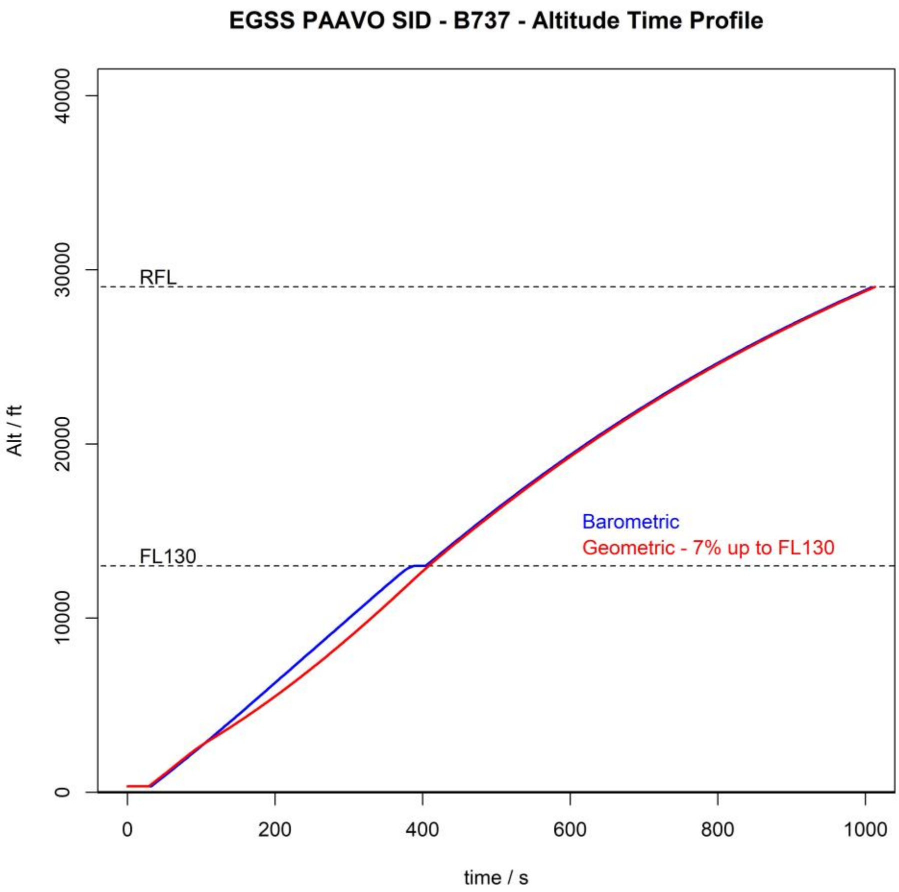

Figure 10: EGSS PAAVO SID profile for a B737 from FTS.

PAVVO SID – B737 – The barometric design has a single minor level-off limitation at FL130. The Geometric design no longer requires a level off. The low-level climb performance of an B737 exceeds 7%, with the SID ending at FL130. The net effect is an alignment of profiles by the end of the SID. This comparison returns a fuel disbenefit as the geometric profile has a longer period of climb, whereas in the baseline the BADA 4.2 model returns a more optimum profile with a higher climb rate and a period of level flight (which is always a lower fuel rate than climb). The disbenefit observed in the geometric profile for this departure is likely linked to the high usage of B737 aircraft with a high climb gradient profile. Lower climb rate aircraft may see no significant difference between barometric limitations and geometric procedures.

The figures presented below (Table 21) are combined annual totals (T) for departures for all four airports.

	DEPARTURES	
	Fuel Burn (T)	CO_2e (T)
2023	-331	-1,042
2035	302	952

Table 21: Total summarised fuel and CO2e impact for departures

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A.3.2.2 OBJ-GreenGEAR-0406-TRL2-ERP-ENV1 Results

Overall a significant CO_2 emissions benefit was indicated. However, the size of the benefit only shows a potential scale of benefit as there were limitations with the modelling capability because speed profiles could not be adjusted according to the climb or descent rate. Therefore, the calculated emissions differences between Reference and Solution Scenarios are based on the difference in the vertical profiles and lateral track distance.

The environmental results were derived as a direct factor of the fuel results because the analysis only considered a measure of the CO_2 equivalent emissions (CO2e) directly generated from the fuel burn: fuel x 3.15. Therefore, the results for ENV1 are captured under Section A.3.2.1.

A.3.2.3 OBJ-GreenGEAR-0406-TRL2-ERP-CAP Results

Overall, no capacity increase was indicated through the proxy metrics analysed. However, there was no conclusive significant detriment to capacity either.

The average sector entries per hour varies by sector due to different traffic flows entering or not entering a sector in the Reference scenario and Solution scenario. This is because climb and descent rate changes cause some traffic flows to climb above while others remain below certain sector. Overall, the trend between the models is similar and as expected with no difference to traffic levels spread across the day. For the 2035 traffic sample, across all hours of the day there are on average 36 hourly sector entries in the reference scenario compared to 33 hourly sector entries in the solution scenario.

In terms of sector occupancy, on average flights spend an extra 7 seconds longer across all the sectors in the solution scenario compared to the reference scenario in 2035. This is due to the less steep 7% climb profiles than statistically observed at 8% on the SIDs. This is more noticeable in the EGTTLAM, EGTTJAC and EGTTSAB sectors where the aircraft are spending longer climbing in these sectors. Overall, there has been a marginal increase in occupancy times between the reference and solution scenarios.

Sector counts and occupancy analysis is completed by running the Reference and Solution Scenario fast time models each 20 times, with randomised flight departure times. This adds robustness to the analysis by using the average hourly sector entries and average sector occupancy duration per flight. As the Green GEAR option involves changes to aircraft climb and descent profiles, only a fully Westerly runway configuration is assessed. Figure 11 illustrates the sectors examined in the following sections.

The analysis has indicated that the overall number of interactions between aircraft in the Scenario has increased by 27% compared to the Reference Scenario for the 2035 traffic sample. This is mainly due to increased interactions between Heathrow arrivals levelling off at higher levels for the BNN hold interacting with Stansted NUGO and Heathrow WOBUN departures in the EGTTBNN sector. The higher levelling off at the BNN hold is a result of the fast time simulation software sequencing more favourably other holding Heathrow traffic due to the distribution of traffic in the sample. In reality, the operation will tactically manage this to prevent an imbalance in the holds and can stack swap at peak times. Both the Reference and Solution Scenario models have removed the BPK interaction hotspot and expanded to other regions where interaction hotspots may exist in reality today. Further improvements could be found by de-conflicting certain flows in each sector and in particular, in five hotspot areas identified in the analysis.

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Sector Entries

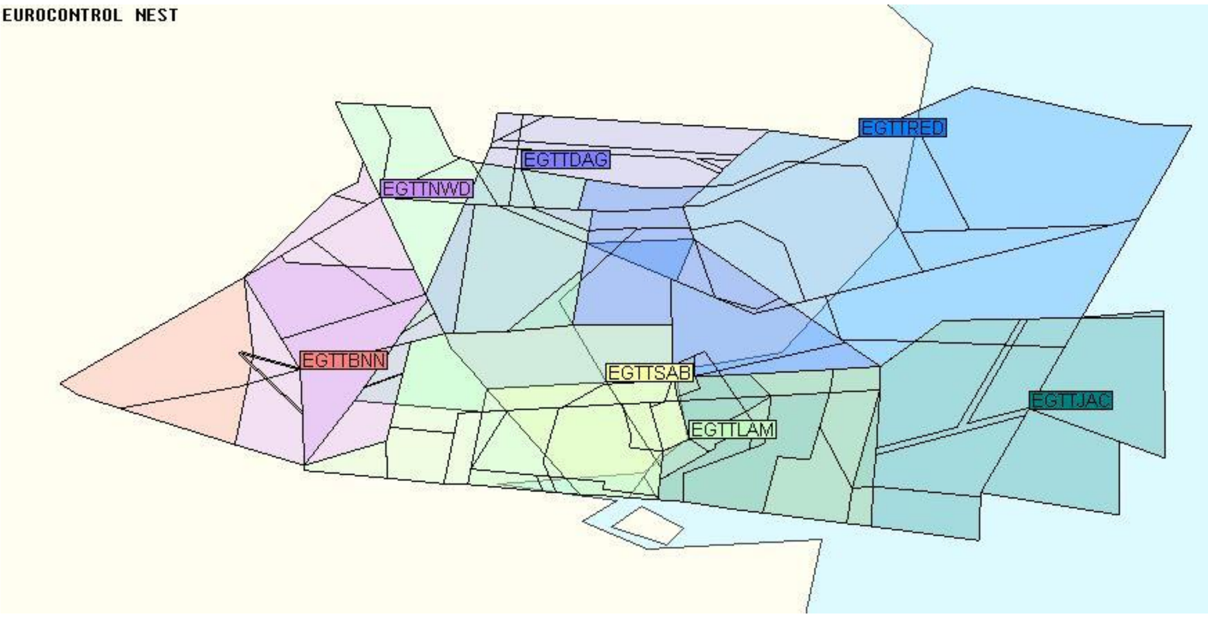

Figure 11: A map of the sectors.

Note that the sector EGTTNWA is above EGTTNWD but not shown.

The average number of sector entries is defined as the distinct number of flights entering a sector per hour. Flights that enter and exit the same sector multiple times in the same hour are only counted once.

Table 22 shows that the average sector entries per hour vary by each sector as different traffic flows enter or do not enter sectors in the Reference and Solution Scenario. Only the EGTTDAG, EGTTRED and EGTTSAB sectors to the East have similar average hourly sector counts between the models.

The highest number of sector entries occur between the morning peak hours of 6am-7am with the second peak hour at 3pm-4pm. On average, across all hours of the day there are 31 hourly sector entries in the Reference Scenario compared to 29 hourly sector entries in the Solution Scenario.

Sector	EGTTBNN		EGTTDAG		EGTTJAC		EGTTLAM		EGTTLOR		EGTTNWA		EGTTNWD		EGTTRED		EGTTSAB	
Hour	BL	SC	BL	SC	BL	SC	BL	SC	BL	SC	BL	SC	BL	SC	BL	SC	BL	SC
0	7	7	3	3	3	0	4	2	8	7	2	1	3	4	5	5	1	1
1	5	5	5	5	3	1	5	5	4	4	0	0	4	4	4	4	4	4
2	8	7	2	2	5	4	5	4	5	6	1	1	4	3	3	3	4	6
3	11	13	7	7	3	2	8	9	6	5	1	1	7	8	7	7	6	6
4	11	11	7	5	6	2	18	15	10	9	2	1	16	14	10	8	13	12
5	33	45	38	40	22	19	108	91	28	17	16	16	78	81	30	36	43	42
6	45	56	44	46	20	14	144	115	43	29	18	21	100	100	33	33	45	45
7	30	39	40	41	22	18	102	84	33	22	17	18	80	83	29	29	24	22
8	36	41	34	33	24	19	70	60	27	21	10	19	62	67	28	27	28	24
9	41	40	32	33	28	19	73	41	39	36	5	8	66	53	29	29	24	22
10	30	35	36	35	29	22	83	63	52	41	13	16	64	63	33	34	25	22
11	40	48	36	37	21	13	79	59	55	40	13	18	82	81	32	34	23	21
12	34	37	38	37	21	15	81	61	35	27	10	15	73	71	40	37	28	26
13	36	41	32	33	24	14	81	58	36	31	10	19	80	77	30	30	29	27
14	43	49	34	35	27	20	84	65	42	34	10	22	88	87	30	31	25	24
15	35	42	47	48	28	24	110	87	46	38	11	18	87	85	40	41	40	38
16	28	34	43	44	33	28	112	79	50	41	12	15	86	82	34	33	34	34
17	31	34	34	35	29	21	93	72	35	28	12	16	83	80	34	31	32	29
18	32	37	38	37	19	12	94	62	44	36	12	19	79	75	31	26	22	21
19	31	34	45	46	13	9	91	58	42	39	11	15	71	62	35	37	20	20
20	22	26	27	27	18	7	56	38	34	27	13	15	61	56	23	22	21	18
21	15	16	27	28	7	2	43	19	37	34	5	7	44	36	18	19	8	8
22	2	3	12	11	7	0	17	9	39	29	6	4	13	10	14	13	6	4
23	2	1	8	8	5	0	10	4	20	20	3	2	7	6	6	7	2	2
Average	25	29	28	28	17	13	65	48	32	26	9	12	56	53	24	24	21	20

Table 22: Average hourly sector counts per sector in the Reference and Solution Scenarios with 2023 traffic

Table 23 shows that the average sector entries per hour vary by each sector as different traffic flows enter or do not enter sectors in the Reference and Solution Scenarios.

The highest number of sector entries occur between the morning peak hours of 6am-7am with the second peak hour at 3pm-4pm. On average, across all hours of the day there are 36 hourly sector entries in the Reference Scenario compared to 33 hourly sector entries in the Solution Scenario.

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Sector	EGTTBNN		EGTTDAG		EGTTJAC		EGTTLAM		EGTTLOR		EGTTNWA		EGTTNWD		EGTTRED		EGTTSAB	
Hour	BL	SC	BL	SC	BL	SC	BL	SC	BL	SC	BL	SC	BL	SC	BL	SC	BL	SC
0	7	9	3	3	4	0	6	4	11	6	4	3	5	7	6	6	1	1
1	5	5	5	6	3	1	6	5	5	4	0	0	5	5	4	4	4	4
2	7	7	2	2	6	6	5	5	9	8	1	1	4	4	5	5	4	6
3	11	13	8	9	3	2	9	10	6	4	1	1	9	9	7	7	6	6
4	12	11	11	8	7	2	19	17	15	13	2	1	18	15	13	11	13	13
5	36	49	45	49	24	20	121	105	34	18	19	19	85	90	36	43	48	45
6	49	61	53	55	25	17	160	130	47	29	19	23	110	110	42	44	49	48
7	29	41	47	50	26	20	113	96	39	22	22	21	86	94	36	37	27	23
8	39	45	39	38	32	25	81	72	30	22	12	21	71	72	32	30	29	25
9	46	44	36	39	34	24	83	49	44	37	4	7	72	60	33	35	29	25
10	32	36	43	43	34	27	95	75	60	42	13	16	67	63	37	38	25	24
11	44	53	43	45	23	15	89	69	69	44	16	22	89	94	37	41	27	24
12	35	40	47	46	23	15	93	72	43	30	13	17	79	79	51	48	32	29
13	40	44	36	37	26	15	88	64	44	33	14	22	85	83	33	34	30	27
14	43	51	37	39	31	26	95	77	53	37	14	26	94	93	33	34	29	27
15	37	47	55	56	33	30	128	104	59	40	17	26	95	98	47	47	43	41
16	28	37	51	53	44	36	124	91	58	39	14	17	91	89	42	39	39	39
17	33	38	40	41	34	24	108	83	45	33	17	19	94	89	38	35	35	31
18	34	40	42	41	23	14	104	69	52	39	15	23	86	80	35	28	23	22
19	35	40	57	58	17	11	111	76	49	40	13	19	79	72	47	49	27	25
20	25	27	31	34	21	9	66	49	44	32	17	18	67	62	29	29	19	19
21	16	16	37	36	8	2	53	26	48	37	7	9	51	41	22	23	10	9
22	2	4	14	16	8	0	21	13	45	33	8	5	16	11	16	17	6	5
23	1	1	10	10	5	0	11	5	28	18	4	2	8	8	7	7	2	2
Average	27	31	33	34	20	15	74	57	39	27	11	14	61	59	28	28	23	21

Table 23: Average hourly sector counts per sector in the Reference and Solution Scenarios with 2035 traffic

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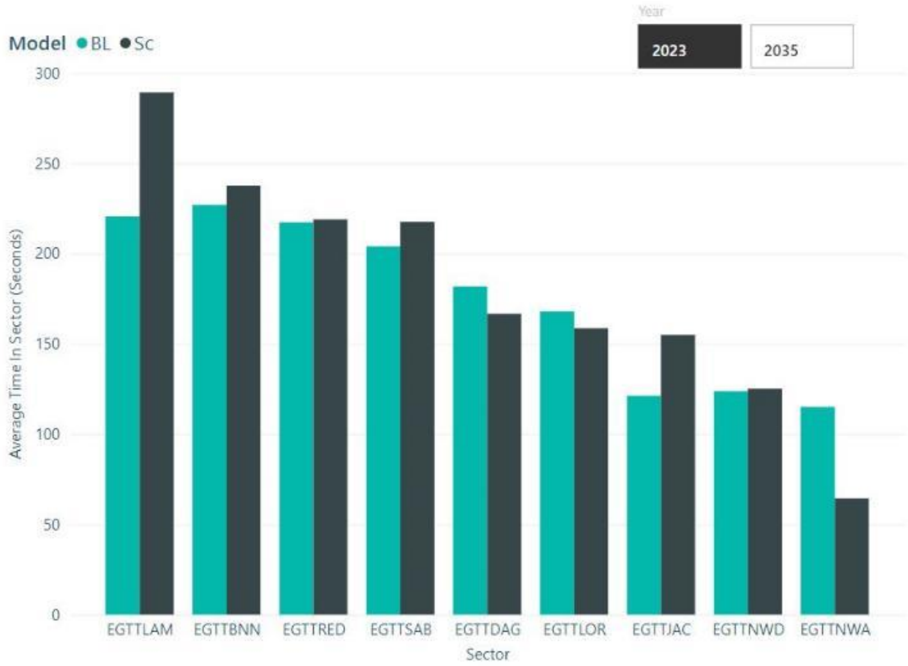
Sector Occupancy

The average sector occupancy per flight is defined as the average time (in seconds) a flight spends in each sector.



Sector	BL	Sc
EGTTBNN	227	238
EGTTDAG	182	167
EGTTJAC	121	155
EGTTLAM	220	289
EGTTLOR	168	159
EGTTNWA	115	64
EGTTNWD	124	125
EGTTRED	217	219
EGTTSAB	204	218
Total	**175**	**181**

Figure 12: Average sector occupancy per flight in each sector in 2023.

Figure 12: Average sector occupancy per flight in each sector in 2023.On average, flights spend between 1 minute 55 seconds in the EGTTNWA sector and the longest at 3 minutes 47 seconds in the EGTTBNN sector in the Reference Scenario for the 2023 traffic sample. In the Solution Scenario, this varies between 1 minute and 4 seconds in the EGTTNWA sector and the longest at 4 minutes and 49 seconds in the EGTTLAM sector. On average across all the sectors, flights spend an extra 6 seconds longer in the Solution Scenario compared to the Reference Scenario, due to the less steep 7% climb profiles than statistically observed at 8%. This is more noticeable in the EGTTLAM, EGTTJAC and EGTTSAB sectors where the aircraft are spending longer climbing in these sectors.

However, in the EGTTNWA sector, flights are spending 51 seconds longer in the Reference Scenario compared to the Solution Scenario. This is mainly due to the Stansted departures are given unrestricted climb on the NUGBO and UTAVA SIDs in the Reference Scenario and spend approximately 1 minute 50 seconds on average climbing in the EGTTNWA sector. In the Solution Scenario these no longer enter the EGTTNWA sector as they level off at 8,900ft and 9,500ft until the end of the SIDs.

There are also a greater number of Heathrow WOBUN departures entering and climbing for an average of 1 minute 7 seconds in the EGTTNWA sector in the Solution Scenario. In the Reference Scenario, these Heathrow WOBUN departures level off at 8,000ft on the SID and remain in the lower EGTTNWD sector. However, the duration of these Heathrow WOBUN departures in the Solution Scenario has been offset by the longer climbing duration of the Stansted departures in the Reference Scenario.

Figure 13 shows a similar picture, and on average flights spend an extra 7 seconds longer across all the sectors in the Solution Scenario compared to the Reference Scenario. In addition to the EGTTLAM, EGTTSAB and EGTTJAC sectors, flights are also spending slightly longer in the EGTTLOR sector in the Solution Scenario. Overall, there has been a marginal increase in occupancy times between the Reference and Solution Scenarios.

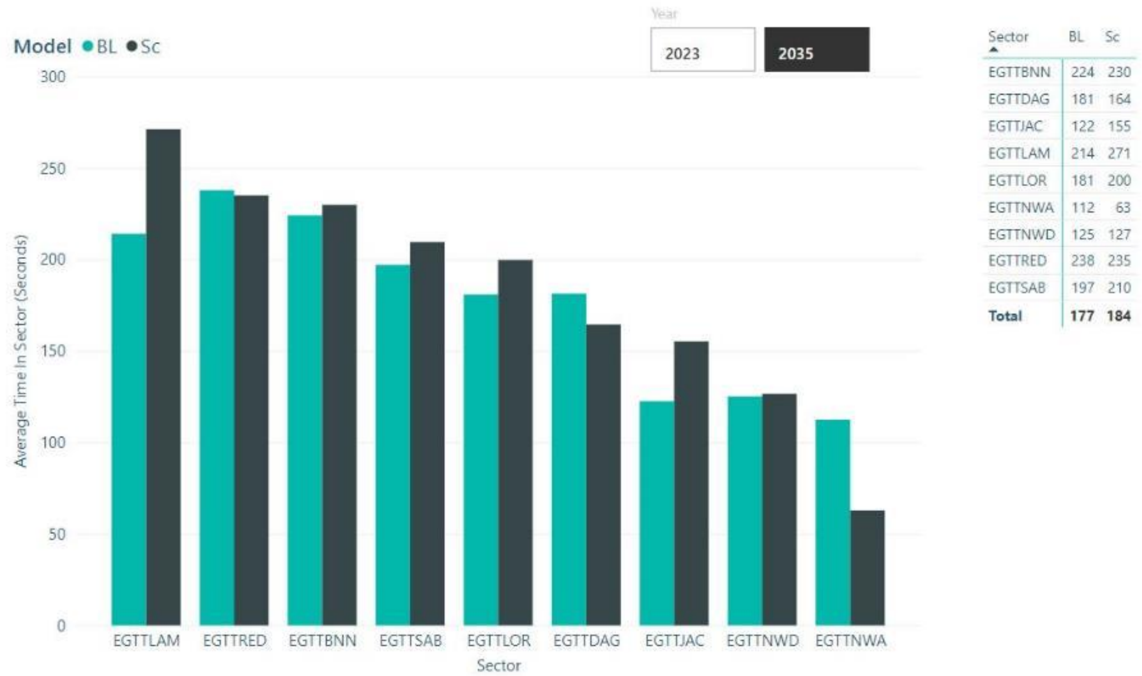


Figure 13: Average sector occupancy per flight in each sector in 2035.

Traffic Interactions

Interactions are an assessment method where the simulations assess if an aircraft pair come into close contact. By considering the number of such 'interactions' we can make a first pass assessment on the likelihood of increased workload and/or additional safety events. A decreasing count in interactions may mean an increase in capacity and a safer airspace design. The exact improvement in capacity and safety cannot be directly correlated to the interaction count, but it is a good indicator if there may be a problem for Air-Traffic Control (ATC) with the new airspace design.

Interactions are analysed with simple table of counts, which can be further split by interaction type (crossing etc…) and by viewing interaction hot-spots on a map by plotting their location. The location is the mid-point of the two interacting aircraft but can still give context on the nature of the flows that are conflicting.

The analysis then considers a threshold of closest approach. Procedural breaches are where aircraft come within 1,000ft and 3NM (minimum separation in LTMA) which are conflictions that must be resolved by ATC.

Interaction analysis is completed by running the fast-time models for the Reference and Solution Scenarios each 20 times, with randomised flight departure times. This adds robustness to the analysis by reducing the magnitude of chance encounters and avoiding over-looking near-misses. As the Green GEAR option involves changes to aircraft climb and descent profiles, only a fully Westerly runway configuration is assessed. Interactions between aircraft that have both reached their initial approach fix (IAF) at 8,000ft are omitted from the data due to a known limitation of the simulations.

Flights are simulated 'on-rails' with no track deviation such as tactical vectoring, navigation inaccuracies, and controller instructions that may cause flights to deviate from their flight planned path. This might mask a potential safety risk as in reality, tactical intervention by controllers is typically used to separate aircraft and avoid any potential safety risks.

In the Solution Scenario, the routes have been designed to be separated by 1,500ft when one or both are non-level to ensure minimum radar separation of 1,000ft (i.e. allowing for vertical position errors) for all traffic in the region. The following section looks at interactions within 1,000ft and 3NM.

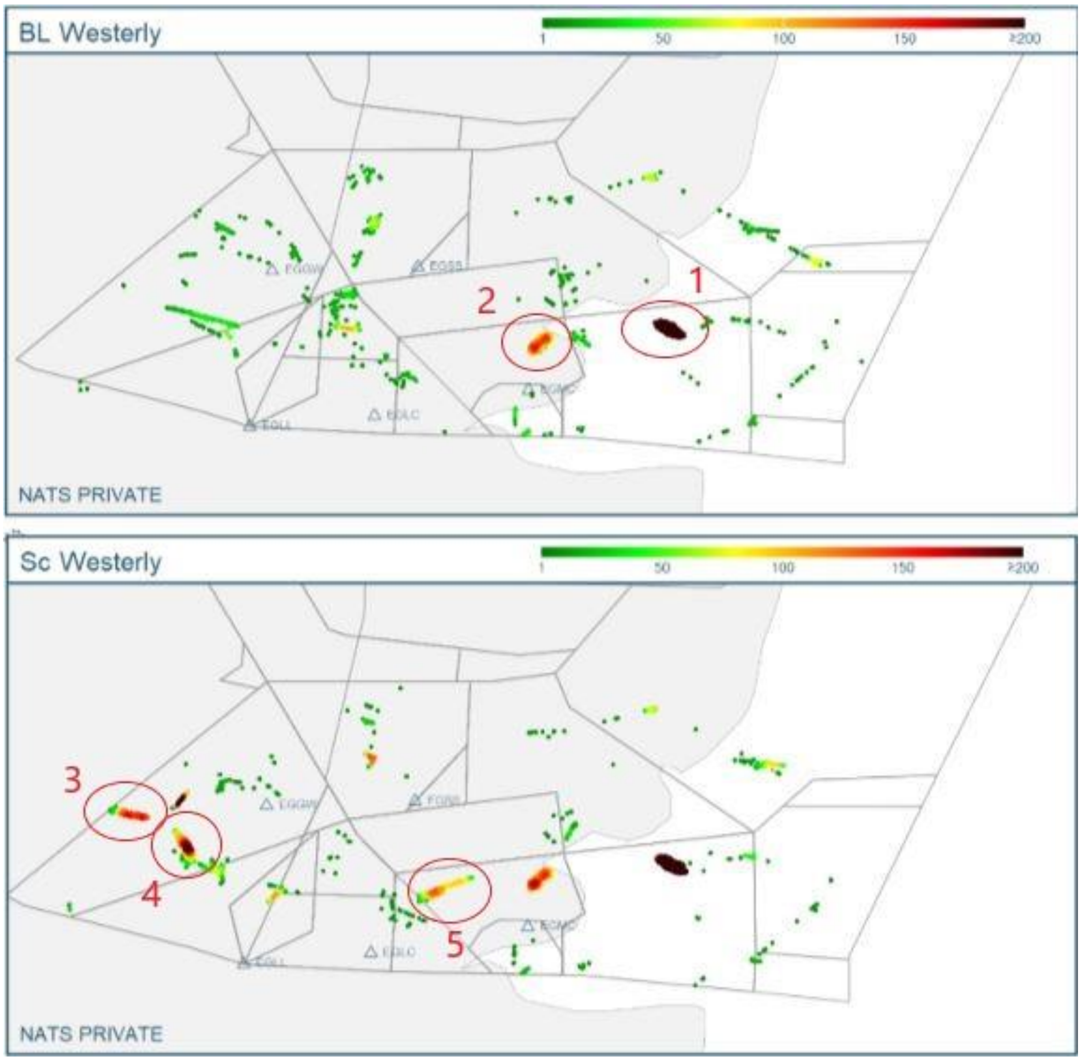


Figure 14: Interaction density plot for 2023 traffic sample in the Reference and Solution Scenario models.

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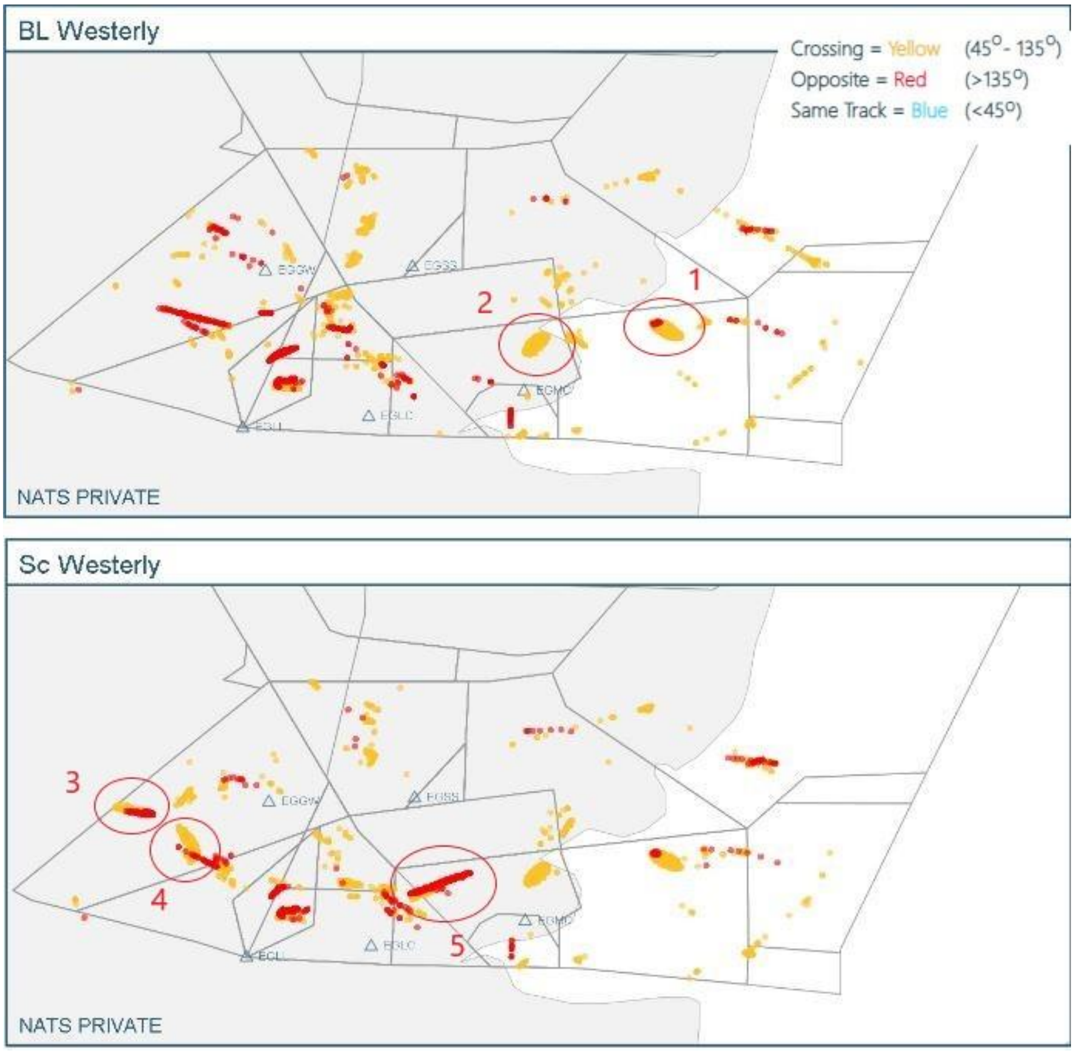

Figure 15: Interaction types for 2023 traffic sample in the Reference and Solution Scenario models

Figure 14 illustrates the interaction hotspots in the LTMA region in the Reference and Solution Scenarios within 1,000ft vertical and 3NM horizontal separations and Figure 15 shows the interaction type. There are more conflict hotspots in the Solution Scenario compared to the Reference Scenario where the 5 key locations are:

1. Stansted departures and Heathrow arrivals crossing in the SABER sector, which has increased by 6% in the Solution Scenario compared to the Reference Scenario. The analysis shows that there has been a shift in these interactions from around FL210/FL220 in the Reference Scenario to FL200/FL210 in the Solution Scenario.

2. Gatwick departures and Heathrow arrivals crossing in the LAM sector, which has increased by approximately 20% in the Solution Scenario compared to the Reference Scenario, particularly between FL130-FL150. In addition, this interaction hotspot has been amplified in the Solution Scenario due to crossing London City departures and Heathrow arrivals.

However, there are more additional interaction hotspots in the Solution Scenario:

3. Heathrow arrivals on the NUGRA STAR and Stansted NUGBO departures crossing between FL140-FL160 in the BNN sector. These occur around the WCO waypoint at peak times where the Heathrow arrivals are levelling off at higher levels for the BNN hold and the Stansted departures are climbing from the end of the NUGBO SID. Generally, the Stansted NUGBO departures are climbing above the Heathrow NUGRA arrivals where the routes cross and therefore no interactions will occur.
4. Similarly, Heathrow arrivals on the NUGRA STAR and Heathrow WOBUN departures crossing between FL100-FL120 in the NWD sector. These occur around the BNN waypoint at peak times where the Heathrow arrivals are levelling off at higher levels for the BNN hold and the WOBUN departures are climbing from the end of the WOBUN SID. Generally, the higher WOBUN departures will not interact with the lower BNN arrivals.
5. London City BINNY departures and Heathrow arrivals on the BARMI/LOGAN STARs crossing on opposite tracks around FL100 in the LAM sector. Some flights are not laterally separated where London City flights climbing on the BINNY SID are crossing the Heathrow arrivals descending to the IAF just before the LAM hold.

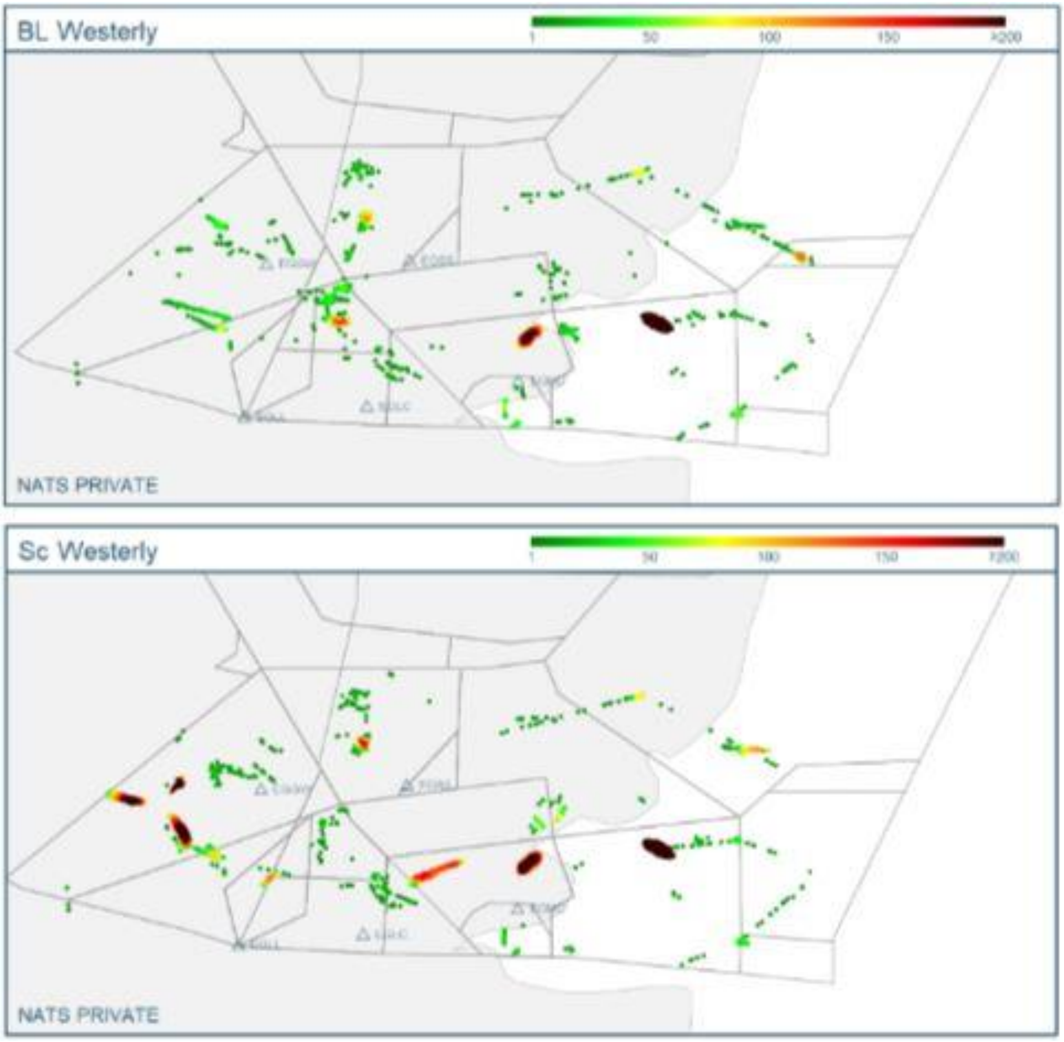

Figure 16: Interaction density plot for 2035 traffic sample in the Reference and Solution Scenario models.

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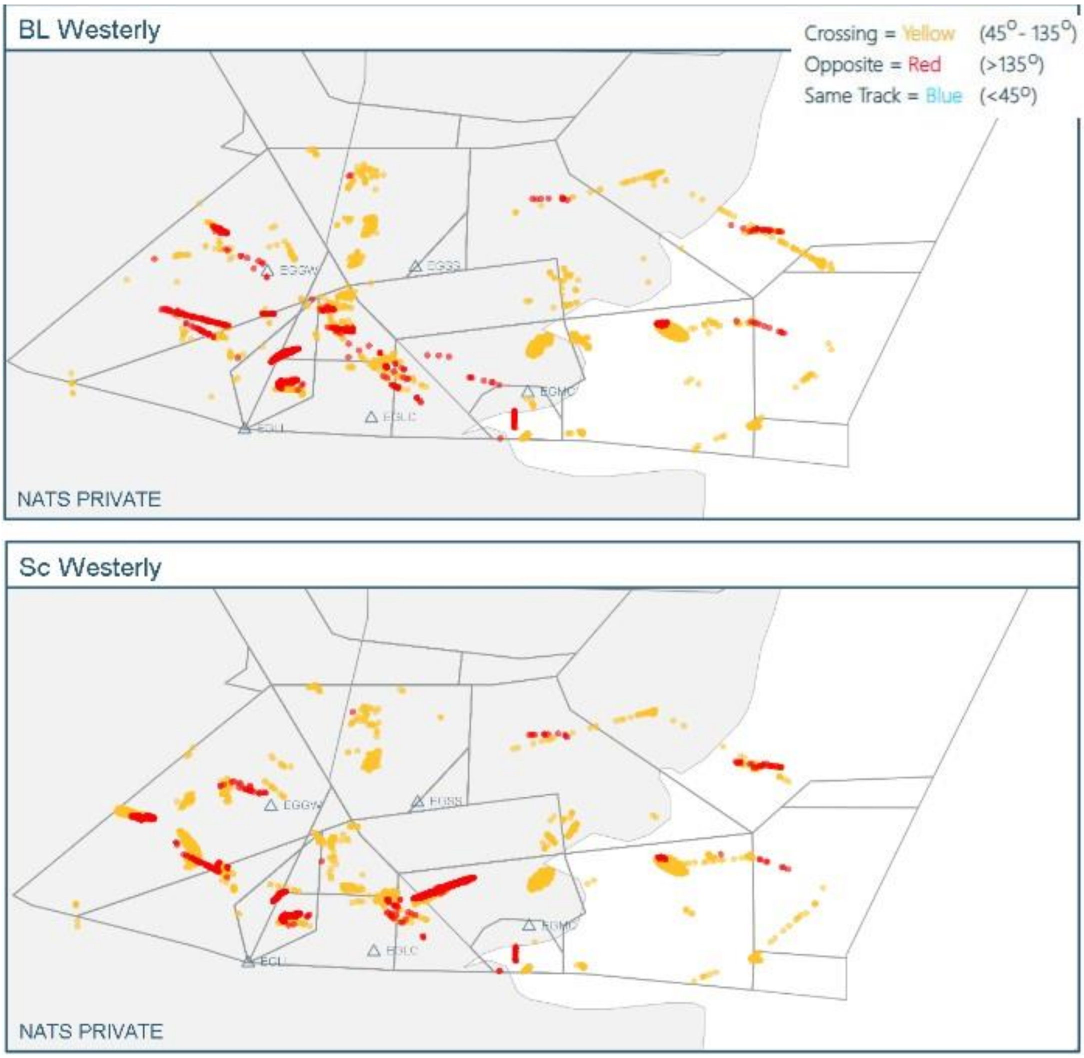

Figure 17: Interaction types for 2035 traffic sample in the Reference and Solution Scenario models.

Sector	2023 Traffic Sample			2035 Traffic Sample		
	BL Count	SC Count	Difference	BL Count	SC Count	Difference
EGTTBNN	24	435	1,713%	23	515	2,139%
EGTTDAG	46	93	102%	43	189	340%
EGTTJAC	164	53	-68%	237	84	-65%
EGTTLAM	796	1,455	83%	1,034	1,836	78%
EGTTLOR	219	220	0%	320	283	-12%
EGTTNWA	49	165	237%	77	238	209%
EGTTNWD	2,466	2,382	-3%	2,537	2,429	-4%
EGTTRED	145	268	85%	184	351	91%
EGTTSAB	1,173	1,238	6%	1,472	1,582	7%
Total	5,082	6,309	24%	5,927	7,507	27%

Table 24: Total number of interactions in the Reference and Solution Scenario models.

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Figure 16 illustrates that the number of interactions at the hotspots identified increase in 2035 due the higher traffic levels. The types of interactions remain the same as Figure 17 shows.

Table 24 provides a summary count of all interactions for each model and the percentage differences. It shows that the for the 2023 traffic sample, the number of interactions in the Solution Scenario has increased by 24% compared to the Reference Scenario. In 2035 this increases to 27% for the Solution Scenario compared to the Reference Scenario. This is predominantly due to increased interactions in the EGTTBNN sector where Heathrow arrivals levelling off at higher levels for the BNN hold are interacting with Stansted NUGBO and Heathrow WOBUN departures in the Solution Scenario (See Figure 5). The higher levelling off at the BNN hold is a result of the fast time simulation software sequencing more favourably other holding Heathrow traffic due to the distribution of traffic in the sample. In reality, the operation will tactically manage this to prevent an imbalance in the holds and can stack swap at peak times.

In summary, both models have removed the BPK interaction hotspot and expanded to other regions where interaction hotspots may exist in reality today. The Solution Scenario has increased the number of interactions compared to the Reference Scenario; however, these interactions could all be resolved through changes in the airspace design (extending SIDs, changing climb gradients or re-orienting holds) or ATC tactical management. Further improvements could be found by de-conflicting certain flows in each sector and in particular in the five hotspot areas identified.

A.3.3 Unexpected behaviours/results

It could not be demonstrated that the solution would increase TMA capacity as per objective OBJ-GreenGEAR-0406-TRL2-ERP-CAP. However, the results indicate that capacity could be maintained compared to an optimised PBN route structure - there was no significant difference to traffic levels spread across the day -, whilst delivering reductions in fuel and emissions.

The Reference and Solution Scenarios were fed with the same traffic samples, so handled the same number of flights. The unexpected behaviour was that the number of traffic interactions significantly increased under the Solution Scenario. Five conflict hotspots are identified above, in the 'OBJ-GreenGEAR-0406-TRL2-ERP-CAP Results' section. These five hotspots were subject to post-analysis review to determine whether there were fundamental concept flaws or merely shortcomings of the test case airspace design.

1. Stansted departures and Heathrow arrivals crossing in the SABER sector.
   Following post-analysis review, it was determined that this issue could be resolved by design. The conflict occurs when EGSS departures leave the SID at PAAVO and turn south to KONAN on the FIR boundary. To resolve this conflict, the PAAVO 1Y SID could be extended after PAAVO. Multiple SIDs, or Enroute Transitions, could be used to facilitate the multiple directions required after PAAVO. Alternatively, ATC tactical management of the vertical profiles could be applied after the end of the SID.

2. Gatwick departures and Heathrow arrivals crossing in the LAM sector.
   Following post-analysis review, it was determined that this issue could be resolved by design. EGKK departures were out of scope of the test-case airspace design.

3. Heathrow arrivals on the NUGRA STAR and Stansted NUGBO departures crossing between FL140-FL160 in the BNN sector.

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Following post-analysis review, it was determined that this issue could be resolved by design. The conflict occurs when EGSS departures leave the NUGBO 1R SID and continue westward to WCO, where they conflict with the EGLL arrivals heading south-east to BNN. To resolve this conflict, the SID could be extended out to WCO. Multiple SIDs, or Enroute Transitions, could be used to facilitate the multiple directions required after waypoint MBR12. Alternatively, ATC tactical management of the vertical profiles could be applied after the end of the SID.

4. Heathrow arrivals on the NUGRA STAR and Heathrow WOBUN departures crossing between FL100-FL120 in the NWD sector.
   Following post-analysis review, it was determined that this issue could be resolved by design. The conflict occurs when EGLL departures heading north to WOBUN cross EGLL arrivals heading to BNN at LLX01. The design is for the departures to pass 1,589ft below the arrivals. However, when traffic enters the lower levels of the BNN hold the holding pattern comes into conflict with the departures. This conflict could be resolved in a number of ways. The SID could be moved laterally to avoid the hold, but this would add 3NM to SID track distance. The SID climb gradient could be reduced to 3.6% but this would make a shallow climb. The hold could be changed from a right hand to left hand turn and reoriented to avoid the SID; this would have minimal impact to fuel efficiency.

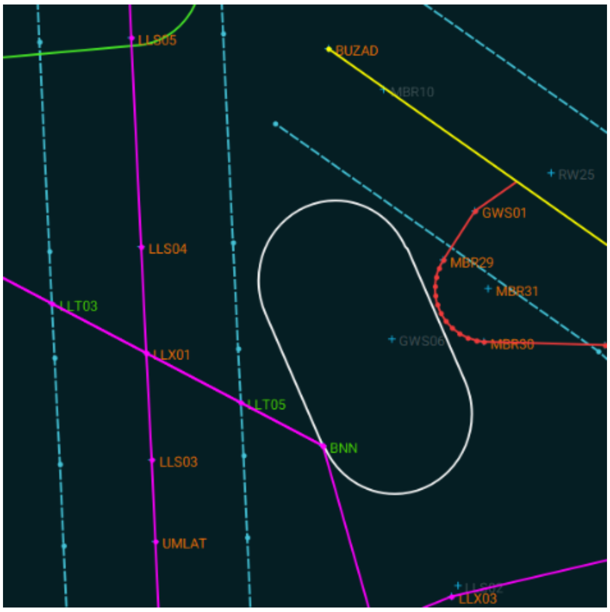

Figure 18 - Airspace design solution to interaction point: change turn direction and track to 155°

5. London City BINNY departures and Heathrow arrivals on the BARMI/LOGAN STARs crossing on opposite tracks around FL100 in the LAM sector.
   The conflict occurs when EGLC departures heading north-east to BINNY cross EGLL arrivals heading west to LAM near LLX08. The design is for the departures to pass below the arrivals. However, when traffic enters the lower levels of the LAM hold the holding pattern comes into conflict with the departures. This conflict could be resolved by using a 5% climb gradient on the SID instead of 7%.

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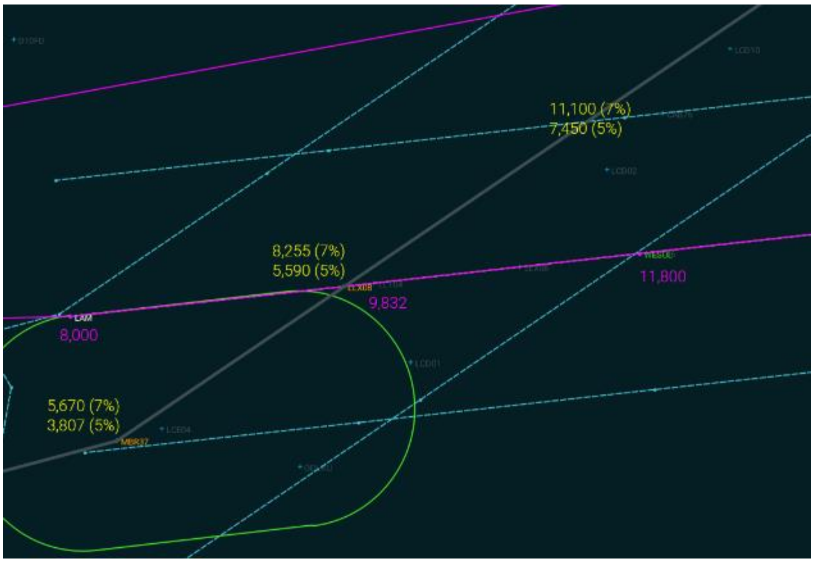

Figure 19: Airspace design solution to interaction point: change climb gradient from 7% to 5%

It was determined that these unexpected results were caused by shortcomings of the airspace design rather than the concept itself; these would be caught and resolved through standard iterative airspace design processes.

A.3.4 Confidence in results of validation exercise #01

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

Wider Applicability

The validation was based on the conflicting routes through, or close to, the Brookmans Park (BPK) waypoint. This is currently an area of highly complex route interactions, so a real-world test case applicable to the concept solution of using GeoAlt to improve efficiencies in airspace design.

It is considered that, if the concept could be applied and this environment, it could be applied to the vast majority of European TMAs. The design principles would need to be adapted to the environment. For TMAs with fewer route interactions, the constraints could be reduced, e.g. less time required to adhere to a specified geometric vertical profile and/or a greater level of path tolerance.

Limitations of the results

For reasons of practicality and proportionality for a low maturity level concept, the test case airspace design was only based on a proportion on the London TMA, rather than the TMA as a whole. However, a highly complex portion of the LTMA was deliberately chosen to fully exert the concept.

The assessment was conducted only in fast-time simulation, i.e. without controller or pilot input, which is appropriate for a low maturity level concept.

Environmental benefits only considered CO_2 equivalent emissions directly derived from fuel burn. No consideration was given for other emissions, noise or non-CO_2 effects such as contrail creation.

Only nominal conditions were considered, with ISA meteorological conditions. This is because the aim of exercise #01 was only to determine the feasibility of airspace design using the GeoAlt concept and the level of potential benefit that it could deliver. Non-nominal conditions were considered as part of exercise #02.

Assessment was only of an extrapolated end state of the GeoAlt concept. It did not cover alternative end states or transitory states described in the Initial OSED [24]. However, these were considered as part of exercise #02.

A.3.4.2 Quality of validation exercises results

The quality of the exercise validation results is sufficient to achieve TRL2 maturity.

The NATS internal DesignAir tool was used to create the airspace design; this tool is the standard tool used by NATS for all formal airspace design through the CAP1616 airspace change process.

An industry standard fast-time simulation tool, AirTOp® (Air Traffic Optimisation), was used to conduct the analysis using Flight Plans imported from the EUROCONTROL NEST (Network Strategic Monitoring Tool) and using the EUROCONTROL BADA (Base of Aircraft Data) Aircraft performance models.

Traffic samples used for the analysis were grown to 2035 levels using the EUROCONTROL STATFOR forecast.

The minimum radar separation applied to the model was consistent with the current operational application in the London TMA: 3nm / 1,000ft. The vertical tolerance applied to the climbing and descending route separation was derived from the Minimum Aviation System Performance Standards (MASPS) Required Navigation Performance for Area Navigation [26]

The size of the fuel and environmental benefits only show a potential scale of benefit as there were limitations with the modelling capability because speed profiles could not be adjusted according to the climb or descent rate. However, the analysis was successful in demonstrating significant potential benefits to fuel and the environment.

The results apply to the test case airspace design only and cannot be transferred like-for-like to other specific airspace volumes. Extrapolation of the results will be considered as part of the project's ECO-EVAL.

A.3.4.3 Significance of validation exercises results

The results obtained for fuel/CO_2e from the Exercise #01 FTS are based on a BADA 4.2 model. The model is stable and returns the exact fuel rate for the same input parameters. However, during FTS the trajectories are recorded at a 4s resolution, and trimmed to the UK FIR, leading to a minor digitisation of the dataset. This can lead to variances between a baseline (barometric model in this report) and scenario (Geometric) due to the resolution and trimming.

The amount of variation in kg is a dependent on the aircraft type being modelled and the phase of flight.

For the uncertainty due to trimming, the max difference in each profiles fuel is equal to 4s flight time. This represents the baseline/scenario being trimmed by up to one full step more than the partner scenario/baseline result, thus impacting the returned difference. This trimming can be assumed to be near cruise altitude (as the UK is an island allowing sufficient time to reach a level near or at cruise in all travel directions). An example of the 4s fuel consumption for a typical medium aircraft (A320) and heavy aircraft (B789) for climb/cruise/descent around FL350 for nominal mass is presented in Table 25. The max error associated with each fuel value is plus or minus half of this value.

Aircraft	Phase	4s fuel from BADA 4.2 @ FL350	Max uncertainty
A320	Climb	3.41kg	±1.71kg
	Cruise	2.66kg	±1.33kg
	Descent	0.38kg	±0.19kg
B789	Climb	7.95kg	±3.98kg
	Cruise	6.00kg	±3.00kg
	Descent	0.72kg	±0.36kg

Table 25: Example digitisation error margins.

In addition, the change in vertical level or speed over 4s, while minor for each step, can impact the fuel rate by up to ±0.05kg. This is the max size of the digitisation error per step. However, aggregated over the duration of the flight profile this can become significant, with longer flights having a potentially much higher uncertainty.

Applying these two sources of uncertainty into a Monte-Carlo model (10,000 runs per aircraft simulated), with the uncertainty assumed to be independent for the baseline and scenario, with a uniform distribution probability between negative and positive max uncertainty, we are able to assess the uncertainty range on the benefit/disbenefit claimed. The result of this analysis for the data in this report are presented in Table 26.

	Fuel Burn Benefit standard deviation per departure (kg)	Fuel Burn Benefit standard deviation per arrival (kg)
EGLL	0.51	0.25
EGSS	0.24	0.09
EGGW	0.29	0.13
EGLC	0.85	-
All	0.38	0.17

Table 26: Standard deviation to fuel burn benefits/penalties per aircraft.

The significance is that the standard deviation is many times lower than the claimed changes to fuel. Therefore, inaccuracies potentially introduced due to digitisation and trimming of the FTS results does not impact the conclusions.

Scaling up the per flight uncertainty by the annual traffic figures allows us to estimate the standard deviation to the total fuel benefits between the baseline and scenario as per Table 27.

	Fuel Burn Benefit standard deviation total departures (T)	Fuel Burn Benefit standard deviation total arrivals (T)
EGLL	22.0	34.9
EGSS	23.0	8.7
EGGW	0.2	8.3
EGLC	13.4	-
All	21.7	20.8

Table 27: Standard deviation to fuel burn benefits/penalties for annual benefits.

This uncertainty analysis only covers the sources within the FTS processing. In comparing FTS results to actual real-world fuel and CO_2e values there are other sources of variation. In essence, the FTS makes assumptions about the following parameters that would influence the real fuel/CO_2e.

- Aircraft mass is assumed to be either nominal for departures, or low for arrivals. In actuality, there would be a wide variation. This impacts both the BADA 4.2 fuel rates and would be a dependent variable in the IAS/TAS/ROCD of the aircraft.
- FTS assumes standard pressure and temperature with no local variation or wind influencing the flights.
- There are no divergences (from any source) from the flight planned path.

The first two of these are very hard to model due to the number of permutations involved. However, as a simulated comparison we can exclude the influence of all three as we assume that all parameters or external influences would interact with each flight in exactly the same manner between baseline and scenario. This leads us to have confidence in the direction of benefit/disbenefit from FTS analysis, though the achieved benefits can vary significantly between analysis and reality.

Typically, our internal estimation of the impact this has on the FTS is to consider fuel changes (scenario minus baseline) only to be accurate within ±5kg per aircraft. This can scale significantly if applied to traffic flows with a high volume of traffic. However, other than the change to EGGW departures, this uncertainty estimate would not lead the fuel impact of this report to be questioned. It should be noted that this should only be applied to individual flows not combined totals. As an overall low impact change could be a composite of a large benefit and large disbenefit, with each benefit/ disbenefit itself being accurate.

	Error margin FTS to actual per aircraft (kg)	Error margin FTS to actual Annual Total Departures (T)	Error margin FTS to actual Annual Total Arrivals (T)
EGLL	5	220	699
EGSS	5	479	485
EGGW	5	4	321
EGLC	5	77	-

Table 28: Estimated error to benefits comparing FTS to actuals

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A.4 Conclusions

A.4.1 Conclusions on concept clarification

The concept of using geometric altimetry for vertical guidance outside of Final Approach is feasible from an airspace and route design perspective. A test case airspace design was successfully created using the concept:

- Instrument Flight Procedures define the vertical geometric path that the aircraft FMS has to follow.

This could be applied to a TMA environment and could be used as the basis of Vertical-RNP procedures through new vertical containment requirements. The greatly reduced uncertainty of both lateral (PBN) and vertical (V-RNP) profile enables maximised use of the available airspace to optimise the efficiency of airspace design

A.4.2 Conclusions on technical feasibility

From an ATC/ground system perspective, the concept is primarily one of airspace and route design. Ground system support is likely to be required, e.g. for conformance monitoring, but this was covered as part of exercise #02.

Technical feasibility at an airborne implementation level was covered under exercise #03.

A.4.3 Conclusions on performance assessments

The concept of using Instrument Flight Procedures to define the vertical geometric path that the aircraft FMS has to follow, provides the potential for significant fuel and environmental benefits at the network level. This is primarily through enabling the airspace designer to reduce the impact of procedural conflicts on climb and descent profiles, leading to a greater number and/or greater duration of continuous climbs and continuous descents. The concept also provides opportunities to shorten lateral track distances by having more usable airspace.

A greater amount of usable airspace is provided by reduction in the uncertainty buffers that have to be built in due to the pressure variation / the Transition Layer and the position of the aircraft in-between waypoints.

A.5 Recommendations

The maturity of the concept should be developed through higher-fidelity simulations and human-in-the-loop assessment.

Contrasting analysis of alternative end states should be explored, primarily:

- Instrument Flight Procedures define a set of geometric height constraints at waypoints and the vertical path between constraints is defined by the aircraft FMS.

This could be applied with or without airspace or route changes.

Analysis of the likely transitory steps should be undertaken to determine whether and how benefits could be delivered prior to an idealised end state.

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Appendix B Validation exercise #02 report

B.1 Summary of the validation exercise #02 plan

As in the ERP SESAR solution 0406 (D3.2 – Geometric Altimetry).

B.1.1 Validation exercise description and scope

Exercise #02 is Exercise TVAL.01.2-Green-GEAR-0406-TRL2 in the ERP [25]; covering: 1) Use Case 4 – Fully Geometric TMA, including Departure, Climb, Descent, Initial Approach and Final Approach; 2) Use Case 5 – Single aircraft loss of GNSS; 3) Use Case 6 - Single aircraft loss subject to GNSS Spoofing; 4) Use Case 7 Complete loss of GNSS.

The Safety and HP assessment was carried out via a workshop focus group paper exercise to identify the key features for ATC in a fully geometric environment. The workshop involved a diverse group of experts to explore the implications of GeoAlt, participants included three Subject Matter Experts (SME) in ATM department, one TC South Controller and Capital Controller, and one Heathrow Approach Controller. During the workshop the participants were asked to consider the use of a Geometric Altimetry (GeoAlt) use case, non-nominal use cases, as well as a mix mode of operation between Geometric and Barometric to consider the potential risks during the transitional phase from one datum to another. The workshop covered both nominal conditions and fallback due to GNSS loss or spoofing, which were identified as the major risk with geometric operations during a previous internal stakeholder workshop. The workshop was performed by NATS Human Factors and Safety Specialists and the primary focus on the project was **OBJ 1.1;** The determination of whether GeoAlt can enable safe removal of the Transition Layer. Additionally, with a further HP objective of assessing the impact on roles and responsibilities; technical support systems; team structures and communication and transition factors. From a safety perspective, the risks of implementation and transition were assessed, specifically seeking to identify any major risks that would be difficult to mitigate and could potentially hinder the progress of the research.

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

SESAR solution validation objective	SESAR solution success criteria	Coverage and comments on the coverage of SESAR solution validation objective in exercise #02	Exercise validation objective	Exercise success criteria
OBJ-GreenGEAR-0406-TRL2-ERP-SAF1 Determine whether GeoAlt can enable safe removal of Transition Layer	CRT-GreenGEAR-0406-TRL2-ERP-SAF1.001 There are no safety showstoppers identified for removal of the Transition Layer	Partially covered as assessment limited to the key focus areas defined in the Initial OSED. Additionally, partially covered due to scope of exercise #02 covering ATM perspective, not aircraft perspective.	EX2-GreenGEAR-0406-TRL2-ERP-SAF1 Determine the key safety consideration s of GeoAlt.	The key Safety issues relating to Geometric Altimetry have been identified and assessed.
OBJ-GreenGEAR-0406-TRL2-ERP-HP1 To assess the preliminary Human Performance aspects under the Geometric Altimetry solution for any showstoppers.	CRT-GreenGEAR-0406-TRL2-ERP-HP1.001The geometric solution demonstrates no critical human performance showstoppers.	Partially covered as assessment limited to the key focus areas defined in the Initial OSED. Additionally, partially covered due to scope of exercise #02 covering ATM perspective, not aircraft perspective.	EX2-GreenGEAR-0406-TRL2-ERP-HP1 Determine the key human performance consideration s of GeoAlt.	All potential human performance risks and impacts are comprehensively identified, engaged upon, and addressed with actionable recommendations.

Table 29: Validation Objectives addressed in validation exercise #02

B.1.3 Summary of validation exercise #02 validation scenarios

For this exercise, the following scenarios were considered:

Current Day (Barometric Altimetry) (Baseline)

This scenario maintains the current use of barometric altimetry for determining altitude, relying on atmospheric pressure settings. No changes are made to existing airspace structures, separation standards, or operational protocols. It serves as a baseline for comparison with other scenarios, reflecting the status quo of global air traffic management. Throughout the workshop, SMEs were encouraged to use the current day scenario as the basis to decide the impact on their operations.

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Lateral Path + Geometric Altimetry Constraints (No Airspace Change)

Geometric altimetry, which uses GNSS for precise altitude determination, is introduced alongside current lateral path operations. Airspace structures remain unchanged, and the focus is on enhancing accuracy without redesigning sectors or separation standards. This approach involves moderate updates to training and procedures to incorporate geometric data to cover the removals of the transition layer.

Lateral Path + Geometric Altimetry Constraints (Airspace Optimisation)

This scenario integrates geometric altimetry with targeted airspace redesign to improve efficiency and capacity. Optimisation includes adjustments to routes, sectors, and procedures, enabling controllers to leverage precise altitude data for better traffic flow management. It requires updates to technology, training, and communication protocols.

Lateral Path + Vertical Path (Airspace Optimisation)

Geometric altimetry supports both lateral and vertical path optimisation, enabling seamless navigation and tailored flight profiles. Airspace redesign aligns with performance-based navigation principles, incorporating features like continuous descents and climbs. Sub-options include using V-RNP monitoring for added safety or relying on procedural controls. This represents the most advanced scenario, requiring significant technological and operational changes.

A summary of the use cases, within these airspace designs, consisted of the consideration of the nominal scenario under Use Case 4 - Fully Geometric TMA, including Departure, Climb, Descent, Initial Approach and Final Approach. Plus, the failure modes under: Use Case 5 - Single aircraft loss of GNSS, Use Case 6 - Single aircraft subject to GNSS Spoofing and Use Case 7 - Complete loss of GNSS. When considering each scenario, we also used the following use cases to discuss the differing effects on Safety and Human Performance depending on the amendments that were made to the airspace alongside introduction of geometric altimetry.

Due to time constraints, the concept of a more “systemised airspace” does not focus on the detailed specifics of the two outlined scenarios [Lateral Path + Geometric Altimetry Constraints and Lateral Path + Vertical Path]. Rather, the workshop focused more generally of the introduction of airspace changes and their potential to influence the impact of integrating geometric altimetry into operations when compared to the Baseline and No Airspace Change scenario. Rather than differentiating between specific redesign options, the discussion centred on the broader implications of transitioning to a more optimised airspace. Further research should delve into the more detailed specifics of airspace optimisation. For now, this assessment provides an initial exploration of the overarching safety and human performance operational impacts of implementing geometric altimetry within the four airspace scenarios.

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B.1.4 Summary of validation exercise #02 validation assumptions

Assumption ID	Assumption title	Assumption description	Justification	Impact assessment
ASS-GreenGEAR-0406-TRL2-ERP-003	Aircraft Performance	It is assumed that all aircraft have equipage with geometric vertical navigation.	To enable benefit analysis of the fully geometric end state	Benefits analysis captures a specific option end state only
ASS-GreenGEAR-0406-TRL2-ERP-004	Aircraft Equipage with V-RNP	Aircraft navigation systems have been developed to comply with a vertical tolerance applied to Instrument Flight Procedures (IFPs)	To enable benefit analysis of the fully geometric end state	Benefits analysis captures a specific option end state only
ASS-GreenGEAR-0406-TRL2-ERP-005	Airspace layout using Vertical Route Separation	Vertical route separation rules for the geometric test case airspace design will be based on: Routes crossing or overlapping whilst in level flight= 1,000 ft Route crossing or overlapping whilst one or both are not in level flight= 1,520ft	To enable benefit analysis of the fully geometric end state. The separation is based on 2x the largest Vertical Path Performance Limits defined in ED-75/DO-236.	The benefits of geometric route design are based on a research assumption that is not formally defined but is simply an extrapolation of the lateral PBN logic.
ASS-GreenGEAR-0406-TRL2-ERP-006	GeoAlt Regulation	The use of geometric altimetry for vertical navigation within the TMA has been mandated	To enable benefit analysis of the fully geometric end state.	Benefits analysis captures a specific option end state only
ASS-GreenGEAR-0406-TRL2-ERP-007	Traffic Characteristics	Traffic will be based on London arrivals and departures	Use of historic traffic data for London TMA is the most representative traffic for the test case	Not all aircraft types will be assessed.

Table 30: validation exercise #02 assumptions overview

B.2 Deviation from the planned activities

There were no deviations from the ERP [25].

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B.3 Validation exercise #02 results

B.3.1 Summary of validation exercise #02 results

Exercise #02 validation objective ID	Exercise #02 validation objective title	Exercise #02 success criterion ID	Exercise #02 success criterion	Sub-operating environment	Exercise #02 validation results	Exercise #02 validation objective status
OBJ-GreenGEAR-0406-TRL2-ERP-SAF1	Determine whether GeoAlt can enable safe removal of Transition Layer	CRT-GreenGEAR-0406-TRL2-ERP-SAF1.001	There are no safety show-stoppers identified for removal of the Transition Layer	TMA HC	The workshop concluded that GeoAlt can enable the safe removal of the transition layer with no show stoppers. However, for a more systemised airspace several aspects would need to be researched further. This would include managing the shift in controller's roles from active to monitoring, ensuring robust technological tools for aspects such as conformance monitoring and conflict detection, and developing clear procedures for handling emergencies and fallback scenarios involving both barometric and geometric. Additionally, during transition periods with mixed mode operations, attention must be given to providing clear indicators, updated phraseology and thorough training.	OK

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Exercise #02 validation objective ID	Exercise #02 validation objective title	Exercise #02 success criterion ID	Exercise #02 success criterion	Sub-operating environment	Exercise #02 validation results	Exercise #02 validation objective status
OBJ-GreenGEAR-0406-TRL2-ERP-HP1	To assess the preliminary Human Performance aspects under the Geometric Altimetry solution for any showstoppers.	CRT-GreenGEAR-0406-TRL2-ERP-HP1.001	The geometric solution demonstrates no critical human performance show-stoppers.	TMA HC	The workshop findings indicate no insurmountable human performance show stoppers. However, transitioning to geometric altimetry, particularly in a systemised airspace, requires comprehensive planning, robust support systems, and extensive training. While geometric altimetry has the potential to enhance safety and efficiency, careful management of risks such as situation awareness impacts, communication errors, and system vulnerabilities is crucial is ensure operational safety and performance.	OK

Table 31: validation exercise #02 results

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

B.3.2.1 OBJ-GreenGEAR-0406-TRL2-ERP-SAF1 Results Summary

To address the primary objective on whether GeoAlt could enable the safe removal of the transition later (**OBJ 1.1.**), controllers indicated that removing the transition layer in a fully geometric environment would be feasible and pose minimal hazards to the operation, in the context of the current day operation prior to airspace systemisation. This positive feedback suggests that removing the transition layer, from a controller point of view, would simplify altitude management without introducing significant operational challenges. Removing the transition layer associated with pressure datum changes between QNH and standard pressure eliminates the need for pilots to adjust altimetry mid-flight or the potential for the wrong QNH given. No major safety hazards were identified with the move to Geo Alt and the removal of the transition layer, additional consideration and analysis will be required for the transition to a systemised airspace on top of the transition to Geo Alt.

B.3.2.2 OBJ-GreenGEAR-0406-TRL2-ERP-HP1 Results Summary

To address the validation objective of assessing human performance, no critical showstoppers were identified, primarily, for the scenario (Appendix B.1 Summary of Validation Scenarios) which would introduce geometric operations by changing barometric height constraints at waypoints for geometric, i.e. without a significant change to ATC MOPS. Controllers felt that transitioning to this configuration would require minimal adjustments to existing procedures.

By contrast, the majority of human performance impacts were associated with the airspace scenarios (Appendix B.1 Summary of Validation Scenarios), where a shift to geometric altimetry is coupled with a more systemised airspace that is more tightly defined in both the vertical and lateral planes, incorporating fixed vertical and lateral geometric paths. While an increase in a more systemised airspace, whether using barometric or geometric altimetry, entails changes such as a shift in controller roles to a system monitoring role, the introduction of GeoAlt presents additional consideration, for example it would require controllers to adjust to a new way of interpreting altitude information. However, this report focuses specifically on the implications of GeoAlt within a systemised airspace, rather than examining systemisation within barometric altimetry. Transitionary factors, particularly in mixed mode operations, require significant attention as the controllers emphasised the importance of clear visual indicators and consistent phraseology to distinguish between barometric and geometric operations, especially when in failure scenarios. Training will play a critical role in ensuring controllers and pilots are equipped to manage new procedures effectively.

Overall, while GeoAlt presents opportunities and benefits to the operation, a careful phased approach to its implementation will be essential to address any human performance issues as well as establishing the appropriate airspace design. Whilst no significant HP issues were identified, it should be noted that this was an early theoretical assessment that encompassed of several use cases and airspace environments. A switch from barometric to geometric constraints without changing the airspace was considered to be relatively simple and may results in managing less complex and easier interactions. However, with the development of an airspace change to a more optimised airspace, this in turn impacts the severity of the effect on roles, technology, communication and training for the controller. This highlighted the need to adjust the transitionary steps of geometric altimetry to the following:

1) Geo Initial Approach

2) Lateral Path + Geo Alt constraints (no airspace change)

3) Geo TMA (Approach, Descent & Climbs), potentially through a set of smaller changes, e.g. airport per airport, i.e. could be a mix of Geo Alt constraints and Geo Vertical Path.

4) Airspace block (Cruise, Approach, Descent & Climbs)

With the progression to a more systemised airspace, every step of this transitionary period would require an in-depth human performance and safety assessment, to further investigate the impact. Such a transition would, in the end, involve significant changes in controller roles and responsibilities, require advancements in technology, updates to communication and teamwork, as well as extensive training requirements, as such influencing the impact on human performance. While further investigation into these specific details of these changes may uncover potential challenges, the controllers did not identify any major showstoppers during the workshop that would halt the progression of the project from an ATC human performance perspective at this stage when working under the assumptions outlined. However, further established mitigations and protocols will be required for fallback scenarios, emergencies and failures and outlined in Appendix B Validation Exercise Report #02.

B.3.2.3 Additional Results: Use Case 4 – Fully Geo Environment

Roles and Responsibilities

In the geometric environment, where geometric altimetry is implemented within the constraints of today's operational practices and airspace design, the impact on the controller's roles and responsibilities would be minimal. Controllers could manage altitude assignments and monitor conformance with minimal procedural adjustments, as geometric altimetry would integrate with existing IFPs and separation standards. As a result, this working environment may not decrease or minimise controllers' situational awareness and increase workload, as the operational framework remains largely unchanged.

Conversely, the geometric environment, with predefined three-dimensional lateral and vertical paths, may significantly impact the controller's role. This would result in a transition to a monitoring focused role, where controllers oversee adherence to structured geometric routes, which without the appropriate mitigations could lead to a gradual reduction in SA. Continuous monitoring without active intervention risks delayed detection of deviations, particularly in high traffic scenarios. Depending on the fall-back scenario, emergencies requiring rapid decision-making would pose significant challenges, especially so for less experienced controllers who may lack the procedural control skills necessary to handle barometric fallbacks during GNSS disruptions or system failures.

New and trainee air traffic controllers may require foundational training in barometric altimetry and a fundamental understanding of procedural control to effectively manage a geometric altimetry environment. While they may initially lack experience in handling the unique challenges associated with such fall-back scenarios, targeted training programs and mitigations could bridge these gaps and equip them with the necessary skills to navigate both routine operations and exceptional scenarios, such as GNSS disruptions. Although the frequency and impact of events like spoofing or jamming remain uncertain, a proactive approach to training and system resilience would ensure controllers are well prepared to maintain safety and efficiency in all circumstances.

Teams Structure and Communication

As per today's operation, team structures and communication protocols would remain largely consistent with current operations. Controllers noted that managing aircraft using geometric altimetry is achievable with adequate training and updated phraseology.

In a more systemised environment, geometric altimetry could streamline operations by reducing the need for repeated QNH readbacks, which would lower RT frequency and potentially reduce the potential for verbal communication errors. Eliminating QNH could also decrease pilot and controller errors during altitude adjustments. As a result, fewer readbacks may enhance communication efficiency, an important benefit in a more systemised airspace where controllers may be required to focus on monitoring rather than frequently issuing instructions. Transitioning fully to geometric altimetry would require new phraseology standards, which would need to be agreed upon as part of a broader operational shift.

Despite these advantages, the dual terminology required for transitionary mixed-mode operations significantly raises the risk of miscommunication, particularly under high pressure conditions or emergencies. In such scenarios, inadequate communication could result in pilots and controllers misinterpreting altitude instructions, leading to separation breaches or conflicting trajectories. To address this, clear communication protocols and robust training programs are essential to mitigate the risks associated with these changes.

B.3.2.4 Additional Results: Use Case 5 – Single Aircraft Loss of GNSS

During the workshop, we explored scenarios involving single aircraft and complete GNSS loss, as well as GNSS spoofing affecting individual aircraft. In the event of a single GNSS loss (Use Case 5), the causes were identified as system failures (local, regional or onboard), space weather, and reliance on backup systems. The response to such a cause would depend on the fall-back systems. Fallback procedures would be reliant on DME to DME or IRS for navigation, similar to the current day fallback. For operations relying fully on geometric altimetry, response to GNSS loss would hinge on the accuracy of backup systems. Controllers would likely need to increase lateral or vertical separation for affected aircraft, particularly if they revert to barometric altimetry while others remain on geometric. If one aircraft loses GNSS in the operational environment as per today's operation, this could lead to short term workload spikes for controllers as they would need to adhere to separation standards. They would need tools to calculate separation adjustments quickly, with clear visual displays and established procedures to guide their responses. Within a more systemised airspace, this would exacerbate the situation so the controllers would need to ensure the aircraft stays as close as possible to their 3D trajectory. Controllers may need to revert to traditional techniques of barometric altimetry to ensure separation.

Mode switching between barometric and geometric could create further risks, such as incorrect phraseology. Radar and display interfaces would need to flag affected aircraft to avoid manual conversions between geometric and barometric measurements as well as dedicated SQUAWK codes to indicate GNSS disruption. Although situational awareness during this emergency might not be substantially different from barometric operations today, controllers would benefit from clear HMI to retain operational clarity. ATC systems would also require a unified common datum source to ensure consistent altitude comparisons across aircraft.

B.3.2.5 Additional Results: Use Case 6 - Single Aircraft Subject to GNSS Spoofing

For GNSS spoofing, the impacts would mirror those of a single aircraft GNSS loss. The workshop emphasised the need for a dedicated alert system, and enhanced conformance monitoring to alert controllers and pilots to potential discrepancies, supported by a cross-checking capability to compare between geometric and barometric values. Similar to GNSS loss, impacts on situation awareness and workload would be exacerbated through the controller having to monitor both geometric and barometric altimetry positions. Without careful planning of processes and procedures, controllers may face increased stress due to uncertainty about the integrity of altitude data, which could hinder their ability to manage the airspace effectively. Likewise, controllers would need enhanced technological support tools to manage these challenges.

B.3.2.6 Additional Results: Use Case 7 - Complete Loss of GNSS All Aircraft

A complete loss of GNSS across multiple aircraft presents many of the same workload and situation awareness challenges, whilst also necessitating fallback procedures similar to the current reliance on DME or IRS navigation. Be that as it may, in this use case of a complete loss a controller would be required to adopt a different method of operation, as the fallback for complete loss could result in substantial workload increases due to having to apply traditional separation methods and having to use 'old school' barometric techniques. Controllers may face heightened situation awareness loss and potential loss of separation as discrepancies between altimetry modes (barometric and geometric) emerge.

Nonetheless, for a single or a complete loss of GNSS radar and display systems would need to indicate the affected aircraft and have the ability to convert between barometric and geometric altimetry. A common and known altitude datum for all aircraft as a backup would be necessary to maintain operational clarity. In terms of communication, a significant challenge would involve managing both geometric and barometric altimetry during emergencies and failure scenarios, which might slightly increase the risk of mode-switching errors for controllers.

In scenarios involving complete GNSS loss a key consideration would be the timing of the controller's awareness of the issue across all aircraft. A proposal was suggested for pilots to issue a SQUAWK code indicating GNSS loss; if controllers notice multiple such codes, they could infer a system wide loss and revert to barometric procedures. Across both single and complete GNSS loss situations, there would likely be a notable increase in controller workload and a decrease in situational awareness, with some mode-switching errors as controllers navigate mixed altimetry modes.

This part of the workshop also focused on defining a more complete use case for the complete aircraft loss of GNSS. The following use case was defined and discussed with SMEs for complete loss of GNSS:

Failure of all GNSS sources. Pilots selects GNSS failure SQUAWK.
Any aircraft on procedures or ATS route continue on Multi DME for lateral route. (Potentially may not be a viable fallback due to causes such as space weather)
Pilots is able to access and see barometric height for the aircraft in the cockpit.
The controller brings up the barometric height of the flights on the Track Data Block (TDB) at the Controller Working Position (CWP). Both barometric and geometric height are reported at the CWP.
Controller broadcast QNH & awareness of GNSS issue (standard broadcast message?) barometric reversion for all airspace users.
The controller reports the flight's current barometric height (FL above TA, Alt below) and confirms SPS (1013.2) or arrival airport QNH, positive affirmation could be received from each aircraft on next clearance.
The pilot confirms their barometric height and reads back relevant pressure datum setting.
The controller notifies their supervisor of the GNSS loss.

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The ATC supervisor ensures appropriate actions are taken within the ATC sector group adjoining areas, as necessary.
The controller manages all flights based on barometric procedures.
At the Transition Level, the pilot switches from Standard to local QNH. (Needs to be explored how flight crew would be aware of transition altitude/level).
Traffic is stopped/restricted as necessary, departures and traffic at boundaries stopped.
The controller notifies their supervisor of the GNSS loss.
The ATC supervisor ensures appropriate actions are taken within the ATC sector group adjoining areas, as necessary.
The controller manages all flights based on barometric procedures.
Traffic is stopped/restricted as necessary, departures and traffic at boundaries stopped.

B.2.3.7 Additional Results: Mixed Mode Environment

As outlined in the OSED (section 1.1.1.2 Transition Stages), towards the end of the workshop we investigated a mixed capability environment focussing on different flight phases at a time i.e. Final Approach & Initial Approach; Final Approach, Initial approach & Descent; Final Approach, Initial approach, Descent & Climb; and Cruise. A notable outcome of the workshop was that implementing Geometric in final approach may reduce the complexity compared to implementing geometric altimetry across all flight phases where it may introduce more complexities. However, the benefits of such a limited application may not be as apparent.

During the workshop, controllers acknowledged that transitioning to a mixed-mode operation, where both geometric and barometric altimetry are used simultaneously, presents unique challenges Controllers would need to switch between altimetry modes depending on the aircraft’s equipment, which could increase the likelihood of mode-switching errors, such as issuing incorrect altitude clearances. Further exploration needs to be conducted to understand a geometric to barometric conversion, as a major component to the transitionary environment would be that all airspace users would need a common datum to refer to. Communicating altitude commands may lead to misunderstandings, as controllers must convey commands using both geometric and barometric terminology. These communication challenges, combined with differing altimetry systems, could exacerbate the risk of conflicting altitude clearances, particularly during busy or high workload periods. Depending on the phase of flight and how often, this transitory period may temporarily strain situational awareness and elevate workload, particularly until controllers gain proficiency with both altimetry systems. To mitigate these risks, controllers voiced the need for clear visual indicators on displays to highlight an aircraft's altimetry mode and emphasised the importance of standardised training to address potential mode switching scenarios.

Within a mixed mode environment, transition may be more feasible in a smaller, lower density airport where the transition between barometric and geometric altimetry could introduce less operational complexity. Smaller density airports may find it simpler and safer to transition entirely to geometric procedures, and this could avoid any potential issues associated with a mixed mode transitionary period. However, even in a lower-density airport whilst the risks are reduced, a key question arises regarding the interaction of geometric procedures with airports operating under traditional barometric procedures. As such, transitioning all airspace users to geometric altimetry holds human

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performance and safety challenges. Further exploration on the specific details of the transitionary period impact on both ATC and flight crew is required to assess its practicality and safety implications.

B.3.3 Unexpected behaviours/results

No unexpected behaviours or results were identified during the discussions of the one-day internal workshop. The workshop proceeded as planned, with participants engaging in thoughtful dialogue around the concept of transitioning to geometric altimetry and the removal of the transition layer.

The identified points and feedback during the exercise were consistent with the expected discussions regarding operational feasibility, human performance considerations, and potential challenges related to the concept.

B.3.4 Confidence in results of validation exercise #02

The confidence in the results from this validation exercise is moderate but still impacted by the scope and informal nature of the workshop. Key considerations include:

Strengths:
The workshop successfully brought together ATM expertise, providing a diverse set of operational insights and feedback on the concept.
Discussions around human performance and safety were insightful, especially in terms of identifying potential risks and challenges with geometric altimetry.
Limitations:
The workshop was limited to one working day and discussion-based, preventing deep dives into operational simulations or quantitative data collection but covering a wide range of scenarios and use cases.
The small, UK-specific group limits the ability to extrapolate the findings to broader European contexts.

Despite these limitations, the results offer valuable initial insights, though further validation is needed for broader application and more definitive conclusions.

B.3.4.1 Level of significance of validation exercise results

The results obtained from Validation Exercise #02 are considered to provide a foundational understanding of the implications and feasibility of geometric altimetry within operational air traffic control environments. By engaging air traffic controllers with experience in different validation scenarios, the exercise offered qualitative insights into the concept's potential impacts on roles, technological systems, and communication practices. These findings are representative of initial operational considerations and highlight areas requiring further investigation and refinement.

B.3.4.2 Quality of validation exercises results

The quality of the results can be assessed based on the following factors:

Accuracy: As the results stemmed from a discussion-based format, they reflect qualitative feedback from the participants. This limits the precision of the findings but provides a good foundation for further exploration.

Confidence: Given the informal nature of the workshop and the limited number of participants, the confidence in the results is moderate.

Overall, the findings represent valuable qualitative data but require further validation through more formal exercises.

B.3.4.3 Significance of validation exercises results

Statistical Significance: Due to the nature of the workshop, statistical significance cannot be applied to the results. The findings are qualitative and reflect the perspectives of a small group of participants.

Operational Significance: The results are operationally significant within the UK context, as they provide useful insights into the challenges air traffic controllers might face with the transition to geometric altimetry. However, these results need further testing in broader European environments to confirm their applicability.

B.4 Conclusions

B.4.1 Conclusions on concept clarification

The qualitative analysis from the workshop highlighted the varying implications for roles, technological systems, and communication based on the operational environment where geometric altimetry might be implemented. In environments with defined lateral and altitude constraints, where geometric altimetry aligns with current operations, participants expressed confidence in a low-impact transition. Controllers suggested that implementation could occur almost seamlessly, requiring minimal training potentially as little as a briefing.

Conversely, the second, more systemised environment represents a significant shift, necessitating technological advancements, enhanced training programs, and revised communication protocols. While systemised airspace holds the promise of greater efficiency and optimisation, its implementation requires careful planning to address potential challenges, such as maintaining situational awareness, managing fallback scenarios, and ensuring resilience during disruptions.

At this early stage of development, no significant human performance or safety barriers have been identified through the workshop. However, further research is essential to define the future operating environment and fully understand the implications of transitioning to geometric altimetry.

B.4.2 Conclusions on technical feasibility

The need for advanced tools is closely linked to the airspace design rather than just the switch from barometric to geometric altimetry. In the first geometric environment, the need for additional technical systems would be limited, as the operations would not fundamentally differ from current operations. However, any tools in the current controller working position could be optimised to enhance safety by identifying deviations from geometric altitude in real time, ensuring consistency and accuracy within the altitude management.

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In contrast, moving to a fully geometric system within a structured airspace design would necessitate the use of robust support tools, particularly an enhanced conformance monitoring tool to assist controllers in the transition from active controlling to monitoring the systemised airspace. As controllers shift from active controlling, continuous monitoring of predefined geometric paths could lead to a gradual decline in situation awareness over time. However, conformance monitoring tools alert and support the controllers to know when an aircraft has gone off track, improving their situation awareness. Controllers highlighted that in airspace with predefined trajectories, conformance monitoring becomes essential, allowing them to ensure that aircraft stay within assigned paths and are capable of tracking aircraft along continuous geometric paths, rather than at waypoints. Conformance monitoring would also support tactical collision avoidance and validate strategic conflict detection and resolution in real-time. Without such tools, deviations from planned trajectories might remain undetected, which could lead to increased risks of loss of separation in high-density airspace.

Additionally, ATC systems would need capabilities for cross-checking geometric and barometric altitude readings, which would alert controllers to discrepancies during events such as GNSS disruptions, jamming, or spoofing incidents. Departure and arrival management would also become more complex in a more systemised airspace due to the structured nature of three-dimensional routes. Controllers may need to rely on tools to accommodate traffic efficiently, particularly in unpredictable conditions such as weather. However, reliance on technological tools increases vulnerability to system failures or GNSS disruptions, which could impair controllers' ability to maintain safe operations, therefore careful research and implementation is necessary. Any future tools considered should provide clear, intuitive displays to support controllers during high workload scenarios and facilitate efficient decision-making.

B.4.3 Conclusions on performance assessments

Capacity: Initial discussions suggest that geometric altimetry could enable the removal of the transition layer and more efficient use of airspace, particularly in systemised environments. By supporting enhanced vertical and lateral separation, the concept has the potential to increase traffic handling capacity.

Safety: No significant human performance and safety showstoppers were identified during the workshop, indicating that geometric altimetry could be safely implemented within the current operational framework with appropriate training and standardised procedures. However, further assurance activities (including simulations) are required to ensure that safety margins are maintained, particularly during non-nominal conditions such as GNSS disruptions, fallback scenarios or in the future systemised airspace.

Security: While not directly addressed in the workshop, the reliance on GNSS technology introduces potential security considerations, including vulnerabilities to spoofing or jamming. These risks will need to be mitigated through robust technological solutions and operational protocols.

B.5 Recommendations

Further Concept Clarification: Detailed technical guidance is needed to define how geometric altimetry will seamlessly integrate into existing ATC systems and workflows. This includes specifying the software and hardware modifications required, data processing and transmission protocols, compatibility with current surveillance and navigation tools, and interoperability with legacy barometric systems during mixed-mode operations. Additionally, clear documentation of the roles and responsibilities for controllers, pilots, and supporting systems during implementation will help mitigate ambiguity and ensure consistent operation across all stakeholders.

Establish Defined Airspace for Implementation: A clearly defined airspace should be established for the transition to Geo Alt, whether this be in current procedures or a more systemised environment. This will require a more in-depth analysis to determine the exact operational, technical and procedural requirements and the impact on safety and human performance.

Broader Controller Engagement: Expanding the engagement to include a more diverse group of air traffic controllers and flight crew from different European regions is essential to evaluate the operational feasibility of geometric altimetry under various airspace configurations and regulatory environments. This broader involvement should account for regional variations in traffic density, operational practices, and technology availability. Future workshops should include controllers from both en-route and terminal areas, ensuring comprehensive feedback on potential challenges and the practicality of integrating geometric altimetry across varying airspace contexts.

Scenario-Based Validation: Future validation exercises should prioritise scenario-based simulations that replicate diverse operational settings. These scenarios should include a range of traffic densities, weather conditions, equipment capabilities, and contingencies such as GNSS disruptions or mixed-mode operations. By testing the concept under realistic conditions, we can better understand the impacts on safety, situational awareness, workload, and communication. Insights gained from these exercises will provide critical data to refine the concept, optimise procedures, and support decision-making for broader implementation.

Phased Implementation: Phased implementation of geometric altimetry to maximise its benefits while ensuring safety and operational readiness. Start with Geo Initial Approach to introduce geometric altitude management in a controlled, low-risk context. Progress to Lateral Path + Geo Alt Constraints without airspace changes to familiarise stakeholders with geometric operations. Gradually expand to Geo TMA (covering approach, descent, and climb phases) through incremental changes at selected airports or routes, enabling progressive optimisation. Conclude with the integration of geometric altimetry across Airspace Blocks e.g. for a TMA as a whole (covering initial approach, descent, and climb phases), achieving full systemisation and unlocking the greatest efficiency, capacity, and environmental benefits. This structured approach balances immediate improvements with long-term airspace optimisation. However, this is based on ATC feedback and future research needs to consider the input from flight crew for a more collaborative agreement for phased implementation, where cruise may not work for geometric altimetry (Exercise #03 results).

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Appendix C Validation exercise #03 report

C.1 Summary of the validation exercise #03 plan

C.1.1 Validation exercise description and scope

This validation exercise consists in an expert judgement assessment addressing the impact of the Green GEAR's GeoAlt concept of operations as described in the Initial OSED on aircraft functions, architecture and cockpit systems, focused on large commercial aircraft (Airbus families).

It covers the two GeoAlt Solution variants identified in the OSED, that is:

- Option 1: Current paradigm of flight procedures being vertically defined by altitude constraints, with such constraints becoming geometric altitudes instead of barometric.
- Option 2: Paradigm change in flight procedures, now being vertically defined by published geometric paths with vertical containment assumptions, with two sub-options:
  - Sub-option 2.1 - without V-RNP: navigation and guidance capability with vertical containment performance demonstrated at aircraft certification / ops approval level but without RNP-like onboard monitoring and alerting.
  - Sub-option 2.2 - with V-RNP: navigation and guidance capability with vertical containment performance supported by RNP-like onboard monitoring and alerting.

Different aspects were intended to be addressed:

- FMS & Displays notional impacts
- Vertical TSE budget sizing and feasibility
- Impacts assessment on navigation architecture and functions users of GNSS altitude vs Baro Altitude:
  - RNP & RNP AR related functions
  - SLS and GLS functions: transition between RNP (FMS) and xLS approaches modes consequences
- GNSS jamming and spoofing risk assessment in light of new geometric altitude utilisation:
  - Based on GNSS spoofing in-service experience up to S4 (collateral spoofing), are there any new risk brought by geo altitude?
  - Use of baro as a reversionary mode: practicality and preliminary impact
- Compatibility assessment with other navigation and surveillance functions:
  - Transition between different sources of altitude
  - Surveillance functions: ADS-B out, TAWS, TCAS
- Compatibility assessment with energy management considerations, especially for Option 2 (procedurally imposed vertical paths). Coordination with exercise “Aircraft Performance & Procedures” will be established to address this point.
- Qualitative business value assessment.

- Operational, crew and preliminary training impacts and safety benefits
    - Management of mixed aircraft configurations
    - Differences in flight operations related to the new geo-based airspace management principles

However, due to time and resources availability constraints, not all items have been addressed, or at least not with the expected level of detail.

The assessment has been conducted with a team of experts in ATM, Cockpit Operations, Flight Management System (FMS) and Navigation systems (other than FMS), also supported by Flight Performance specialists. The assessment has covered technical and operational feasibility considerations in the following areas:

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

The nature of this exercise in the frame of Green GEAR Exploratory Research project corresponds to TRL1 maturity level.

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

Exercise #03 validation objective ID	Exercise #03 validation objective title	Exercise #03 success criterion ID	Exercise #03 success criterion
OBJ-GreenGEAR-0406-TRL2-ERP-FEA1	Feasibility in Initial Approach	CRT-GreenGEAR-0406-TRL2-ERP-FEA1.001	No technical showstopper is identified at airborne implementation level. This actually has two dimensions: Technical feasibility: the necessary evolutions on aircraft architecture and systems to support the new operational concept are identified, and their associated technological maturity risk and qualitative development cost estimation are deemed reasonable. Operational feasibility: potential impacts on aircraft operation and performance when conducting the new operational concept with the foreseen technical solution are identified and deemed acceptable from airspace users' perspective (both regarding flight crew operation and airline business considerations).

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Exercise #03 validation objective ID	Exercise #03 validation objective title	Exercise #03 success criterion ID	Exercise #03 success criterion
OBJ-GreenGEAR-0406-TRL2-ERP-FEA2	Feasibility in Climb and Descent	CRT-GreenGEAR-0406-TRL2-ERP-FEA2.001	No technical showstopper is identified at airborne implementation level. This actually has two dimensions: Technical feasibility: the necessary evolutions on aircraft architecture and systems to support the new operational concept are identified, and their associated technological maturity risk and qualitative development cost estimation are deemed reasonable. Operational feasibility: potential impacts on aircraft operation and performance when conducting the new operational concept with the foreseen technical solution are identified and deemed acceptable from airspace users' perspective (both regarding flight crew operation and airline business considerations).

Table 32: Summary of validation exercise #03 validation objectives

C.1.3 Summary of validation exercise #03 validation scenarios

Two solution scenarios have been addressed according to the two operational concept variants defined in OSED for GeoAlt solution:

- Solution Option 1: Current paradigm of flight procedures being vertically defined by altitude constraints, with such constraints becoming geometric altitudes instead of barometric.
- Solution Option 2: Paradigm change in flight procedures, now being vertically defined by constant angle published geometric paths with vertical containment assumptions, with two sub-options:
    - Sub-option 2.1 - without V-RNP: navigation and guidance capability with vertical containment performance demonstrated at aircraft certification / ops approval level but without RNP-like onboard monitoring and alerting.
    - Sub-option 2.2 - with V-RNP: navigation and guidance capability with vertical containment performance supported by RNP-like onboard monitoring and alerting.

C.1.4 Summary of validation exercise #03 validation assumptions

There are no validation assumptions specific to this exercise. Solution-level validation assumptions are captured in the main body of the document.

C.2 Deviation from the planned activities

At project launch, this exercise was expected to focus on airborne technical feasibility aspects, but while defining the Exploratory Research Plan (ERP), it was clarified that the assessment scope would also cover operational feasibility aspects.

Also, while the Solution definition is focused on Climb, Descent & Initial Approach phases, this validation exercise has had the opportunity to also address Cruise phase.

On the other hand, due to time and resources availability constraints, not all items identified in the ERP have been addressed, or at least not with the expected level of detail.

C.3 Validation exercise #03 results

C.3.1 Summary of validation exercise #03 results

Exercise #03 validation objective ID	Exercise #03 validation objective title	Exercise #03 success criterion ID	Exercise #03 success criterion	Sub-operating environ-ment	Exercise #03 validation results
OBJ-GreenGEAR-0406-TRL2-ERP-FEA1	Feasibility in Initial Approach	CRT-GreenGEAR-0406-TRL2-ERP-FEA1.001	No technical showstopper is identified at airborne implementation level. This actually has two dimensions: <u>Technical feasibility</u>: the necessary evolutions on aircraft architecture and systems to support the new operational concept are identified, and their associated technological maturity risk and qualitative development cost estimation are deemed reasonable. <u>Operational feasibility</u>: potential impacts on aircraft operation and performance when conducting the new operational concept with the foreseen technical solution are identified and deemed acceptable from airspace users' perspective (both regarding flight crew operation and airline business considerations).	TMA HC	**<u>Solution Option 1:</u>** Technically feasible but open points regarding management of jamming & spoofing threats and FMS predictions. **<u>Solution Option 2:</u>** Technically feasible but open points regarding management of jamming & spoofing threats, FMS predictions, and speed management on constant FPA segments.

Exercise #03 validation objective ID	Exercise #03 validation objective title	Exercise #03 success criterion ID	Exercise #03 success criterion	Sub-operating environ-ment	Exercise #03 validation results
OBJ-GreenGEAR-0406-TRL2-ERP-FEA2	Feasibility in Climb and Descent	CRT-GreenGEAR-0406-TRL2-ERP-FEA2.001	No technical showstopper is identified at airborne implementation level. This actually has two dimensions: Technical feasibility: the necessary evolutions on aircraft architecture and systems to support the new operational concept are identified, and their associated technological maturity risk and qualitative development cost estimation are deemed reasonable. Operational feasibility: potential impacts on aircraft operation and performance when conducting the new operational concept with the foreseen technical solution are identified and deemed acceptable from airspace users' perspective (both regarding flight crew operation and airline business considerations).	TMA HC	**Solution Option 1:** Climb and Descent: Technically feasible but open points regarding management of jamming & spoofing threats and FMS predictions. **Solution Option 2:** Descent: Technically feasible but open points regarding management of jamming & spoofing threats, FMS predictions, and speed management on constant FPA segments. Climb: In addition to open points regarding operational feasibility, not possible to conclude on technical feasibility due to major FMS impacts. Further R&D work with FMS suppliers required.

Table 33: validation exercise #03 results

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

C.3.2.1 OBJ-GreenGEAR-0406-TRL2-ERP-FEA1 Results

Results for this validation objective (Feasibility in Initial Approach) are covered by results for the next validation objective.

C.3.2.2 OBJ-GreenGEAR-0406-TRL2-ERP-FEA2 Results

The assessment of this validation objective (Feasibility in Climb and Descent) also covers Initial Approach (previous objective).

The main technical and operational challenges for Solution feasibility on airborne side that have been addressed by this exercise, can be classified into the following topics:

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

Some challenges are common to Solution Option 1 and Solution Option 2, whereas others are specific to Solution Option 2. The results for the common ones are presented first, followed by those specific to Solution Option 2.

<u>Results common to both Solution Options</u>

Navigation Systems (other than FMS)

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

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

The available altitude sources are:

- GPS altitude augmented by RAIM called GPS altitude
- GPS altitude hybridised with inertia called hybrid altitude
- GPS augmented by SBAS called SBAS altitude
- GPS augmented by GBAS called GBAS altitude

Design considerations regarding the choice of altitude source are provided hereafter. The conclusion for the airborne feasibility Validation Objective is that there is no technical showstopper regarding this topic.

GBAS altitude

We should discard GBAS altitude since the current GBAS standards defined by ICAO SARPs and RTCA MOPS DO-253 do not fully enable GBAS positioning service beyond DMAX=20 NM of each runway end served by a GBAS station. In the case where DMAX would be extended, several challenges will be faced such as ensure the integrity allocation to the vertical domain and the possibility to receive VDB at a greater distance than 23 NM. Besides, the number of GBAS stations in Europe and the number of aircraft equipped with this option limit the value to target GBAS as a solution, also considering that no GBAS station in Europe has promulgated GBAS positioning service.

Hybrid altitude

Hybrid altitude would probably be a good option. Indeed, the first advantage to use this solution is the fact that it is available everywhere without the need for any additional service from the ground infrastructure. Therefore, outside of SBAS area such as EGNOS service area and in particular in oceanic regions (for the cruise phase), geometric altitude would still be available. However, while the hybridisation function available in modern ADIRS and compliant with either RTCA DO-229 Appendix R or RTCA DO-384 provide a hybrid altitude, this parameter has no performance requirement in terms of integrity and accuracy and no performance commitment is provided by manufacturers because the specific need was never expressed in specifications. Currently, hybrid altitude is available at the output of the ADIRS as well as quality factors metrics (VFOM, VIL) and besides the performance qualification to be done on these parameters, a modification of interface between the FMS and the ADIRS would be required to replace the IRS/barometric altitude by the hybrid altitude. Other factors not to be neglected are the refresh rate, the transmission rate and the data latency. Indeed, they must be compatible with the performance needs from the guidance loop. The transmission rate of hybrid altitude being higher than 10 Hz, and the latency being similar to the rest of the hybrid parameters used for guidance of the aircraft, it is a priori compatible with the guidance needs.

GPS altitude

GPS altitude is also available at the output of the MMR and also echoed by the ADIRS including the respective quality factors (VFOM/VIL). However, the geometric altitude integrity allocation is not optimised and not guaranteed. In case GPS altitude is selected, a modification of interface between the FMS and the ADIRS or MMR would be required to replace the IRS/barometric altitude by the GPS altitude. However, the transmission rate of GPS altitude is usually of 1 HZ and sometimes 5 Hz when matching a higher refresh rate (i.e. computation rate). Besides, the data latency is usually of 1200 ms. In order to use this data for guidance, these characteristics must probably be improved beyond 10 Hz with a latency of a few hundred of ms. An analysis will need to be done to assess the compatibility of this refresh rate and the guidance loop needs. It is to be noted that using the GPS altitude at the output of the ADIRS will add an extra latency to be considered as well.

SBAS altitude

SBAS altitude provides a high integrity (up to 10-7/hour integrity risk) geometric altitude in the service area of EGNOS. According to EGNOS SDD, the performance commitment in the LPV service area is different than in the NPA service area and the consequence of performance needs and the transition between the two areas should be studied. The SBAS altitude is provided by the MMR and echoed by

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the ADIRS. Like the GPS altitude, the refresh and transmission rate are limited at 5 Hz. An analysis will need to be done to assess the compatibility of this refresh rate with the guidance loop needs. It is to be noted that using the SBAS altitude at the output of the ADIRS will add an extra latency to be considered as well.

Additional considerations

The MMR and ADIRS, when using GPS-based parameters, are sensors which have different requirements per flight phase as defined in ICAO SARPs Table 3.2.7.4-1. However, the MMR and the ADIRS do not change their moding and provide their performance to the best of their capability according to the available GPS and SBAS satellites and their geometry. It is the FMS localisation function role to assess the performance provided by these sensors by looking at xIL and xFOMs with x=H or V and comparing these parameters with alert limits according to the flight phase or the intended operation to be conducted (e.g. RNP 0.3). Additional comparisons and monitoring may be done. Therefore, according to the flight phase among climb, cruise, descent or approach, it would be the role of the FMS to select the most relevant altitude. We could consider to select SBAS altitude in priority when available and select hybrid altitude otherwise, pending the performance of this parameter can be characterised and demonstrated. In case they are not available, reversion to the barometric altitude must be considered.

Flight Management System (FMS) and Flight Performance

From FMS standpoint, building a theoretical descent profile or predicting a climb phase in geometric reference (rather than a combination of STD/QNH) would not create any major issue. It can even be seen as a simplification of current situation as this will simplify the management of the transition layer in the profile computation, which is currently seen as a complexity.

However, the underlying FMS predictions would be impacted by the switch to geometric reference as the performance of the aircraft is always tied to barometric conditions. Thus, the use of both altitude references is still needed to preserve FMS predictions accuracy.

Unlike the real-time use of both references, which is easily ensured by the availability of both baro and geo sensors onboard, the use of both references for prediction is more complex as it requires baro/geo conversion capability.

For this baro/geo conversion capability, the case of climb and descent would most likely be less penalised than the cruise phase (see Additional Results below) as a reference QNH and Delta-ISA information are available on both departure and destination airports. But for the conversion to be computed by FMS, it is also necessary to have geographical information about the offset between the Earth geoid (MSL) reference for barometric altitudes/elevations and the WGS-84 ellipsoid reference for geometric altitudes.

Possible ways forward:

- Assess if FMS predictions inaccuracy along climb and descent could be acceptable, which might be the case for fuel and time considering the short duration and thus the limited accumulated error along these phases, and might also be acceptable for altitude and speed as long as the accuracy of EPP predictions is not critical for ATC operations.

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- Develop FMS upgrades using meteorological data with pressure forecast grids at different geometric altitudes (as currently done with wind and temperature at different barometric altitudes/FLs).
- Develop FMS upgrades using QNH and DISA already available to pilots through ATIS reports, together with geographical data providing the static offset between geometric altitude and ISA barometric altitude at airports and waypoints. This geographical data could either provide both altitude values (geo and ISA baro), or one of them together with an offset for the other similarly to current MagVar publication.

It is to be noted that current FMS does not use geometric reference and is not currently foreseen in the short term, so even if feasibility of Solution Option 1 for climb and descent seems achievable, a more detailed impact assessment would be needed in further Solution maturity steps.

Management of Jamming & Spoofing Threats

Since the preparation and the launch of Green-Gear project, the geopolitical and operational context of civil aviation has changed drastically. Indeed, the number of GNSS interference events (jamming & spoofing) daily affects thousands of aircraft (not only Airbus) with different impacts such as undue surveillance alerts, erroneous GPS data, erroneous GPS/IRS data and erroneous time. Some locking of specific models of GPS receivers have been observed by the aviation community depending on the nature of the jammers.

The threat seems to evolve in terms of numbers of events, size of affected areas and sophistication of the threats. However, the aviation community (including authorities and ICAO) do not consider that the civil aircraft are the primary targets of this evolving threat but are rather collateral victims. This explains that, while the effects of such interferences lead to an operational burden, they are detectable by the crew.

In order to mitigate jamming and spoofing and become more resilient, the industry is planning to implement in industry airborne standards from RTCA and EUROCAE, several anti-jamming and anti-spoofing features that will provide more robust navigation capability under interference such as detection capability, return to normal after exiting the interference areas, authentication of GNSS signal (e.g. Galileo OS NMA and SBAS authentication are planned in 2030+).

Beside those ongoing airborne standards evolutions, the necessary mitigations identified by this exercise to deal with the unavailability of GNSS-based altitude sources due to jamming & spoofing threats are listed below:

- a reversion to barometric altitude will be required on-board the aircraft (automatic or manual) upon detection but more likely preferable before entering the interference area.
- a reversion to barometric based airspace and management of all aircraft affected in the area by air traffic controllers such as clearance and RVSM constraints must be performed.
- a robust jamming and spoofing detection tool (on the ground and/or on-board) must be operational in order to ensure aircraft can timely and concurrently revert to barometric altitude approximately at the same locations
- the management of the transition between an airspace managed in barometric altitude and a geometric altitude: This is already needed under normal conditions but this situation might

occur very often in some regions near conflict zones, which could lead to decide to not switch to geometric altitude at all in some airspaces.

The conclusion for the airborne feasibility Validation Objective is that the use of geometric altitude in climb, cruise and descent should probably not be considered before the introduction and deployment of these mitigation features, as the jamming & spoofing threats will complexify the flight crew and air traffic controllers operations to an extent that may be unacceptable in larger areas with less interference detection means as of today.

Compatibility with Surveillance Functions

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

It is to be noted that several other sensors can be used to perform comparisons and add robustness, and the surveillance part does not only rely on GPS altitude. Since the objective is to have a "safety net", it could be useful to consider that the sources of GPS-based altitudes utilised by surveillance and navigation are different, for instance one using SBAS altitude or GPS altitude whereas the other would be the GPS-IRS hybrid altitude.

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

The conclusion for the airborne feasibility Validation Objective is that there is no technical showstopper regarding this topic.

Cockpit Systems and Flight Crew Operation

In addition to the main operational challenges already mentioned, related to FMS Predictions and to Jamming & Spoofing, some open points can be identified for the design of the cockpit HMI and flight crew operating procedures.

Note: this list does not intend to be exhaustive, it just provides the outcomes of the preliminary assessment conducted during this exercise.

<u>Provision of both geo and baro altitudes to flight crew</u>

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

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

Manual vs Automatic altitude reference switching

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

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

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

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

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

Results specific to Solution Option 2

Flight Management System (FMS) and Flight Performance – Descent and approach

Current Airbus implementation of Continuous Descent Operation for segments between two 'AT' altitude constraints is based on a "single FPA" design, that is, the FMS basically builds a straight line between the altitude constraints, regardless of speed constraint requirements. This means that current FMS design regarding vertical path definition is already similar to the expected design for Solution Option 2 as long as 'AT' constraints are used.

Note: this applies to Airbus aircraft manufactured in recent years equipped with CDA function. In-service fleet with older FMS standards have a different design.

However, Airbus has received feedback from operational stakeholders (airspace users and ATC) about this design being not efficient regarding speed management.

Indeed, in-service experience has shown that speed brakes or conf extension are sometimes used quite early, due to a profile on which aircraft cannot efficiently decelerate. Indeed, this requires the aircraft to initiate deceleration before commencing a challenging flight path angle. This has led to some flights having their approach DECEL point and associated conf extension at as high as FL150.

To improve this design, a new CDA profile is being implemented for next FMS standard and will be applicable to the whole Airbus fleet.

The design essentially relies on building a profile that “breaks” the FPA between constraints into two parts: a nominal FPA with constant speed, followed by a shallower FPA (still not a level-off) allowing for a nominal deceleration rate.

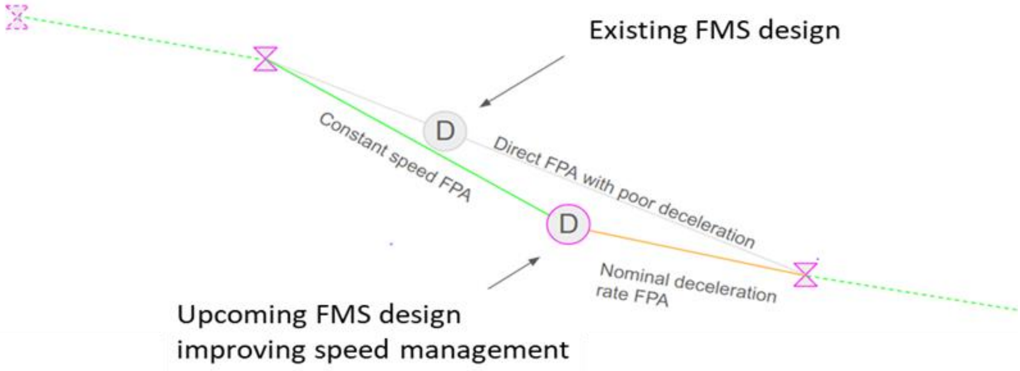

Figure 20: Upcoming Airbus FMS design improving speed management

In addition to avoiding too early speed brakes or conf extension, this new design also allows for a more efficient speed monitoring for flight crew and ATC, as speed changes are more obvious and take less time to complete.

Green-GEAR’s Solution Option 2, by publishing and forcing all aircraft to guide on a single FPA, would go against this improved design philosophy and exacerbate the very challenge that Airbus attempts to overcome.

In addition, there is a huge diversity of aircraft deceleration performance, which means that, under the same weather conditions on the same descent path, some aircraft may be able to manage their speed comfortably while others may not be able to decelerate without speed brakes or early flaps / landing gear extension, with the associated impact on noise and maintenance costs.

The proposed way forward would be to limit the use of fixed vertical paths to complex airspace seeking to systemise traffic separation, while still allowing the use of the improved FMS profile anywhere else. When designing fixed vertical paths, the diversity of aircraft deceleration performance must be considered to avoid speed management issues.

From a technical standpoint, this proposed way forward involves developing FMS capable of flying both the improved profile when allowed (e.g. segments with altitude constraints only) and the fixed vertical path when published (e.g. segments with imposed FPA). Design principles to fly the fixed vertical path descent could be inspired from existing design for RNP AR approaches.

Flight Management System (FMS) and Flight Performance – Climb

In today’s design, no profile exists for the Climb phase (unlike the descent), the aircraft is never guided on a vertical trajectory. This is done to ensure that each aircraft manages its own energy efficiently and climbs at its best rate.

This is particularly important during all acceleration phases (acceleration altitude in initial climb, speed constraints sequencing / speed limit transition at 10000ft, etc) where an energy sharing has to take place, to ensure both detectable speed trend and adequate climb rate.

The published altitudes constraints on the procedures are matched by the aircraft by simply preventing it from climbing above any downstream applicable constraint, and the aircraft flight path compliance status for each altitude constraint (achieved or missed) is published accordingly on FMS pages / ND / VD thanks to the FMS prediction computation.

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

The use of a fixed climb profile would also have a significant impact on flight performance as, in order to ensure flyability by all the expected diversity of aircraft in the expected range of weather conditions, the flight path angle considered for procedure design would have to be significantly lower than current climb rates of most aircraft, thus heavily penalising flight efficiency.

This negative impact might be partially mitigated by publishing two departure procedures with different vertical profile, one for high climb performance traffic and other for low climb performance traffic. But further R&D work would be required to assess if such a discrete number of authorised climb profiles would satisfy the operational needs.

Moreover, during the initial climb phase where the aircraft has to accelerate from take-off speed to the 250kt speed limit (or to its optimal climb speed if lower than 250kt), such speed change induces a significant local reduction of the aircraft flight path angle. Such acceleration phase can be delayed by the pilot during flight preparation by adapting the acceleration initiation altitude (“ACCEL” FMS parameter with default value 1500ft AGL), but it should remain at a reasonable altitude AGL to let the aircraft fly in clean configuration as soon as possible.

Thus, it is recommended to avoid using fixed vertical angle paths at low altitudes where aircraft would normally be accelerating from take-off speed to climb speed, unless such paths could be discontinued soon enough (e.g., no later than 5000ft AGL) to allow for a timely switch to clean configuration.

Furthermore, aircraft climb performance decreases with altitude due to the dependence of engine thrust and aerodynamics on air density, so fixed vertical angle departure procedures cannot provide optimised climb profiles. In order to be flyable, the designed vertical angle would need to fit the lower climb performance at the end (higher altitude) part of the departure procedure, thus reducing flight efficiency along the most part of the procedure.

This negative impact might be partially mitigated by progressively decreasing the required vertical angle along subsequent segments of the departure procedure. But further R&D work would be needed to assess the potential challenges associated to the transitions between segments with different vertical angle.

The proposed way forward for Solution Option 2 in climb phase would be to avoid using fixed vertical angle paths in this phase if possible, or, if absolutely necessary in complex airspace requiring systemisation of traffic separation, limit them to the smallest extent possible while still allowing free climb profile anywhere else.

Cockpit HMI for V-RNP onboard monitoring and alerting

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

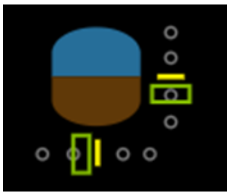

Figure 21: Notional HMI with V-RNP vertical guidance monitoring

Note: this HMI image is for illustration purposes only, it does not represent actual cockpit design for the SESAR Solution.

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

C.3.2.3 Additional Results

While the Solution definition is focused on Climb, Descent & Initial Approach phases, this validation exercise has had the opportunity to also address Cruise phase.
Two significant operational challenges have been identified for Cruise phase, applicable both for Solution Option 1 and Solution Option 2:

- FMS predictions
- Flight envelope and cruise altitude optimisation

FMS Predictions

FMS is responsible for providing predictions to the crew from preflight to landing, among which fuel & time are the most operationally critical since these predictions are used by the flight crew to conduct the flight follow-up to ensure that the safety and mission needs are satisfied.

Aircraft performance computations are always tied to barometric conditions, so the use of a geometric cruise altitude would require the system to make assumptions on the "equivalent isobar" to the cruise altitude to make the predictions.

The FMS could locally correlate a geometric altitude with an equivalent barometric flight level based on local temperature/pressure, but this equivalence would not be relevant for the whole flight as the isobar will most likely vary and the FMS does not have this information in advance, so predictions along the remaining flight would be inaccurate.

Note: the inaccuracy of the fuel & time predictions would be partly related to the inaccurate prediction of the aircraft true airspeed and thus ground speed.

To meet safety objectives regarding fuel, the FMS would need to make conservative assumptions such as considering a lower pressure altitude along the geometric cruise than the one expected with local conditions at departure, in order to cover possible barometric variations along the flight.

The assumptions of potential barometric variation would have to be the result of a statistical analysis performed by meteorological agencies similar to wind forecast error used in RTA/4D demonstrations.

The fact of making conservative assumptions with regards to fuel consumption prediction would also impact fuel planning, as more fuel would need to be carried, which would bring increased fuel consumption.

Finally, it must also be highlighted that most of the FMS predicted parameters (e.g. time, altitude, speed) can also be shared with ATC through EPP, so the predictions inaccuracy could also impact ATC operations relying on these data.

This operational impact could be mitigated by upgrading FMS and OCC flight planning tools to use meteorological data with pressure forecast grids at different geometric cruise levels (as currently done with wind and temperature at different barometric FLs) to maintain a satisfactory accuracy of FMS predictions.

Since this would involve a major avionics upgrade, with high development costs and time, an intermediate solution could be foreseen based on only upgrading OCC flight planning tools (easier to deploy than FMS ones).

However, this could lead to significant inconsistencies between the airline flight plan predictions and the FMS predictions, which is unlikely to be operationally acceptable considering that flight crew is expected to perform fuel monitoring based on FMS predictions compared to the planned fuel.

Flight envelope and cruise altitude optimisation

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

In today's operations, pilots can contribute to flight optimisation by requesting, when possible, a cruise flight level as close as possible to the optimum flight level computed by the FMS. The optimum altitude ("OPT ALT") is generally a few thousand feet below the maximum recommended altitude ("REC MAX"), which is considered as the upper limit for safe operation.

The REC MAX is computed by the FMS, not only based on the aircraft maximum certified altitude, but also on performance considerations that depend on flight and weather conditions. It is defined as the lowest of:

- Maximum altitude at maximum cruise thrust in level flight
- Maximum altitude at maximum climb thrust with 300 ft/min vertical speed
- Maximum certified altitude
- 1.3 g buffet limited altitude.

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It must be highlighted that the REC MAX can be several thousand feet below the aircraft maximum certified altitude for a flight operating close to its Maximum Take-off Weight (MTOW) or in hot weather conditions (DISA>>0).

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

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

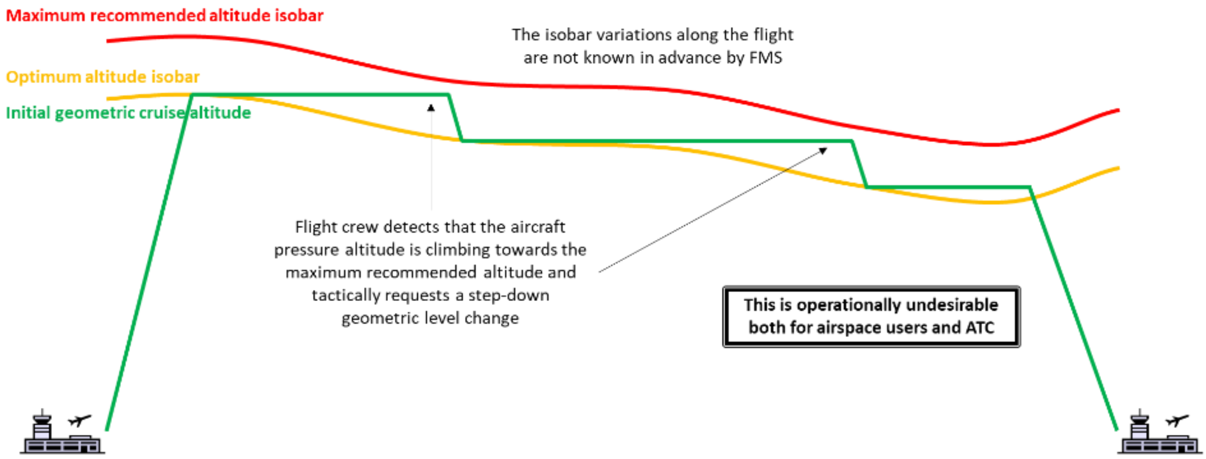

Figure 22: Geometric navigation in cruise – flight envelope and cruise altitude optimisation challenge (a)

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

However, the marginal (if any) potential benefits of using geometric altitude in cruise cannot counterbalance neither the costs of developing the associated enablers, nor the remaining operational hurdles of the increased number of level changes.

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

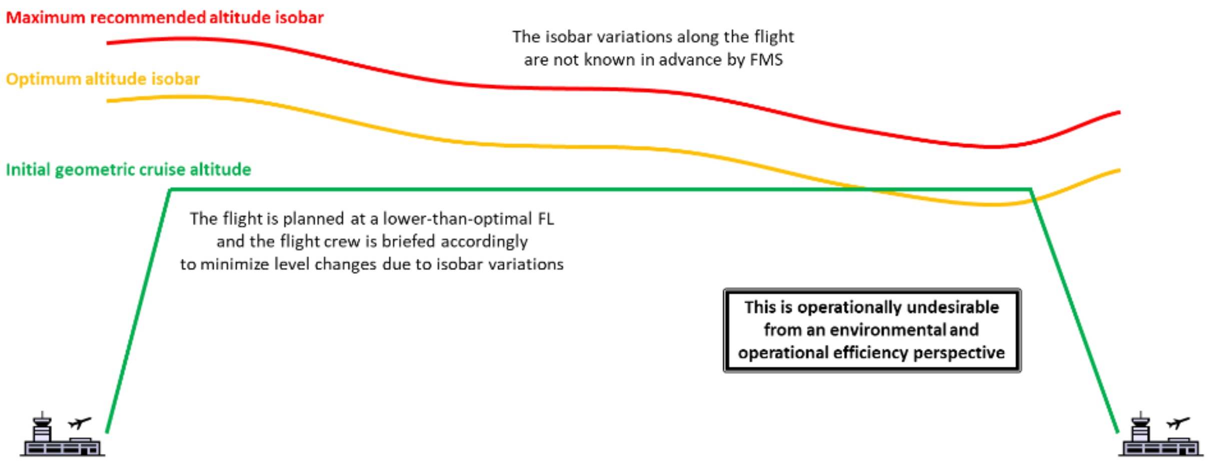

Figure 23: Geometric navigation in cruise – flight envelope and cruise altitude optimisation challenge (b)

It has been concluded that this operational challenge is significant enough to constitute a showstopper for the use of geometric altitude in cruise phase.

C.3.3 Unexpected behaviours/results

While the Solution definition is focused on Climb, Descent & Initial Approach phases, this validation exercise has had the opportunity to also address Cruise phase.

It has concluded that the use of geometric altimetry is not operationally suitable for cruise phase, due to significant challenges inherent to the dependency of aircraft performance on barometric conditions, particularly regarding flight envelope (e.g. maximum operating altitude) and cruise altitude optimisation.

C.3.4 Confidence in results of validation exercise #03

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

The main limitation is the scope of the exercise, which has been focused on large commercial aircraft (Airbus families), so specific impact on other aircraft types has not been addressed.

Some conclusions might be generalisable, but others strongly dependent on the aircraft systems architecture might not. This is probably the case of differences regarding navigation architecture between aircraft using IRS-GNSS hybridisation as primary navigation means (most airliners and business jets) and aircraft using only GNSS as primary navigation means (mainly general aviation).

C.3.4.2 Quality of validation exercises results

While it has not been possible to cover all the initially expected scope, the produced results come from expert judgement that can be considered as highly reliable, as far as this type of qualitative exercise can be.

C.3.4.3 Significance of validation exercises results

Based on the nature of this validation exercise, no relevant consideration on statistical or other operational significance applies beyond what has been indicated in the preceding sections.

C.4 Conclusions

Conclusions will be provided for both Solution Options, that is:

Solution Option 1: use of geometric instead of barometric altimetry, while keeping current instrument flight procedures philosophy for vertical navigation based on altitude constraints at waypoints while letting the aircraft freely define its vertical path respecting those constraints.

Solution Option 2: Extends Solution 1 by introducing, in addition to the use of geometric altitude, a new airspace design philosophy based on departure and arrival procedures imposing constant flight path angle segments with vertical containment expectations (i.e. V-RNP).

While the Solution definition is focused on Climb, Descent & Initial Approach phases, this validation exercise has had the opportunity to also address Cruise phase. The related conclusions are also provided.

C.4.1 Conclusions on concept clarification

Conclusions common to both Solution Options

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

Such mitigations are listed in the Recommendations section below.

Conclusions specific to Solution Option 2

This Solution Option has significant operational drawbacks requiring further R&D work to consolidate the impact assessment for Descent & Approach and to conclude on technical and operational feasibility for Climb.

Regarding **Descent & Approach**, the main operational drawbacks that have been identified for Solution Option 2 are related to speed management, with respect to two aspects:

Aircraft deceleration along a fixed vertical angle path is not the most operationally efficient, since in some cases the aircraft may need to start deceleration very soon and with a low deceleration rate, both of which are operationally unpractical for flight crew and ATC for speed management purposes.

There is a huge diversity of aircraft deceleration performance, which means that, under the same weather conditions on the same vertical path, some aircraft may have an adequate deceleration rate in clean configuration while others may not be able to decelerate without speed brakes or early flaps / landing gear extension, with the associated impact on noise and maintenance costs.

The proposed way forward for Solution Option 2 in descent and initial approach phases would be to:

Limit the use of fixed vertical paths to complex airspace seeking to systemise traffic separation, while still allowing the use of optimised FMS profile anywhere else.

Consider the diversity of aircraft deceleration performance when designing the vertical profile of arrival and initial approach procedures to prevent speed management issues.

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Regarding **Climb**, the main operational drawbacks identified for Solution Option 2 are summarised below:

Climb phase is currently driven by a flight performance paradigm where the aircraft climbs at its best rate while following speed targets, with no notion of vertical path to be flown other than some altitude constraints not to be exceeded. Moving towards a new paradigm where a defined vertical path would need to be flown during climb, involves a significant change in flight crew operation, and rises some concerns regarding the potential interference between the new paradigm and the still necessary aircraft performance considerations to ensure flyability and flight efficiency.

There is a huge variety of aircraft climb performance so, in order to ensure flyability by all the expected diversity of aircraft in the expected range of weather conditions, the flight path angle considered for procedure design would have to be significantly lower than current climb rates of most aircraft, thus heavily penalising flight efficiency.

Moreover, during the initial climb phase where the aircraft has to accelerate from take-off speed to the 250kt speed limit (or to its optimal climb speed if lower than 250kt), such speed change induces a significant local reduction of the aircraft flight path angle. Such acceleration phase can be delayed by the pilot during flight preparation by adapting the acceleration initiation altitude (“ACCEL” FMS parameter with default value 1500ft AGL), but it should remain at a reasonable altitude AGL to let the aircraft fly in clean configuration as soon as possible.

Furthermore, aircraft climb performance decreases with altitude due to the dependence of engine thrust and aerodynamics on air density, so fixed vertical angle departure procedures cannot provide optimised climb profiles. In order to be flyable, the designed vertical angle would need to fit the lower climb performance at the end (higher altitude) part of the departure procedure, thus reducing flight efficiency along the most part of the procedure.

The proposed way forward for Solution Option 2 in climb phase would be to avoid using fixed vertical angle paths in this phase if possible, or, if absolutely necessary in complex airspace requiring systemisation of traffic separation, assess the design considerations provided in the Recommendations section below.

Additional conclusions – Cruise phase

The use of geometric altimetry has been found not operationally suitable for Cruise phase, due to significant challenges inherent to the dependency of aircraft performance on barometric conditions, particularly regarding flight envelope (e.g. maximum operating altitude) and cruise altitude optimisation.

Indeed, geometric-based cruise would lead to an increased number of cruise level changes (not only step-up but also step-down) following isobar variations in order to keep the aircraft within its flight envelope and as close as possible to its optimum cruise altitude. Such operational complexity would be undesirable from Airspace Users and ATC perspective.

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

C.4.2 Conclusions on technical feasibility

For Solution Option 1, this exercise has identified some design considerations with no technical showstopper identified so far for Climb, Descent and Approach.

For Solution Option 2, this exercise has identified some design considerations with no technical showstopper identified so far for Descent and Approach, while further R&D work would be required to establish technical feasibility for Climb.

The identified design considerations for both Solution Options are summarised hereafter.

Conclusions common to both Solution Options

Navigation Systems (other than FMS)

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

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

Design considerations addressing this topic are provided above as part of the results for Validation Objective OBJ-GreenGEAR-0406-TRL2-ERP-FEA2, with no technical showstopper identified so far.

Flight Management System (FMS) Predictions

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

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

A simple solution could use conservative assumptions to meet safety objectives regarding fuel, such as considering a worst-case geo-baro offset based on statistical data. A worst-case offset from fuel consumption perspective would bring a lower bound of the baro altitude at a given geo altitude, which would also impact other performance computations such as speed, time, vertical profile, etc.

However, such conservative approach would degrade the accuracy of FMS predictions, leading to a negative impact on predictability, which may also degrade fuel efficiency if airline flight planning requires loading of additional fuel. Flight crew tasks and ATC operations relying on FMS predictions may potentially be also impacted.

The impact of such a simple solution would be too high if geometric reference is used all along the flight, especially due to the cumulated error on fuel and time predictions, but it could be interesting for future R&D work to assess if the impact might remain within acceptable limits when the use of geometric reference is limited to Climb, Descent and Approach.

A more advanced solution to tackle this challenge could rely on upgrading both FMS and OCC flight planning tools to use meteorological data with pressure forecast grids at different geometric altitudes, as currently done with wind and temperature at different barometric altitudes/FLs. In addition to the FMS and OCC systems impact, it could be interesting for future R&D work to assess the potential impact on MET services to have the forecast data (pressure, wind and temperature) referenced to geometric altitudes.

For the use of geometric altimetry limited to Climb, Descent and Approach, an alternative solution could be based on making the FMS and the OCC flight planning tools able to compute the pressure altitude at an expected geometric altitude by themselves, using the necessary static geographical information (e.g. offset between baro and geo altitudes in ISA conditions) and the dynamic local atmospheric conditions (e.g. QNH and temperature at departure and destination airports).

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

Compatibility with Surveillance Functions

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

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

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

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

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

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

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

Manual vs Automatic altitude reference switching

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

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

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

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

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

<u>Conclusions specific to Solution Option 2</u>

FMS climb profile computation

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

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

Cockpit HMI for V-RNP onboard monitoring and alerting

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

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

C.4.3 Conclusions on performance assessments

Based on the nature of this exercise, no quantitative performance assessment has been conducted.

However, qualitative considerations related to performance areas such as Safety, Human Performance, Operational Efficiency and Environment have been addressed as part of the feasibility assessment. See conclusions above.

C.5 Recommendations

This section summarises the main recommendations addressing technical or operational feasibility risks identified by this exercise. For additional airborne design considerations, please refer to detailed results above.

Recommendations common to both Solution Options

Management of Jamming & Spoofing Threats

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

- A reversion to barometric altitude will be required on-board the aircraft (automatic or manual) upon detection but more likely preferable before entering the interference area.
- A reversion to barometric based airspace and management of all aircraft affected in the area by air traffic controllers such as clearance and RVSM constraints must be performed.
- A robust jamming and spoofing detection tool (on the ground and/or on-board) must be operational in order to ensure aircraft can timely and concurrently revert to barometric altitude approximately at the same locations.

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- The management of the transition between an airspace managed in barometric altitude and a geometric altitude: This is already needed under normal conditions but this situation might occur very often in some regions near conflict zones, which could lead to decide to not switch to geometric altitude at all in some airspaces.

FMS Predictions

Regarding the impact of using geometric reference on the FMS predictions (which still require anticipating barometric conditions for aircraft performance computation):

- Assess if the degradation of FMS predictions accuracy with a simple solution making conservative assumptions would be low enough when the use of geometric reference is limited to Climb, Descent and Approach.
- Otherwise, consider further R&D work on more advanced solutions allowing FMS and OCC flight planning tools to determine the pressure altitudes associated to the expected geometric altitudes for performance prediction purposes.

Recommendations specific to Solution Option 2

For **Descent and Initial approach phases**:

- Limit the use of fixed vertical paths to complex airspace seeking to systemise traffic separation, while still allowing the use of optimised FMS profile anywhere else.

- Consider the diversity of aircraft deceleration performance when designing the vertical profile of arrival and initial approach procedures to prevent speed management issues.

For **Climb phase:**

Further R&D work in collaboration with FMS suppliers would need to be conducted to assess the technical feasibility of the introduction of vertical profile computation and guidance capability in this phase of flight.

From an airborne operation perspective, it is recommended to avoid using fixed vertical angle paths in Climb phase if possible. Otherwise, consider the following recommendations:

- Limit fixed vertical angle paths to the smallest extent possible, while still allowing free climb profile anywhere else.

- Consider the diversity of aircraft climb performance, for example by publishing two alternative departure procedures with different vertical profile, one for high climb performance traffic and other for low climb performance traffic. Further R&D work would be required to assess if such a discrete number of authorised climb profiles would satisfy the operational needs.

- Avoid using fixed vertical angle paths at low altitudes where aircraft would normally be accelerating from take-off speed to climb speed, unless such paths could be discontinued soon enough (e.g., no later than 5000ft AGL) to allow for a timely switch to clean configuration.

- Progressively decrease the required vertical angle along subsequent segments of the departure procedure. Further R&D work would be needed to assess the potential challenges associated to the transitions between segments with different vertical angle.

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Additional Recommendations – Cruise phase

Keep the Cruise phase in barometric reference as today, due to significant challenges inherent to the dependency of aircraft performance on barometric conditions, particularly regarding flight envelope (e.g. maximum operating altitude) and cruise altitude optimisation.

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Appendix D Validation exercise #04 report

This appendix provides details of the validation exercise #4 "Aircraft Performance & Procedures".

D.1 Summary of the validation exercise #04 plan

Exercise #04 is Exercise **TVAL.04.1- GreenGEAR-0406-TRL2** in the ERP [25]; it covers **Use Case 2 (Geometric Decent)** and **Use Case 3 (Geometric Cruise)** in the initial OSED [24].

D.1.1 Validation exercise description and scope

The validation exercise "Aircraft Performance & Procedures" analysed the effect of the introduction of geometric altimetry on aircraft performance and flying procedures. The exercise was mainly performed by DLR with support by Airbus and NATS.

The key validation objective is the assessment of the effect on fuel consumption (hence fuel-costs and CO2 emissions) from the introduction of geometric altimetry. Scenarios for the assessment are cruise flight and descent/ operations in the TMA.

The validation exercise was performed by means of validated aircraft simulations. One major simulation tool used in the validation exercise is the simulation model of the A320 D-ATRA, which already existed at DLR but needed to be enhanced for the specific validation exercise in the project. With this simulation model, most accurate re-simulations of real flights were performed as well as more generic simulations for a more theoretical investigation of the physical effects. Apart from this already existing A320 simulation tool, a new fast-time-simulation was developed within this validation exercise, which allows to re-simulate a large number of real flights with a simpler but faster simulation model.

The validation exercise aimed at investigating basic flight physical principles, hence the envisaged TRL is 1-2.

D.1.2 Summary of validation exercise #04 validation objectives and success criteria

SESAR solution validation objective	SESAR solution success criteria	Coverage and comments on the coverage of SESAR solution validation objective in exercise TVAL.04.1	Exercise validation objective	Exercise success criteria
OBJ-GreenGEAR-0406-TRL2-ERP-FUE2 Determine the impact to fuel for the individual flight in descent	CRT-GreenGEAR-0406-TRL2-ERP-FEU2.001	Partially covered as assessment limited to single aircraft simulation (A320)	Determine the impact to fuel for the individual flight in descent compared to barometric operations	The introduction of geometric altimetry does not increase the fuel consumption on average

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SESAR solution validation objective	SESAR solution success criteria	Coverage and comments on the coverage of SESAR solution validation objective in exercise TVAL.04.1	Exercise validation objective	Exercise success criteria
OBJ-GreenGEAR-0406-TRL2-ERP-ENV2 Determine the impact to CO_2 emissions for the individual flight in descent	CRT-GreenGEAR-0406-TRL2-ERP-ENV2.001	Partially covered as assessment limited to single aircraft simulation (A320)	Determine the impact to CO_2 emissions for the individual flight in descent compared to barometric operations	The introduction of geometric altimetry does not increase the CO_2 emissions on average
OBJ-GreenGEAR-0406-TRL2-ERP-FUE3 Determine the impact to fuel for the individual flight in cruise	CRT-GreenGEAR-0406-TRL2-ERP-FUE3.001	Partially covered as assessment limited to single aircraft simulation (A320)	Determine the impact to fuel for the individual flight in cruise compared to barometric operations	The introduction of geometric altimetry does not increase the fuel consumption on average
OBJ-GreenGEAR-0406-TRL2-ERP-ENV3 Determine the impact to CO_2 emissions for the individual flight in cruise	CRT-GreenGEAR-0406-TRL2-ERP-ENV3.001	Partially covered as assessment limited to single aircraft simulation (A320)	Determine the impact to CO_2 emissions for the individual flight in cruise compared to barometric operations	The introduction of geometric altimetry does not increase the CO_2 emissions on average

Table 34: validation objectives addressed in validation exercise TVAL.04.1

D.1.3 Summary of validation exercise #04 validation scenarios

The validation scenarios for the validation exercise are mainly

- cruise flight at different flight levels with barometric altimetry (reference scenario)
- cruise flight at different flight levels with geometric altimetry (solution scenario)
- descent operations on four specific arrival routes with simple altitude/speed constraints with barometric altimetry (reference scenario)
- descent operations on four specific arrival routes with simple altitude/speed constraints with geometric altimetry (solution scenario)

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- climb operations on three specific departure routes with simple altitude/speed constraints with barometric altimetry (reference scenario)
- climb operations on three specific departure routes with simple altitude/speed constraints with geometric altimetry (solution scenario)

The atmospheric conditions for all scenarios are either reanalysed numerical weather data (from ERA5 model, for the high-fidelity scenarios including re-simulation of real flights) or generic atmospheric models based on the International Standard Atmosphere ISA (for generic simulations to understand and highlight physical effects).

This validation exercise covers:

Use Case 2, Geometric Descent
Use Case 3, Geometric Cruise

as outlined in the initial OSED [24].

D.1.4 Summary of validation exercise #04 validation assumptions

None of the general assumption on project level are applicable for this validation exercises. However, for the specific simulations performed in this exercise some additional assumptions and limitation had to be applied. These specific assumptions and limitations are described in the specific sub-sections in the result description below.

D.2 Deviation from the planned activities

For exercise #04, the aircraft performance & procedures were assessed for the climb phase in addition to the descent phase. This provides completeness of the aircraft-level quantified assessment alongside the ATC/airspace quantified assessment in Exercise #01.

D.3 Validation exercise #04 results

This section provides results obtained in the validation exercise.

D.3.1 Summary of validation exercise #04 results

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Exercise #04 validation objective ID	Exercise #04 validation objective title	Exercise #04 success criterion ID	Exercise #04 success criterion	Sub-operating environment	Exercise #04 validation results	Exercise #04 validation objective status
OBJ-GreenGEAR-0406-TRL2-ERP-FUE2	Determine the impact to fuel for the individual flight in descent	CRT-GreenGEAR-0406-TRL2-ERP-FEU2.001	The introduction of geometric altimetry does not increase the fuel consumption on average	TMA HC	Descent: The descent analysis showed a decrease in fuel consumption of several percent, which is mostly a result of the optimised vertical profile (enabled by geometric altimetry) and not a result of the geometric altimetry directly. Climb: The climb analysis showed that optimised altitude constraints (enabled by geometric altimetry) can result in fuel savings, but enforcing a fixed climb gradient increases the fuel consumption and this can outweigh the fuel savings and therefore result in an overall negative benefit.	Partially OK

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Exercise #04 validation objective ID	Exercise #04 validation objective title	Exercise #04 success criterion ID	Exercise #04 success criterion	Sub-operating environment	Exercise #04 validation results	Exercise #04 validation objective status
OBJ-GreenGEAR-0406-TRL2-ERP-ENV2	Determine the impact to CO_2 emissions for the individual flight in descent	CRT-GreenGEAR-0406-TRL2-ERP-ENV2.001	The introduction of geometric altimetry does not increase the CO_2 emissions on average	TMA HC	Descent: The descent analysis showed a decrease in CO_2 emissions of several percent, which is mostly a result of the optimised vertical profile (enabled by geometric altimetry) and not a result of the geometric altimetry directly. Climb: The climb analysis showed that optimised altitude constraints (enabled by geometric altimetry) can result in a reduction of CO_2 emissions, but enforcing a fixed climb gradient increases the CO_2 emissions and this can outweigh the reduction of CO_2 emissions and therefore result in an overall negative benefit.	Partially OK

Exercise #04 validation objective ID	Exercise #04 validation objective title	Exercise #04 success criterion ID	Exercise #04 success criterion	Sub-operating environment	Exercise #04 validation results	Exercise #04 validation objective status
OBJ-GreenGEAR-0406-TRL2-ERP-FUE3	Determine the impact to fuel for the individual flight in cruise	CRT-GreenGEAR-0406-TRL2-ERP-FUE3.001	The introduction of geometric altimetry does not increase the fuel consumption on average		Long-term average increase in fuel consumption of about 6 kg (0.2 % of trip fuel) for evaluated short-/medium-range flights	NOK
OBJ-GreenGEAR-0406-TRL2-ERP-ENV3	Determine the impact to CO_2 emissions for the individual flight in cruise	CRT-GreenGEAR-0406-TRL2-ERP-ENV3.001	The introduction of geometric altimetry does not increase the CO_2 emissions on average		Long-term average increase in CO2 emissions relative to increase of fuel consumption for evaluated short-/medium-range flights	NOK

Table 35: validation exercise #04 results

D.3.2 Analysis of validation exercise #04 results per validation objective

This sub-section provides a consolidated description of the analysis performed per validation objective.

D.3.2.1 OBJ-GreenGEAR-0406-TRL2-ERP-FUE2 Results

This sub-section describes the evaluation of aircraft performance in the TMA which includes a descent analysis of several approach procedures as well as a climb analysis of several departure procedures. Originally, only an analysis of descent procedures has been planned, but during the project, it has been decided to perform an analysis of climb procedures as well. An overview of the assumptions and limitations is given first before the results of the evaluation are provided.

D.3.2.1.1 Assumptions and limitations

The evaluation has been performed by using a desktop simulation of an Airbus A320 aircraft. For this purpose, the simulation model of DLR's research aircraft ATRA (Advanced Technology Research Aircraft) is used as described more detailed in chapter 2. The simulation model is used in the research full-flight simulator AVES (Air Vehicle Simulator) but can also be used for a desktop simulation. Because the simulation model is based on data from real flight tests, the flight dynamics of the model are considered to be very accurate. However, the FCS (Flight Control System) and FMS (Flight Management System) are of limited fidelity due to lack of detailed data and due to being implemented in-house with limited resources. Most of these limitations do not affect this evaluation, but a few limitations remain

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relevant. All these limitations have been addressed, and a solution has been established to deal with these limitations so that these do not affect the evaluation negatively. This is covered in detail in section D.3.2.1.1.1.

Normally, the simulation model is used for piloted simulations either in the full-flight simulator or at a desktop computer. Such a simulation requires manual inputs even when the autopilot is used because the pilot has to switch the autopilot modes and sometimes change the autopilot setpoints manually. This evaluation includes several different scenarios that are simulated with different altimetry types and different atmospheric pressure values which results in a high number of required simulation runs. Therefore, piloted simulations with manual inputs for all of these scenario combinations would require unreasonably high effort. Also, in order to allow manual inputs, the simulations should not run much faster than in real time. Thus, it has been decided to implement a simulation environment that allows an automatic switching of the autopilot modes and autopilot setpoints according to a predefined procedure. With this simulation environment, the simulation runs have been fully automated and therefore did not require manual inputs during the simulation runs. This allowed a simulation on a desktop computer 2.5 times faster than in real time. In addition to that, an option to use the geometric altitude instead of the barometric altitude as input to the FCS and FMS has been implemented.

In total, 14 different scenarios have been evaluated (7 procedures, all of these in a baseline configuration and in a solution configuration) with 3 different types of altimetry and 7 different values for the atmospheric pressure. Why three different types of altimetry have been used instead of two (barometric and geometric) is explained in section D.3.2.1.1.3. This resulted in a total number of 14 × 3 × 7 = 294 simulation runs that required about 30 hours of computation time.

D.3.2.1.1.1 Relevant FCS and FMS limitations

As mentioned before, some limitations of the simulation model had to be addressed in this work so that these do not affect the evaluation negatively.

Firstly, the version of the simulation model that has been used for the desktop simulations considers all waypoints as "fly-by" waypoints and does not have an option to use "fly-over" waypoints. It has been decided to define all waypoints of the scenarios as "fly-by" waypoints which has a small influence on the fuel consumption because of the change of the trajectory length. However, this effect is the same for barometric and geometric altimetry and it is therefore negligible when analysing the difference between the different altimetry types. Thus, this limitation can be accepted with no negative influence on the simulation results.

The second relevant limitation is that before starting this evaluation, no managed climb and descent modes had been implemented for this simulation model. For the evaluation of the procedures in the TMA, it is necessary that the aircraft can follow a predefined procedure with several altitude constraints at the waypoints which is the purpose of a managed climb and descent mode and therefore, this was not achievable with the original simulation model. Thus, simplified managed climb and descent modes have been implemented for this evaluation. These modes have been implemented as an additional outer loop around the existing FPA (flight path angle) mode which has been used as an inner loop. The target of the outer loop controller is the vertical deviation with respect to the prescribed profile that is defined by connecting the altitude constraints at the waypoints with straight lines. The outer loop controller has been implemented as a PID (proportional, integral, derivative) controller with anti-windup that targets a vertical deviation of zero by outputting a flight path angle command that is transferred to the FPA mode in the inner loop controller. Additional modifications of the controller and a precise tuning of the controller gains resulted in a good performance when simulating a procedure with several altitude constraints. However, this definition of the vertical profile only allows constraints of the "At altitude" type, for example "5000 ft at waypoint ABCDE". Altitude constraints of other types (e.g. "At or above 5000 ft at waypoint ABCDE") do not allow a direct definition of the vertical profile by connecting the constraints with straight lines. Because no detailed data were available about how the FMS in the real A320 deals with these types of constraints, it has been decided to implement the simplified managed climb and descent modes in such a way that only "At altitude" constraints are allowed. If a procedure includes other types of constraints, then these need to be checked manually or converted to "At altitude" constraints in some situations.

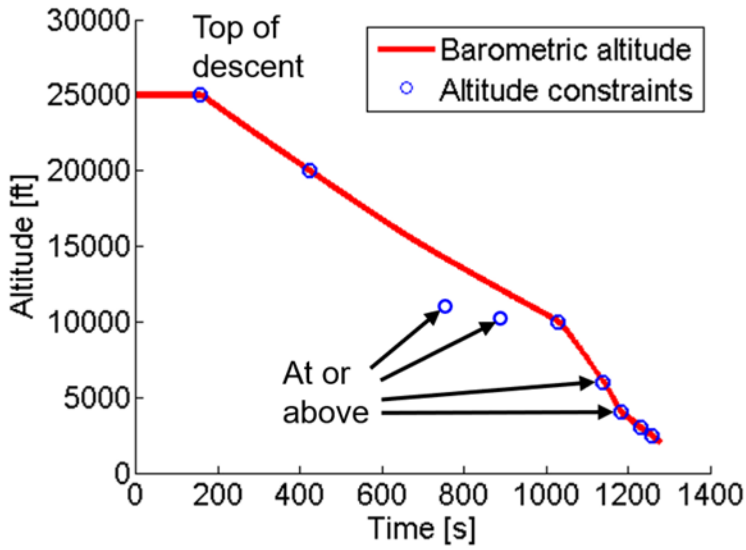

Figure 24: Example scenario to illustrate the method how to deal with different types of altitude constraints

An example scenario to illustrate this method is shown in Figure 24. This scenario consists of the STAR (Standard Terminal Arrival Route) NUGRA1H and the transition BNN27L at London Heathrow Airport. The method illustrated here applies to SID (Standard Instrument Departure) scenarios as well. After the top of descent, this example scenario starts with two "At altitude" constraints that are hit very precisely by the flight controller. Because the profile is plotted as altitude over time, the slope of the profile between the altitude constraints is not constant due to the change of the true airspeed (TAS) when flying a constant indicated airspeed (IAS) in a varying altitude. Plotting the profile as altitude over distance would result in a straight line between the altitude constraints. Between these two constraints at FL200 (20000 ft at standard pressure level) and at FL100 (10000 ft at standard pressure level), there are two "At or above" constraints. Converting these two constraints to "At altitude" constraints would force the aircraft to fly at a lower altitude early and then level off at this altitude which would be very inefficient compared to how this scenario actually is defined. Therefore, these two constraints are not provided as an input to the controller but instead it has been manually checked after the simulation that these constraints are fulfilled. At the end of the procedure, there are two constraints "At or above 6000 ft" and "At or above 4000 ft" that have been converted to "At altitude" constraints because in this part of the scenario, the aircraft would be at approximately these altitudes anyway in order to intercept the ILS (Instrument Landing System) at the last two "At altitude" constraints and therefore a conversion to "At altitude" constraints does not have a significant impact on the fuel consumption. This method required checking all altitude constraints for all 14 scenarios manually, which resulted in additional effort but allowed a satisfactory evaluation of scenarios with different types of altitude constraints despite the mentioned limitations of the simulation model.

In addition to altitude constraints, some waypoints also include speed constraints. For the parts of the scenarios where no speed constraints are specified, a reasonable speed schedule has been defined. It is important to note that the speed schedule has been kept identical for the baseline and solution version of each scenario in order to prevent any effects of different speeds on the aircraft performance.

In summary, for all the relevant FCS and FMS limitations, a solution has been established to deal with these limitations so that these do not affect the evaluation negatively.

D.3.2.1.1.2 Scenario overview

For the evaluation in the TMA, four approach scenarios and three departure scenarios have been selected. The scenarios are based on the procedures that have been defined in task 3.2. The approach scenarios consist of these STARs and transitions to the final approach:

NUGRA1H STAR and BNN27L transition at London Heathrow Airport
LOGAN2H STAR and LAM27L transition at London Heathrow Airport
RINIS1A STAR and ABBOT22 transition at London Stansted Airport
FINMA1N STAR and ZAGZO1T transition at London Luton Airport

The departure scenarios consist of these SIDs:

WOBUN1F SID at London Heathrow Airport
PAAVO1Y SID at London Luton Airport
BINNY1A SID at London City Airport

For all seven scenarios, a baseline version and a solution version have been evaluated in order to compare the influence on the fuel consumption when optimising the procedure definitions. In principle, the baseline versions should be flown with barometric altimetry and the solution versions should be flown with geometric altimetry, but to distinguish between the influence of the altimetry type and the influence of the procedure optimisation, the baseline versions and the solution versions both have been simulated with barometric altimetry and with geometric altimetry.

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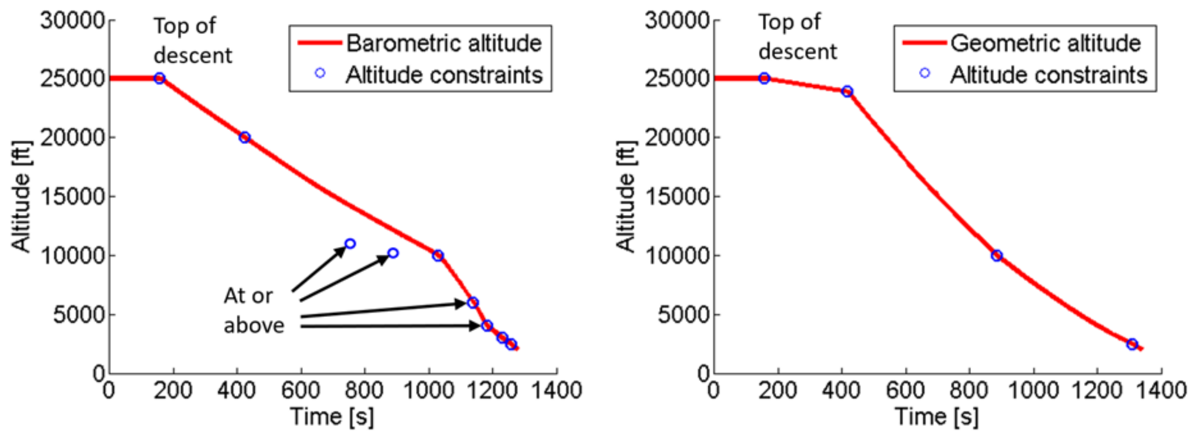

Figure 25: Example scenario to illustrate the difference between the baseline scenario (left hand side) and the solution scenario (right hand side)

The difference between the baseline and the solution scenario is illustrated in Figure 25 using the NUGRA1H STAR and BNN27L transition at London Heathrow Airport as example again. The lateral profile consists of the same waypoints or nearly the same waypoints but with modified altitude constraints. Generally, all solution scenarios only include "At altitude" constraints and no other altitude constraint types. Also, the solution scenarios do not include any level flight segments in the approach procedure but instead only include continuous descent approaches (CDAs). For the departure scenarios, the same principle is applied that the scenarios only include "At altitude" constraints and no other altitude constraint types and no level flight segments. In the example shown here, the main difference between the baseline scenario and the solution scenario is that the first altitude constraint after the top of descent is at FL239 in the solution scenario instead of FL200 in the baseline scenario. This allows the aircraft to stay at a higher altitude for longer and thus reduces the fuel consumption as shown in section D.3.2.1.2.1. Also, the solution scenario includes only two altitude constraints along the STAR (one constraint at the beginning of the STAR at FL239 and one constraint at the end of the STAR at FL100) and then one altitude constraint at the end of the transition for the ILS intercept. The waypoints and altitude constraints are different for each scenario, but the same principle how the solution versions have been optimised compared to the baseline versions applies to all scenarios in the same way.

The ABBOT22 transition at London Stansted Airport originally included a "loop" around the waypoint ABBOT for the descent from FL080 to 6000 ft and then to 4000 ft. This procedure was not compatible with the limitations of the simulation model mentioned in section D.3.2.1.1.1. Therefore, the "loop" has been removed and instead a direct descent to 4000 ft along the RINIS1A STAR has been simulated, which can also be a typical shortcut that would be cleared by the air traffic controller if the traffic situation permits this. Because this shortcut has been applied on the baseline scenario and on the solution scenario, the difference between the two scenarios is not affected by this change.

D.3.2.1.1.3 Selection of the initial/ending altitude

One important parameter for this analysis is the so-called QNH value, which is defined as the atmospheric pressure that would be measured at mean sea level (MSL) at a specified location (normally at an airport). Because most airports are located above MSL, the QNH value cannot be measured directly, but instead it is derived from a measurement of the atmospheric pressure at the airport elevation which is transferred to a pressure value at MSL based on the International Standard Atmosphere (ISA). The standard value of the atmospheric pressure at MSL is defined as 1013.25 hPa, but because the QNH value is normally provided as an integer number, a QNH of 1013 hPa is used as the standard value for the simulations in this task. In order to analyse the influence of the QNH value on the difference in fuel consumption when using geometric altimetry instead of barometric altimetry, all scenarios have been simulated with several different QNH values from 983 hPa to 1043 hPa in increments of 10 hPa.

When using geometric altimetry, the definition of the aircraft's altitude is independent from the QNH. However, when using barometric altimetry, the barometric altitude is in theory (apart from other small influences such as the air temperature) identical to the geometric altitude when referenced to the QNH value, but not identical when using a so-called "flight level" (FL), which is referenced to the standard atmospheric pressure as it is done above the transition layer. Therefore, the same barometric flight level with different QNH values corresponds to different geometric altitudes. When starting the scenarios at a fixed barometric flight level, this results in different geometric starting altitudes and therefore different starting energy levels of the aircraft. Because of this effect, the difference of the fuel consumption between barometric altimetry and geometric altimetry would be skewed when starting at a fixed barometric flight level. The same effect applies to departure scenarios if the scenarios end at a fixed barometric flight level.

In order to prevent this effect, a third altimetry type has been implemented, which has been called "barometric*" altimetry because it is a modified version of the barometric altimetry. The intent of this naming convention is to make it clearer that this is the altimetry type that is compared with geometric altimetry instead of the original barometric altimetry, but with an asterisk to indicate the small modification. When using barometric* altimetry, the scenarios are simulated with barometric altimetry with one exception: in an approach scenario, the starting point is defined as a geometric altitude and as soon as the descent is started, the FCS and FMS are switched to barometric altimetry, while in a departure scenario, the scenario is simulated with barometric altimetry and after the last waypoint is reached, the FCS and FMS are switched to geometric altimetry and an additional waypoint with a geometric altitude constraint is defined to end the scenario always at the same energy level. With this method, the upper edge of the scenario is always a fixed geometric altitude at a fixed waypoint. The lower edge of the scenarios is the ILS intercept for the approach scenarios and a fixed initial altitude for the departure scenarios. Take-off and landing are not simulated because the operations directly on a runway are not affected by the type of altimetry in use.

Using a fixed geometric starting or ending altitude even when using barometric altimetry can result in a barometric altitude that is not an integer number. In practise, altitudes are normally specified in 100 ft increments and in most cases even in 1000 ft increments. Therefore, using a cruise altitude that is not an integer number would not be a realistic procedure in operational practise (even though it might be a possible option for the far future), but for a scientific analysis, it is considered to be the more reasonable option in order to prevent the results being skewed by different starting or ending energy levels. Thus, the results are provided using barometric* altimetry instead of barometric altimetry and then compared with the results when using geometric altimetry.

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D.3.2.1.2 Results

In this section, the results for one example descent scenario and one example climb scenario are shown. The results of the other scenarios are in principle very similar and will be provided in the ERR (Exploratory Research Report) in the near future. Also, a short conclusion is given for both example scenarios.

D.3.2.1.2.1 Descent analysis of the NUGRA1H_BNN27L scenario

For a detailed description of the descent analysis, the scenario that consists of the NUGRA1H STAR and BNN27L transition at London Heathrow Airport is chosen as an example here. The results of the other descent scenarios are summarised in separate sections thereafter. The baseline version and the solution version of this scenario have already been shown in Figure 25. To demonstrate the problem that occurs when using a fixed barometric starting flight level for the barometric altimetry case, as explained in section D.3.2.1.1.3, a comparison of the fuel consumption between using barometric altimetry and using geometric altimetry is shown in Table 36 for the baseline scenario.

QNH [hPa]	Fuel consumption with barometric altimetry	Fuel consumption with geometric altimetry	Fuel savings
983	357.63 kg	347.97 kg	9.66 kg
993	355.56 kg	349.08 kg	6.48 kg
1003	353.47 kg	350.19 kg	3.28 kg
1013	351.37 kg	351.29 kg	0.08 kg
1023	349.37 kg	352.39 kg	-3.02 kg
1033	347.61 kg	353.49 kg	-5.88 kg
1043	346.05 kg	354.57 kg	-8.52 kg

Table 36: Fuel consumption in the baseline scenario when using a fixed barometric starting flight level for the barometric altimetry case

It is clearly visible that the fuel consumption when using barometric altimetry is continuously decreasing with increasing QNH values because the barometric starting flight level of FL250 results in higher geometric starting altitudes for higher QNH values and therefore higher starting energy levels. In contrast, the fuel consumption when using geometric altimetry is increasing with increasing QNH values. This can be explained by the increasing air density with increasing atmospheric pressure which results in a higher drag of the aircraft in these altitudes that are far below the optimum altitude of the aircraft. Thus, the fuel savings are strongly skewed by the different starting energy levels with barometric altimetry being advantageous for higher QNH values and geometric altimetry being advantageous for lower QNH values. If the QNH values are approximately evenly distributed over time (which is a reasonable assumption for mid latitudes), then the differences would approximately cancel out each other in a long-term scenario with varying weather conditions, but with a small advantage remaining for the geometric altimetry. For a QNH value of 1013, the fuel consumption is nearly the

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same for both altimetry types – the remaining very small difference can be explained by the standard value of the atmospheric pressure at MSL being defined as 1013.25 hPa instead of the rounded value of 1013 hPa. In practise, QNH values are typically provided as rounded integer numbers, but for a QNH value of 1013.25 hPa, the difference of the fuel consumption would be exactly zero in this simulation because the barometric altitude and the geometric altitude would be exactly the same in that case.

As explained in section D.3.2.1.1.3, a third altimetry type named barometric* has been implemented to eliminate the influence of the different starting energy levels. A comparison of the barometric* altimetry with geometric altimetry is shown in Table 37. This case is considered to be more reasonable for a scientific analysis.

QNH [hPa]	Fuel consumption with barometric* altimetry	Fuel consumption with geometric altimetry	Fuel savings
983	345.80 kg	347.97 kg	-2.17 kg
993	347.68 kg	349.08 kg	-1.40 kg
1003	349.50 kg	350.19 kg	-0.69 kg
1013	351.27 kg	351.29 kg	-0.02 kg
1023	353.11 kg	352.39 kg	0.72 kg
1033	355.15 kg	353.49 kg	1.66 kg
1043	357.37 kg	354.57 kg	2.80 kg

Table 37: Fuel consumption in the baseline scenario when using a fixed geometric starting altitude

When the results are not skewed by the different starting energy levels, then the fuel consumption when using barometric* altimetry is increasing with increasing QNH values for the same reason as with geometric altimetry. However, the influence of the QNH value is slightly higher for barometric* altimetry than for geometric altimetry which results in a small difference of the fuel consumption remaining in this comparison. In contrast to the barometric altimetry being advantageous for higher QNH values, the barometric* altimetry is more advantageous for lower QNH values than the geometric altimetry. As before, the differences would approximately cancel out each other in a long-term scenario with varying weather conditions, but this time with a small advantage remaining for the geometric altimetry. In comparison with the usage of barometric altimetry, the usage of barometric* altimetry results in the remaining small advantage for the geometric altimetry being even smaller and the influence of the QNH value being turned around into the opposite direction: now a higher QNH value results in positive fuel savings while a lower QNH value results in negative fuel savings.

The results of the analysis of the solution scenario are shown in Table 38. Even though the solution scenario is intended to be flown with geometric altimetry, it has been simulated with barometric altimetry and with barometric* altimetry as well to distinguish between the influence of the procedure change and the influence of the altimetry type. In order to eliminate the influence of the different starting energy levels, the geometric altimetry is compared with barometric* altimetry instead of barometric altimetry as explained previously.

QNH [hPa]	Fuel consumption with barometric* altimetry	Fuel consumption with geometric altimetry	Fuel savings
983	340.35 kg	324.90 kg	15.45 kg
993	337.02 kg	325.95 kg	11.07 kg
1003	332.25 kg	327.02 kg	5.23 kg
1013	328.12 kg	328.09 kg	0.03 kg
1023	328.43 kg	329.23 kg	-0.80 kg
1033	329.36 kg	330.61 kg	-1.25 kg
1043	331.89 kg	332.13 kg	-0.24 kg

Table 38: Fuel consumption in the solution scenario when using a fixed geometric starting altitude

When using geometric altimetry in the solution scenario, the fuel consumption is increasing with increasing QNH values for the same reason as before. However, when using barometric* altimetry, the fuel consumption is at a minimum value between a QNH of 1013 and a QNH of 1023 and is increasing for lower QNH values as well as for higher QNH values. This can be explained by the fact that the first altitude constraint in the solution scenario is at a higher flight level than in the baseline scenario which results in the aircraft being close to its optimal descent profile for a QNH of 1013. A change of the QNH in either direction moves this first flight level constraint slightly upwards or downwards geometrically and therefore moves the aircraft away from its optimal descent profile. When calculating the fuel savings for the usage of geometric altimetry, this results in positive savings for lower QNH values and in only very small negative savings for higher QNH values. In the solution scenario, in contrast to the baseline scenario, the differences would not cancel out each other in a long-term scenario with varying weather conditions, but a noticeable advantage for the geometric altimetry would remain.

Table 39 shows the difference between the baseline scenario and the solution scenario when using a fixed geometric starting altitude. It is clearly visible that for both altimetry types and for this range of QNH values, the fuel savings are always positive, i.e. the fuel consumption in the solution scenario is lower than in the baseline scenario. These fuel savings can be explained by the first altitude constraint in the solution scenario being at a higher flight level than in the baseline scenario which results in the aircraft being closer to its optimal descent profile. When using geometric altimetry, as explained before, the fuel consumption is increasing with increasing QNH values, but because this effect is the same for the baseline scenario and for the solution scenario, the difference between the scenarios is nearly constant at a value of about 23 kg. However, when using barometric* altimetry, the fuel savings are lower for lower QNH values but remain nearly constant for higher QNH values. This can be explained by the effects that have been shown before, which are now combined: in the scenario with barometric* altimetry, the fuel consumption is constantly increasing with increasing QNH values while in the solution scenario with barometric* altimetry, the fuel consumption has a minimum in the QNH range between 1013 and 1023 which results in the fuel savings in the difference between both scenarios not increasing for higher QNH values as much as they are decreasing for lower QNH values. In a long-term scenario with varying weather conditions, the fuel savings in the solution scenario would therefore be higher for geometric altimetry than for barometric* altimetry even though the fuel savings are still positive for barometric* altimetry as well.

QNH [hPa]	Fuel savings with barometric* altimetry	Fuel savings with geometric altimetry
983	5.45 kg	23.07 kg
993	10.66 kg	23.13 kg
1003	17.25 kg	23.17 kg
1013	23.15 kg	23.20 kg
1023	24.68 kg	23.16 kg
1033	25.79 kg	22.88 kg
1043	25.48 kg	22.44 kg

Table 39: Difference between the baseline scenario and the solution scenario when using a fixed geometric starting altitude

Table 40 shows the final results of the descent analysis when the change of the altimetry type and the change of the scenario are combined.

QNH [hPa]	Fuel consumption with barometric* altimetry in the baseline scenario	Fuel consumption with geometric altimetry in the solution scenario	Fuel savings
983	345.80 kg	324.90 kg	20.90 kg
993	347.68 kg	325.95 kg	21.73 kg
1003	349.50 kg	327.02 kg	22.48 kg
1013	351.27 kg	328.09 kg	23.18 kg
1023	353.11 kg	329.23 kg	23.88 kg
1033	355.15 kg	330.61 kg	24.54 kg
1043	357.37 kg	332.13 kg	25.24 kg

Table 40: Final results of the descent analysis when the change of the altimetry type and the change of the scenario are combined

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The fuel savings are always positive and vary only slightly about a value of approximately 23 kg which is about 6.6% of the fuel consumption for this scenario. These 23 kg of saved fuel per flight are mostly not a direct result of the switch to geometric altimetry, but a result of the optimised descent profile in the solution scenario. The change of the altimetry type influences the fuel savings by a very small amount and can be positive or negative depending on the QNH. However, if the optimised descent profile in the solution scenario is considered to be enabled by the usage of geometric altimetry, then the change of the altimetry type indirectly enables these fuel savings of about 23 kg per flight. Also, the usage of geometric altimetry reduces the variance of the fuel consumption and therefore improves the predictability.

D.3.2.1.2.2 Descent analysis of the LOGAN2H_LAM27L scenario

In this section, the results of the descent scenario that consists of the LOGAN2H STAR and the LAM27L transition at London Heathrow Airport are summarised. As shown before, it is clearly visible that the switching from barometric* altimetry to geometric altimetry results in positive or negative fuel savings depending on the QNH, but the difference is close to zero on average. Switching from the baseline scenario to the solution scenario mostly results in positive fuel savings – only for some QNH values, the influence of the QNH slightly outweighs the influence of the scenario modification, but in a long-term scenario with varying weather conditions, positive fuel savings would remain.

QNH [hPa]	Fuel consumption with barometric* altimetry	Fuel consumption with geometric altimetry	Fuel savings
983	250.21 kg	234.84 kg	15.37 kg
993	247.91 kg	236.16 kg	11.75 kg
1003	242.14 kg	237.46 kg	4.68 kg
1013	238.87 kg	238.76 kg	0.11 kg
1023	235.70 kg	240.04 kg	-4.34 kg
1033	232.16 kg	241.33 kg	-9.17 kg
1043	227.08 kg	242.57 kg	-15.49 kg

Table 41: Fuel consumption in the solution scenario when using a fixed geometric starting altitude

QNH [hPa]	Fuel consumption with barometric* altimetry	Fuel consumption with geometric altimetry	Fuel savings
983	255.38 kg	231.42 kg	23.96 kg
993	248.44 kg	232.59 kg	15.85 kg
1003	241.64 kg	235.21 kg	6.43 kg
1013	236.55 kg	236.34 kg	0.21 kg
1023	228.59 kg	237.50 kg	-8.91 kg
1033	222.57 kg	237.42 kg	-14.85 kg
1043	216.67 kg	238.66 kg	-21.99 kg

Table 42: Fuel consumption in the baseline scenario when using a fixed geometric starting altitude

QNH [hPa]	Fuel savings with barometric* altimetry	Fuel savings with geometric altimetry
983	-5.17 kg	3.42 kg
993	-0.53 kg	3.57 kg
1003	0.50 kg	2.25 kg
1013	2.32 kg	2.42 kg
1023	7.11 kg	2.54 kg
1033	9.59 kg	3.91 kg
1043	10.41 kg	3.91 kg

Table 43: Difference between the baseline scenario and the solution scenario when using a fixed geometric starting altitude

QNH [hPa]	Fuel consumption with barometric* altimetry in the baseline scenario	Fuel consumption with geometric altimetry in the solution scenario	Fuel savings
983	250.21 kg	231.42 kg	18.79 kg
993	247.91 kg	232.59 kg	15.32 kg
1003	242.14 kg	235.21 kg	6.93 kg
1013	238.87 kg	236.34 kg	2.53 kg
1023	235.70 kg	237.50 kg	-1.80 kg
1033	232.16 kg	237.42 kg	-5.26 kg
1043	227.08 kg	238.66 kg	-11.58 kg

Table 44: Final results of the descent analysis when the change of the altimetry type and the change of the scenario are combined

D.3.2.1.2.3 Descent analysis of the RINIS1A_ABBOT22 scenario

In this section, the results of the descent scenario that consists of the RINIS1A STAR and the ABBOT22 transition at London Stansted Airport are summarised. As shown before, it is clearly visible that the switching from barometric* altimetry to geometric altimetry results in positive or negative fuel savings depending on the QNH, but the difference is close to zero on average. Switching from the baseline scenario to the solution scenario results in negative fuel savings in this case, because the vertical profile of the solution scenario requires a slightly earlier descent than the vertical profile in the baseline scenario that allows the aircraft to stay at a higher altitude slightly longer. Because in all other descent scenarios a positive result was shown, it can be assumed that the method for designing the solution scenarios mostly leads to positive fuel savings. Nevertheless, this example shows that a negative result is possible, which should be considered when re-designing existing procedures.

QNH [hPa]	Fuel consumption with barometric* altimetry	Fuel consumption with geometric altimetry	Fuel savings
983	148.73 kg	154.69 kg	-5.96 kg
993	151.46 kg	155.48 kg	-4.02 kg
1003	154.24 kg	156.27 kg	-2.03 kg
1013	157.01 kg	157.06 kg	-0.05 kg
1023	159.77 kg	157.84 kg	1.93 kg
1033	162.54 kg	158.62 kg	3.92 kg
1043	165.31 kg	159.39 kg	5.92 kg

Table 45: Fuel consumption in the baseline scenario when using a fixed geometric starting altitude

QNH [hPa]	Fuel consumption with barometric* altimetry	Fuel consumption with geometric altimetry	Fuel savings
983	155.38 kg	161.12 kg	-5.74 kg
993	157.99 kg	161.86 kg	-3.87 kg
1003	160.63 kg	162.60 kg	-1.97 kg
1013	163.29 kg	163.34 kg	-0.05 kg
1023	165.96 kg	164.07 kg	1.89 kg
1033	168.64 kg	164.81 kg	3.83 kg
1043	171.32 kg	165.54 kg	5.78 kg

Table 46: Fuel consumption in the solution scenario when using a fixed geometric starting altitude

QNH [hPa]	Fuel savings with barometric* altimetry	Fuel savings with geometric altimetry
983	-6.65 kg	-6.43 kg
993	-6.53 kg	-6.38 kg
1003	-6.39 kg	-6.33 kg
1013	-6.28 kg	-6.28 kg
1023	-6.19 kg	-6.23 kg
1033	-6.10 kg	-6.19 kg
1043	-6.01 kg	-6.15 kg

Table 47: Difference between the baseline scenario and the solution scenario when using a fixed geometric starting altitude

QNH [hPa]	Fuel consumption with barometric* altimetry in the baseline scenario	Fuel consumption with geometric altimetry in the solution scenario	Fuel savings
983	148.73 kg	161.12 kg	-12.39 kg
993	151.46 kg	161.86 kg	-10.40 kg
1003	154.24 kg	162.60 kg	-8.36 kg
1013	157.01 kg	163.34 kg	-6.33 kg
1023	159.77 kg	164.07 kg	-4.30 kg
1033	162.54 kg	164.81 kg	-2.27 kg
1043	165.31 kg	165.54 kg	-0.23 kg

Table 48: Final results of the descent analysis when the change of the altimetry type and the change of the scenario are combined

D.3.2.1.2.4 Descent analysis of the FINMA1N_ZAGZO1T scenario

In this section, the results of the descent scenario that consists of the FINMA1N STAR and the ZAGZO1T transition at London Luton Airport are summarised. As shown before, it is clearly visible that the switching from barometric* altimetry to geometric altimetry results in positive or negative fuel savings depending on the QNH, but the difference is close to zero on average. Switching from the baseline scenario to the solution scenario mostly results in positive fuel savings – only for some QNH values, the influence of the QNH slightly outweighs the influence of the scenario modification, but in a long-term scenario with varying weather conditions, positive fuel savings would remain.

QNH [hPa]	Fuel consumption with barometric* altimetry	Fuel consumption with geometric altimetry	Fuel savings
983	272.99 kg	254.73 kg	18.26 kg
993	269.44 kg	256.44 kg	13.00 kg
1003	265.13 kg	258.17 kg	6.96 kg
1013	260.09 kg	259.91 kg	0.18 kg
1023	256.04 kg	261.68 kg	-5.64 kg
1033	251.46 kg	263.45 kg	-11.99 kg
1043	245.85 kg	265.25 kg	-19.40 kg

Table 49: Fuel consumption in the baseline scenario when using a fixed geometric starting altitude

QNH [hPa]	Fuel consumption with barometric* altimetry	Fuel consumption with geometric altimetry	Fuel savings
983	255.14 kg	245.63 kg	9.51 kg
993	253.69 kg	246.81 kg	6.88 kg
1003	251.94 kg	247.99 kg	3.95 kg
1013	249.46 kg	249.30 kg	0.16 kg
1023	245.93 kg	250.45 kg	-4.52 kg
1033	243.39 kg	251.63 kg	-8.24 kg
1043	241.68 kg	252.88 kg	-11.20 kg

Table 50: Fuel consumption in the solution scenario when using a fixed geometric starting altitude

QNH [hPa]	Fuel savings with barometric* altimetry	Fuel savings with geometric altimetry
983	17.85 kg	9.10 kg
993	15.75 kg	9.63 kg
1003	13.19 kg	10.18 kg
1013	10.63 kg	10.61 kg
1023	10.11 kg	11.23 kg
1033	8.07 kg	11.82 kg
1043	4.17 kg	12.37 kg

Table 51: Difference between the baseline scenario and the solution scenario when using a fixed geometric starting altitude

QNH [hPa]	Fuel consumption with barometric* altimetry in the baseline scenario	Fuel consumption with geometric altimetry in the solution scenario	Fuel savings
983	272.99 kg	245.63 kg	27.36 kg
993	269.44 kg	246.81 kg	22.63 kg
1003	265.13 kg	247.99 kg	17.14 kg
1013	260.09 kg	249.30 kg	10.79 kg
1023	256.04 kg	250.45 kg	5.59 kg
1033	251.46 kg	251.63 kg	-0.17 kg
1043	245.85 kg	252.88 kg	-7.03 kg

Table 52: Final results of the descent analysis when the change of the altimetry type and the change of the scenario are combined

D.3.2.1.2.5 Climb analysis of the WOBUN1F scenario

For a detailed description of the climb analysis, the scenario that consists of the WOBUN1F SID at London Heathrow Airport is chosen as an example here. The results of the other climb scenarios are summarised in separate sections thereafter. An overview of the climb profile in the baseline scenario and in the solution scenario is provided in Figure 26. Because the profile is plotted as altitude over time, the slope of the profile between the altitude constraints is not constant due to the change of the true airspeed (TAS) when flying a constant indicated airspeed (IAS) in a varying altitude. Plotting the profile as altitude over distance would result in a straight line between the altitude constraints from FL080 onwards.

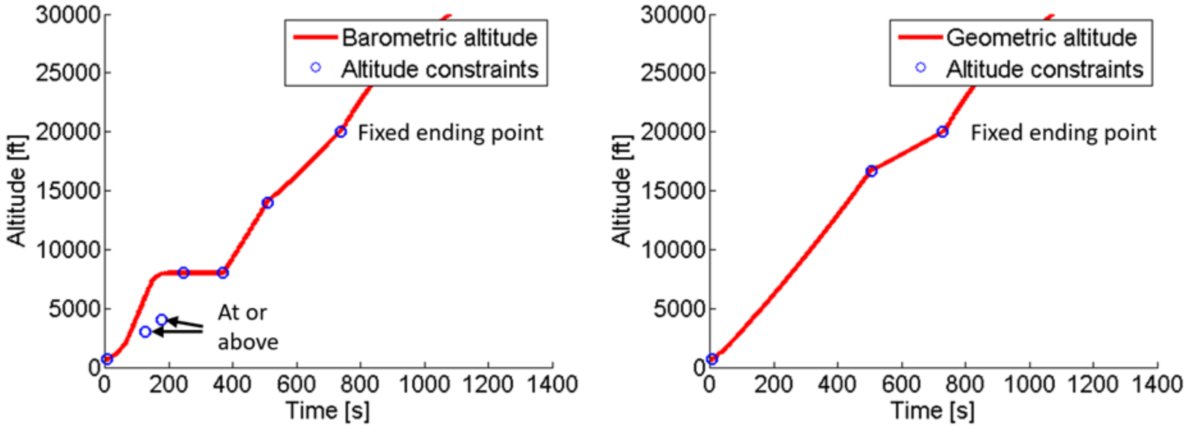

Figure 26: Example baseline scenario (left hand side) and solution scenario (right hand side) for the climb analysis

One important difference is that the level-off segment in the baseline scenario at FL080 is removed in the solution scenario. Instead, the solution scenario only includes one altitude constraint at FL167,

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which is slightly higher than the last altitude constraint at FL140 in the baseline scenario. An additional waypoint with an altitude constraint at FL200 has been added after that to end both scenarios at the same altitude. Between the altitude constraints in the solution scenario, the aircraft is required to fly a fixed climb gradient while in the baseline scenario, the "At" altitude constraints only require the aircraft to be at the specified altitude when crossing this waypoint but allow an arbitrary climb profile between these constraints. This can be clearly seen at the start of the baseline scenario where the aircraft climbs with a high climb rate in open climb mode and therefore reaches FL080 even earlier than required. The differences between the baseline scenario and the solution scenario result in counteracting influences on the fuel consumption that will be further discussed in this section.

To demonstrate the problem that occurs when using a fixed barometric ending flight level for the barometric altimetry case, as explained in section D.3.2.1.1.3, a comparison of the fuel consumption between using barometric altimetry and using geometric altimetry is shown in Table 53 for the baseline scenario.

QNH [hPa]	Fuel consumption with barometric altimetry	Fuel consumption with geometric altimetry	Fuel savings
983	885.56 kg	893.06 kg	-7.50 kg
993	890.20 kg	895.23 kg	-5,03 kg
1003	894.85 kg	897.38 kg	-2,53 kg
1013	899.44 kg	899.51 kg	-0.07 kg
1023	904.02 kg	901.62 kg	2.40 kg
1033	908.58 kg	903.72 kg	4.86 kg
1043	913.11 kg	905.81 kg	7.30 kg

Table 53: Fuel consumption in the baseline scenario when using a fixed barometric ending flight level for the barometric altimetry case

The influence of the QNH value on the fuel savings because of the different ending energy levels is similar to this influence in the descent analysis shown in section D.3.2.1.2.1, but the direction of this influence is turned into the opposite direction because a climb to a higher ending energy level requires more fuel than a climb to a lower energy level while a descent from a higher starting energy level requires less fuel than a descent from a lower starting energy level. The fuel consumption when using geometric altimetry is also increasing with increasing QNH values. This can be explained by the increasing air density with increasing atmospheric pressure which results in a higher drag of the aircraft in these altitudes that are far below the optimum altitude of the aircraft. When using barometric altimetry, this effect is combined with the influence of the different ending energy levels which results in a significantly stronger influence of the QNH value on the fuel consumption than when using geometric altimetry. If the QNH values are approximately evenly distributed over time (which is a reasonable assumption for mid latitudes), then the differences would approximately cancel out each other in a long-term scenario with varying weather conditions.

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Table 54 shows the fuel consumption in the baseline scenario when using a fixed geometric ending altitude. When the results are not skewed by the different ending energy levels, the influence of the QNH value on the fuel consumption with barometric* altimetry is significantly lower than with barometric altimetry and actually even lower than with geometric altimetry. This results in positive fuel savings for lower QNH values and negative fuel savings for higher QNH values. As before, the differences would approximately cancel out each other in a long-term scenario with varying weather conditions.

QNH [hPa]	Fuel consumption with barometric* altimetry	Fuel consumption with geometric altimetry	Fuel savings
983	896.50 kg	893.06 kg	3.44 kg
993	897.50 kg	895.23 kg	2.27 kg
1003	898.52 kg	897.38 kg	1.14 kg
1013	899.53 kg	899.51 kg	0.02 kg
1023	900.57 kg	901.62 kg	-1,05 kg
1033	901.62 kg	903.72 kg	-2.10 kg
1043	902.66 kg	905.81 kg	-3.15 kg

Table 54: Fuel consumption in the baseline scenario when using a fixed geometric ending altitude

QNH [hPa]	Fuel consumption with barometric* altimetry	Fuel consumption with geometric altimetry	Fuel savings
983	892.39 kg	890.81 kg	1.58 kg
993	894.01 kg	892.96 kg	1.05 kg
1003	895.67 kg	895.11 kg	0.56 kg
1013	897.24 kg	897.25 kg	-0.01 kg
1023	898.84 kg	899.38 kg	-0.54 kg
1033	900.56 kg	901.51 kg	-0.95 kg
1043	902.32 kg	903.61 kg	-1.29 kg

Table 55: Fuel consumption in the solution scenario when using a fixed geometric ending altitude

The results of the analysis of the solution scenario are shown in Table 55. Even though the solution scenario is intended to be flown with geometric altimetry, it has been simulated with barometric altimetry and with barometric* altimetry as well to distinguish between the influence of the procedure change and the influence of the altimetry type. In order to eliminate the influence of the different starting energy levels, the geometric altimetry is compared with barometric* altimetry instead of barometric altimetry as explained previously.

In a similar way as in the baseline scenario, the fuel consumption is increasing with higher QNH values and the influence of the QNH value is slightly higher with geometric altimetry than with barometric* altimetry. This results in positive fuel savings for lower QNH values and in negative fuel savings for higher QNH values but compared with the baseline scenario, the fuel differences are smaller in both directions.

Table 56 shows the difference between the baseline scenario and the solution scenario when using a fixed geometric ending altitude. It is clearly visible that for both altimetry types and for this range of QNH values, the fuel savings are always positive, i.e. the fuel consumption in the solution scenario is lower than in the baseline scenario. However, the fuel savings are only slightly positive in the climb scenario and much lower than in the descent scenario. This can be explained by two different effects that are counteracting each other: the removal of the level-off segment in the solution scenario has a positive influence on the fuel savings while forcing the aircraft to fly a fixed climb gradient has a negative influence on the fuel savings. The optimal climb profile would not include any level-off segments but would also not be flown with a fixed climb gradient. Instead, a higher climb gradient at the start of the scenario and then a continuous reduction of the climb gradient towards higher altitudes would be the optimal profile. Therefore, the solution scenario improves the climb profile by the removal of the level-off segment, which is counteracted by the fixed climb gradient, but in total, a small positive benefit remains. These fuel savings are nearly constant when using geometric altimetry, but when using barometric* altimetry, the fuel savings depend on the QNH value.

QNH [hPa]	Fuel savings with barometric* altimetry	Fuel savings with geometric altimetry
983	4.11 kg	2.25 kg
993	3.49 kg	2.27 kg
1003	2.85 kg	2.27 kg
1013	2.29 kg	2.26 kg
1023	1.73 kg	2.24 kg
1033	1.06 kg	2.21 kg
1043	0.34 kg	2.20 kg

Table 56: Difference between the baseline scenario and the solution scenario when using a fixed geometric ending altitude

Table 57 shows the final results of the descent analysis when the change of the altimetry type and the change of the scenario are combined. The fuel savings are mostly positive but are slightly decreasing for increasing QNH values. For the highest QNH value that has been analysed here, this decrease even outweighs the average fuel savings which results in negative fuel savings for this QNH value. For all other QNH values, the fuel savings are positive and thus, in a long-term scenario with varying weather

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conditions, a small benefit would remain. However, this small benefit of about 2 kg per flight for medium QNH values is only about 0.25% of the fuel consumption for this scenario and therefore much lower than the benefit in the descent scenario. Similar to the results of the descent analysis, these fuel savings in the climb scenario are mostly not a direct result of the switch to geometric altimetry, but a result of the optimised climb profile in the solution scenario. As explained before, the reason for the only very low fuel savings are the two counteracting effects in the optimisation of the climb profile.

QNH [hPa]	Fuel consumption with barometric* altimetry in the baseline scenario	Fuel consumption with geometric altimetry in the solution scenario	Fuel savings
983	896.50 kg	890.81 kg	5.69 kg
993	897.50 kg	892.96 kg	4.54 kg
1003	898.52 kg	895.11 kg	3.41 kg
1013	899.53 kg	897.25 kg	2.28 kg
1023	900.57 kg	899.38 kg	1.19 kg
1033	901.62 kg	901.51 kg	0.11 kg
1043	902.66 kg	903.61 kg	-0.95 kg

Table 57: Final results of the climb analysis when the change of the altimetry type and the change of the scenario are combined

The change of the altimetry type influences the fuel savings by a very small amount and can be positive or negative depending on the QNH. However, if the optimised climb profile in the solution scenario is considered to be enabled by the usage of geometric altimetry, then the change of the altimetry type indirectly enables these fuel savings of about 2 kg per flight. In contrast to the descent scenario, the usage of geometric altimetry in the climb scenario increases the variance of the fuel consumption and therefore decreases the predictability. Overall, the optimisation of the climb profile in the solution scenario results in small fuel savings but leaves much more potential for further improvement than the descent scenario.

D.3.2.1.2.6 Additional climb scenario to demonstrate the two counteracting effects

To demonstrate the two counteracting effects mentioned above, an additional climb scenario has been constructed and analysed. This scenario is based on the solution scenario that uses the WOBUN1F SID and consists of the same lateral profile and the same altitude constraints as the original solution scenario. The only change, as shown in Figure 27, is that instead of forcing the aircraft to fly a fixed climb gradient, the altitude constraints are used in the same way as in the baseline scenario, i.e. the aircraft is required to be at the specified altitude at the waypoint, but it can freely choose its pathing between the altitude constraints. Thus, the aircraft can use its climb performance to reach a higher altitude earlier and therefore save fuel compared to the original solution scenario.

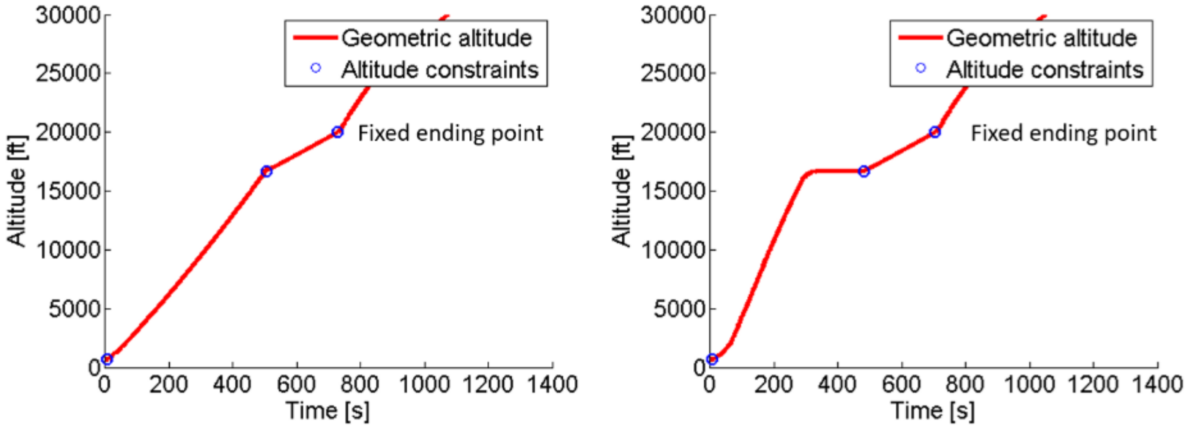

Figure 27: Original solution scenario (left hand side) and modified solution scenario (right hand side)

When using geometric altimetry in both cases and assuming different QNH values, then this modified scenario without the fixed climb gradient requires about 18 kg less fuel that the original solution scenario which is approximately 2% of the fuel used. This demonstrates the negative effect of forcing the aircraft to fly a fixed climb gradient in an isolated scenario, which counteracts the positive effect of the removal of level-off segments.

It is important to note that the effect of a fixed climb gradient is different from the effect of a fixed descent gradient. During climb, the performance of the aircraft mostly depends on the available thrust that is strongly depending on the altitude. With increasing altitude and therefore decreasing air density, the available thrust and therefore the climb performance decreases. When using a fixed climb gradient for the whole departure procedure, a low enough climb gradient must be chosen to make sure that the aircraft can still fly this climb gradient even at higher altitudes. Therefore, the aircraft cannot use its better climb performance at lower altitudes, which results in the vertical profile overall being lower when using a fixed climb gradient, which results in a higher fuel consumption. During descent, the performance of the aircraft mostly depends on the lift-to-drag-ratio that is only slightly depending on the altitude. Thus, using a fixed descent gradient has a much less limiting effect on the aircraft performance as long as a gradient is chosen that can be flown without the usage of spoilers. This explains why in the climb scenarios, the negative effect of the fixed climb gradient partially counteracts or even outweighs the positive effect of the optimised altitude constraints, while in most of the descent scenarios, a positive effect of the optimised altitude constraints is visible that is not counteracted by a negative influence of the fixed descent gradient.

D.3.2.1.2.7 Climb analysis of the PAAVO1Y scenario

In this section, the results of the climb scenario that consists of the PAAVO1Y SID at London Luton Airport are summarised. As shown before, it is clearly visible that the switching from barometric* altimetry to geometric altimetry results in positive or negative fuel savings depending on the QNH, but the difference is close to zero on average. Switching from the baseline scenario to the solution scenario mostly results in negative fuel savings – only for some QNH values, the influence of the QNH slightly outweighs the influence of the scenario modification, but in a long-term scenario with varying weather conditions, negative fuel savings would remain. As shown before, the reason for this negative effect is that the negative influence of the fixed climb gradient counteracts the positive influence of the optimised altitude constraints.

QNH [hPa]	Fuel consumption with barometric* altimetry	Fuel consumption with geometric altimetry	Fuel savings
983	1110.31 kg	1107.94 kg	2.37 kg
993	1111.94 kg	1110.36 kg	1.58 kg
1003	1113.60 kg	1112.82 kg	0.78 kg
1013	1115.28 kg	1115.26 kg	0.02 kg
1023	1116.97 kg	1117.72 kg	-0.75 kg
1033	1118.67 kg	1120.16 kg	-1.49 kg
1043	1243.89 kg	1246.19 kg	-2.30 kg

Table 58: Fuel consumption in the baseline scenario when using a fixed geometric ending altitude

QNH [hPa]	Fuel consumption with barometric* altimetry	Fuel consumption with geometric altimetry	Fuel savings
983	1107.97 kg	1110.50 kg	-2.53 kg
993	1111.11 kg	1112.83 kg	-1.72 kg
1003	1114.16 kg	1115.18 kg	-1.02 kg
1013	1117.53 kg	1117.53 kg	0.00 kg
1023	1120.10 kg	1119.88 kg	0.22 kg
1033	1124.36 kg	1122.27 kg	2.09 kg
1043	1250.36 kg	1248.45 kg	1.91 kg

Table 59: Fuel consumption in the solution scenario when using a fixed geometric ending altitude

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QNH [hPa]	Fuel savings with barometric* altimetry	Fuel savings with geometric altimetry
983	2.34 kg	-2.56 kg
993	0.83 kg	-2.47 kg
1003	-0.56 kg	-2.36 kg
1013	-2.25 kg	-2.27 kg
1023	-3.13 kg	-2.16 kg
1033	-5.69 kg	-2.11 kg
1043	-6.47 kg	-2.26 kg

Table 60: Difference between the baseline scenario and the solution scenario when using a fixed geometric ending altitude

QNH [hPa]	Fuel consumption with barometric* altimetry in the baseline scenario	Fuel consumption with geometric altimetry in the solution scenario	Fuel savings
983	1110.31 kg	1110.50 kg	-0.19 kg
993	1111.94 kg	1112.83 kg	-0.89 kg
1003	1113.60 kg	1115.18 kg	-1.58 kg
1013	1115.28 kg	1117.53 kg	-2.25 kg
1023	1116.97 kg	1119.88 kg	-2.91 kg
1033	1118.67 kg	1122.27 kg	-3.60 kg
1043	1243.89 kg	1248.45 kg	-4.56 kg

Table 61: Final results of the climb analysis when the change of the altimetry type and the change of the scenario are combined

D.3.2.1.2.8 Climb analysis of the BINNY1A scenario

In this section, the results of the climb scenario that consists of the BINNY1A SID at London City Airport are summarised. As shown before, it is clearly visible that the switching from barometric* altimetry to geometric altimetry results in positive or negative fuel savings depending on the QNH, but the difference is close to zero on average. Switching from the baseline scenario to the solution scenario results in positive fuel savings because the positive influence of the optimised altitude constraints outweighs the negative influence of the fixed climb gradient.

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QNH [hPa]	Fuel consumption with barometric* altimetry	Fuel consumption with geometric altimetry	Fuel savings
983	975.02 kg	973.75 kg	1.27 kg
993	977.06 kg	976.22 kg	0.84 kg
1003	979.03 kg	978.69 kg	0.34 kg
1013	981.22 kg	981.21 kg	0.01 kg
1023	983.50 kg	983.76 kg	-0.26 kg
1033	985.83 kg	986.32 kg	-0.49 kg
1043	988.25 kg	988.86 kg	-0.61 kg

Table 62: Fuel consumption in the baseline scenario when using a fixed geometric ending altitude

QNH [hPa]	Fuel consumption with barometric* altimetry	Fuel consumption with geometric altimetry	Fuel savings
983	943.51 kg	942.21 kg	1.30 kg
993	945.29 kg	944.46 kg	0.83 kg
1003	947.12 kg	946.71 kg	0.41 kg
1013	948.93 kg	948.92 kg	0.01 kg
1023	950.77 kg	951.14 kg	-0.37 kg
1033	952.65 kg	953.34 kg	-0.69 kg
1043	954.62 kg	955.54 kg	-0.92 kg

Table 63: Fuel consumption in the solution scenario when using a fixed geometric ending altitude

QNH [hPa]	Fuel savings with barometric* altimetry	Fuel savings with geometric altimetry
983	31.51 kg	31.54 kg
993	31.77 kg	31.76 kg
1003	31.91 kg	31.98 kg
1013	32.29 kg	32.29 kg
1023	32.73 kg	32.62 kg
1033	33.18 kg	32.98 kg
1043	33.63 kg	33.32 kg

Table 64: Difference between the baseline scenario and the solution scenario when using a fixed geometric ending altitude

QNH [hPa]	Fuel consumption with barometric* altimetry in the baseline scenario	Fuel consumption with geometric altimetry in the solution scenario	Fuel savings
983	975.02 kg	942.21 kg	32.81 kg
993	977.06 kg	944.46 kg	32.60 kg
1003	979.03 kg	946.71 kg	32.32 kg
1013	981.22 kg	948.92 kg	32.30 kg
1023	983.50 kg	951.14 kg	32.36 kg
1033	985.83 kg	953.34 kg	32.49 kg
1043	988.25 kg	955.54 kg	32.71 kg

Table 65: Final results of the climb analysis when the change of the altimetry type and the change of the scenario are combined

D.3.2.2 OBJ-GreenGEAR-0406-TRL2-ERP-ENV2 Results

The results from fuel consumption can be directly transferred to CO2 emissions.

D.3.2.3 OBJ-GreenGEAR-0406-TRL2-ERP-FUE3 Results

This sub-section describes the evaluation of aircraft performance in cruise flight. For this purpose, two different ways of evaluation were performed. First generic simulation with the aforementioned simulation model of the A320 ATRA were performed, in order to evaluate generic, flight physical effects, isolated from the mixture of various influencing factors like in real flight. However, in order to evaluate accumulated effects a fast-time simulation was developed, that is able to re-simulate real flights with geometric altimetry.

D.3.2.3.1 Generic evaluation

For the isolated analysis of the influence of a change of air pressure during cruise flight using geometric altimetry simulations with the same simulation model as used for the evaluation described in chapter 3 was applied here as well. The aircraft is trimmed at a certain flight level at constant Mach number. During the flight, only the air pressure was varied with different pressure gradients.

D.3.2.3.1.1 Assumptions and limitations

Some assumptions had to be made for the generic simulations.

The pressure gradients applied in the simulations were verified against real atmospheric data. In order to do so, atmospheric data provided by the ECMWF through its Climate Data Store[5][1] have been evaluated. The analysed atmospheric data comprise datasets of worldwide coverage of altitudes between 0 and 40,000 ft. Datasets of 12 days distributed over the whole year have been analysed, covering the full 24 hours per day. Figure 28 depicts the analysis results in terms of maximum pressure difference and maximum pressure gradient. It must be noted here that the maximum pressure difference is the difference between the worldwide maximum and minimum pressure value at a specific altitude. Hence, the depicted maximum pressure difference is not necessarily stemming from adjacent pressure systems. However, this value is considered as a conservative, but reasonable maximum value.

It was found that the maximum pressure gradient at cruise level is about 20 Pa/NM (see Figure 28). With this value and a maximum simulated flight distance for the generic simulations of 400 NM the maximum pressure difference during the simulations is 80 hPa. This is considered a reasonable value for cruise levels as can be seen in the left part of Figure 28.

The maximum pressure gradient and the resulting maximum pressure difference applied in the simulations can be considered as extreme values than will occur only very rarely under real flight conditions. In reality, the experienced pressure gradients should be significantly smaller in general. Even if those extreme values for pressure gradients occur in reality, they should not be prevailing over such a long distance as applied here in the simulations. For this reason, the maximum pressure changes applied here can be considered conservative.

[5] https://cds.climate.copernicus.eu/

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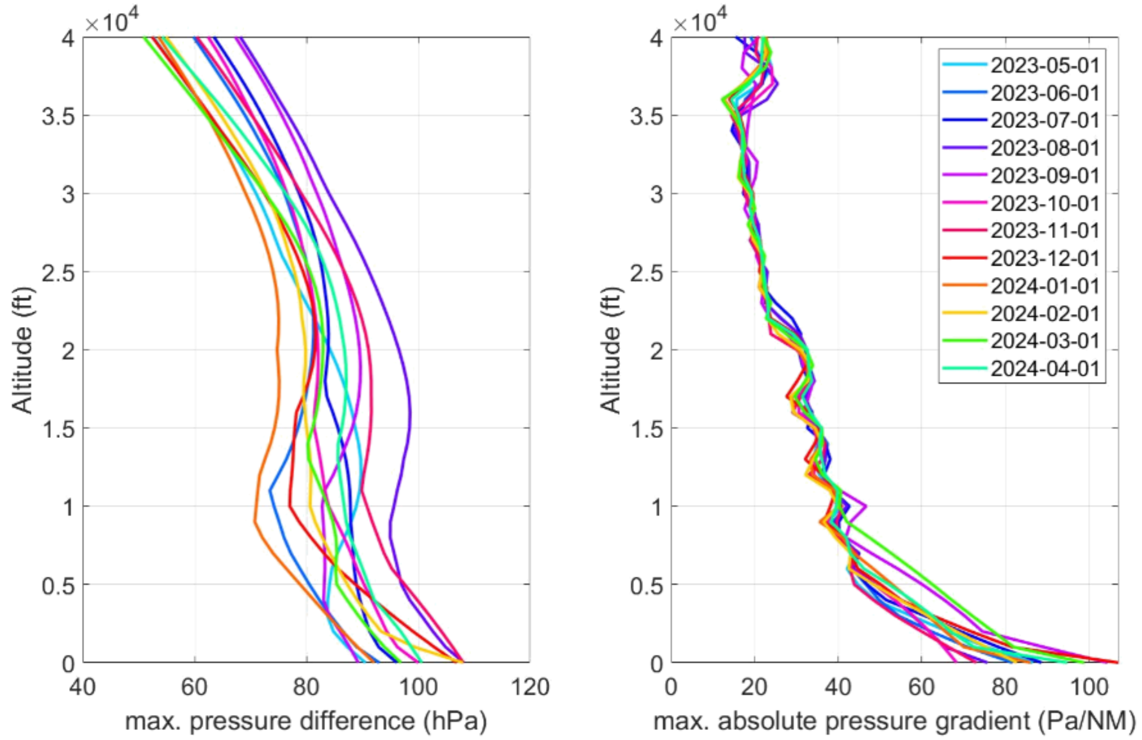

Figure 28: Analysis of worldwide maximum pressure differences (left) and maximum absolute pressure gradients (right) in real atmospheric data

Furthermore, for the generic simulations only the air pressure is changed. The other atmospheric quantities, such as temperature and density are assumed to follow the equations provided by the International Standard Atmosphere.

D.3.2.3.1.2 Results

Based on the aforementioned verification by real atmospheric data, the pressure gradients applied in the simulations are ±2.5 Pa/NM, ±5 Pa/NM, ±10 Pa/NM and ±20 Pa/NM. The simulations are started in a trimmed flight state at different flight levels. During the simulations the air pressure changes linearly. The simulations stop after a flown distance of 400 NM or when the aircraft exceeds a barometric altitude of 40,000 ft (maximum altitude for the validity of the simulation model).

Figure 29 and Figure 30 show exemplary time histories of simulations at FL320 with increasing and decreasing pressure. The simulations at FL320 are shown because in this case the aircraft does not exceed FL400 within the flight distance of 400 NM, even with the maximum pressure gradient of 20 Pa/NM applied. The simulations with pressure at higher flight levels generally show the same characteristics, but with shorter graphs for higher pressure gradients (because of the exceedance of FL 400).

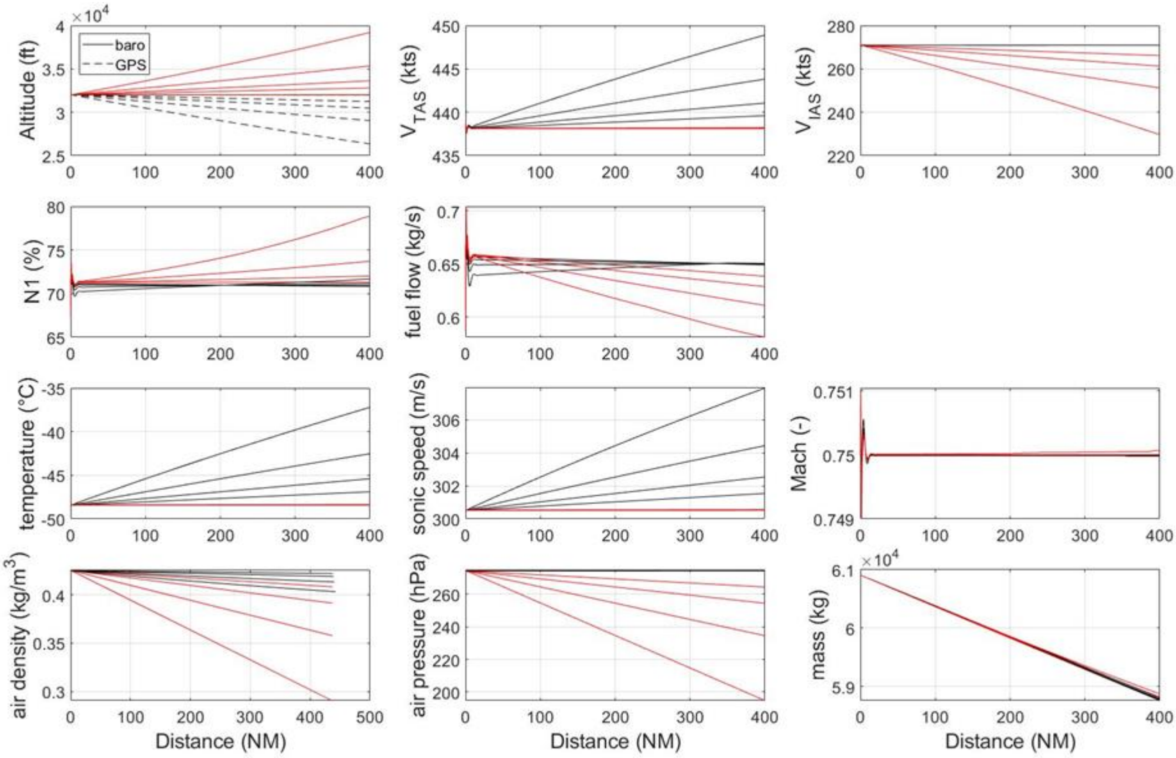

Figure 29: **Simulation results FL320 with pressure decrease (black: barometric altimetry, red: geometric altimetry)**

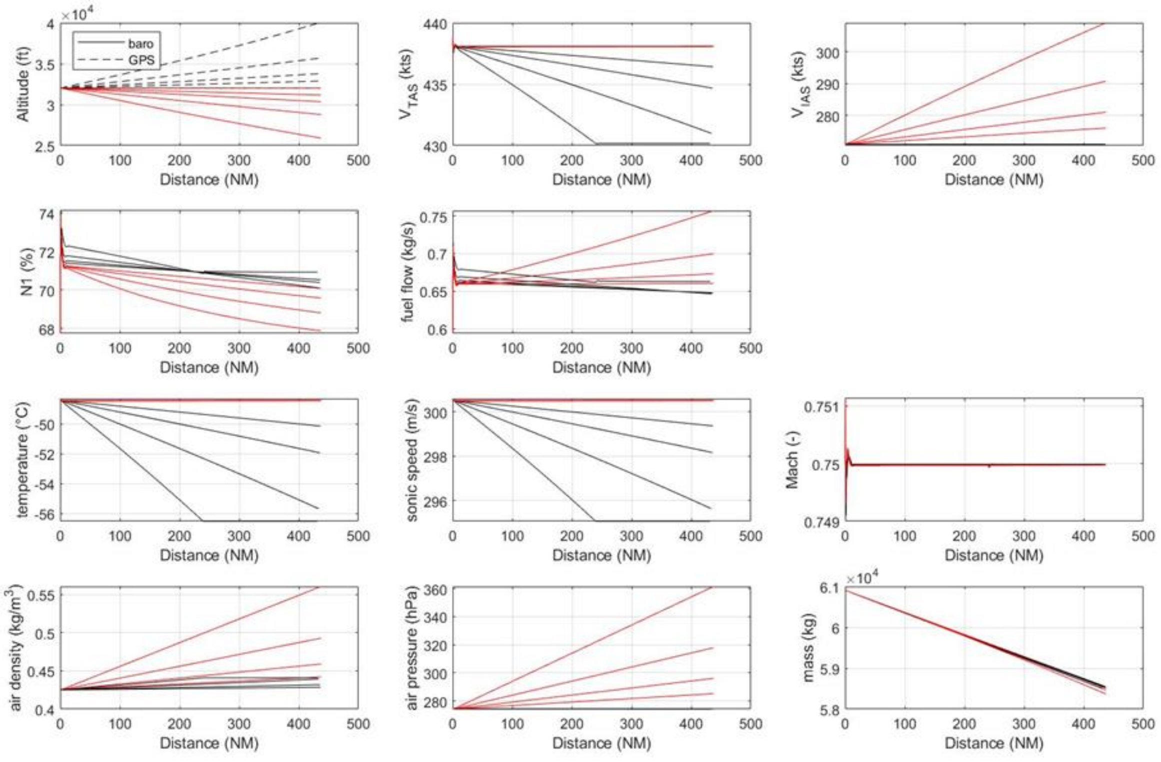

Figure 30: Simulation results FL320 with pressure increase (black: barometric altimetry, red: geometric altimetry)

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One can observe in Figure 29 and Figure 30 that the differing effects on fuel flow stemming from the pressure change and the resulting change of geometric altitude. The important result is the difference of fuel flow between the cases with barometric and geometric altimetry. Figure 31 shows the difference in consumed fuel over the flown distance for pressure decrease (left) and pressure increase (right).

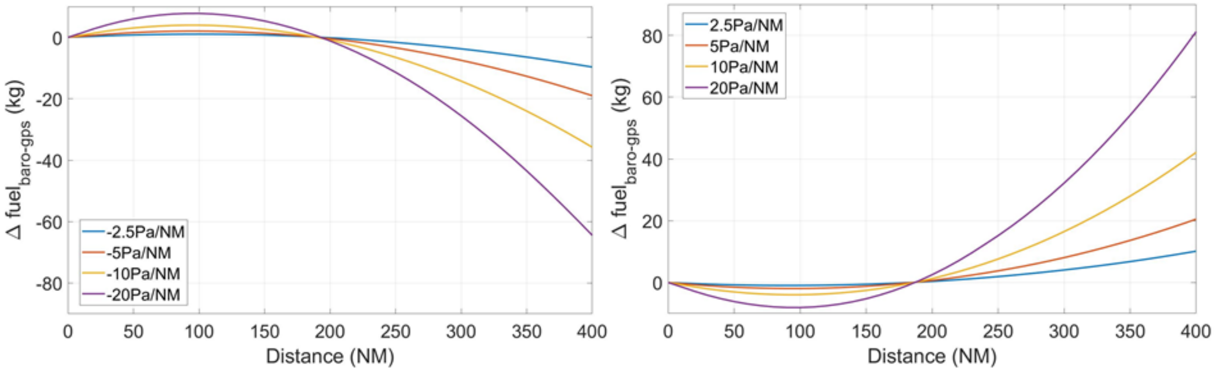

Figure 31: Delta fuel consumption FL320 (left: pressure decrease, right: pressure increase)

One can observe the same behaviour in Figure 31 but with differing sign. By normalising the graphs with the applied pressure gradient, all graphs nearly fall together. Figure 32 shows the normalised graphs of difference in fuel consumption.

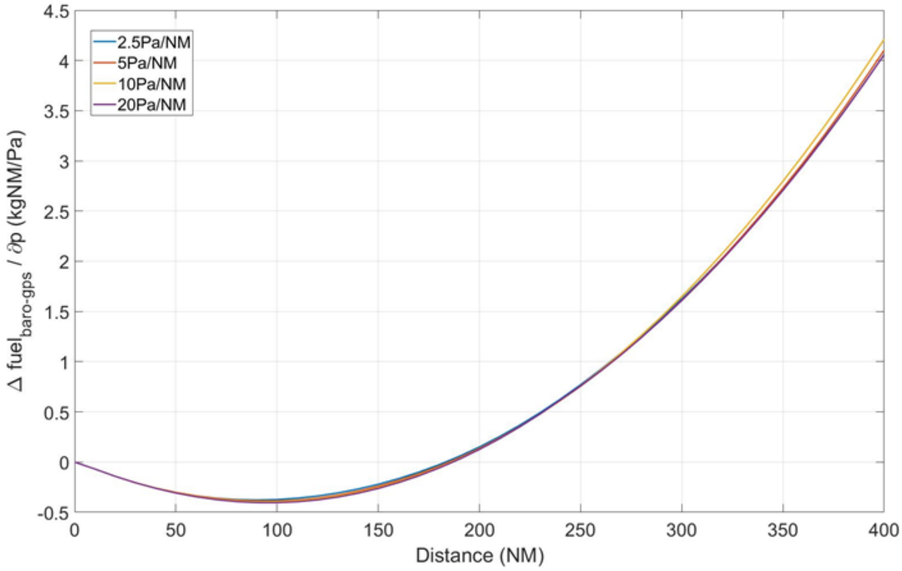

Figure 32: Normalised delta fuel consumption FL320 (pressure increase)

It is obvious in Figure 32 that in normalised depiction the difference in fuel consumption is nearly the same for all applied pressure gradients. However, same as already in Figure 31, one can see that the graph shows an all-pass behaviour, changing sign after a flown distance of about 180 NM. Until this distance the barometric altimetry resulted in lesser fuel consumption, after this distance geometric altimetry resulted in lesser fuel consumption.

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The generic simulations are able to show interesting insight in the flight physical relations when changing the air pressure alone. However, under real flight conditions, this is typically not the case. For this reason, realistic flight scenarios ned to be analysed in order to get a comprehensive look on the effects of the type of altimetry on fuel consumption in cruise flight.

D.3.2.3.2 Fast-time simulations of real flights

In order to evaluate a large number of flights a fast-time simulation was developed. With this simulation tool, real flight data can be evaluated in order to calculate the fuel consumption in case that a specific flight would have been performed with geometric instead of barometric altimetry. With this method the difference in fuel consumption and flight time by using geometric altimetry in comparison to the use of barometric altimetry can be evaluated. The geometric altitude is calculated using the pressure information from the weather data and the given barometric altitude.

D.3.2.3.2.1 Assumptions and limitations

Some assumptions had to be made for the fast-time simulations.

Take-Off mass

The aircraft mass is a crucial parameter that is required for the evaluation. Unfortunately, the available flight data do not comprise information on the aircraft mass as they are ADS-B-based data and ADSB-does currently not include the aircraft mass. For this reason, the take-off mass of each flight was estimated for the simulations. The estimation of the take-off mass is based on the known flight distance of the specific flight. In relation to the maximum flight distance and the maximum fuel capacity of the A320 the fuel mass for this flight is estimated. As there are no information on the flight planning (e.g. alternate airports), an additional fuel mass of 500 kg is assumed for alternate and contingency. The payload mass is estimated with a seat load factor of 83.4 % (average value for international flights from Germany[6]) and an assumed mass of 100 kg per pax including luggage. In case that the aircraft mass assumed this way would be larger than the maximum take-off mass (MTOM), the actual take-off mass is limited to the MTOM.

Geometric cruise flight level

It is assumed that the flights are operated at their optimal cruise flight level, that is operationally feasible. For this reason, the cruise flight levels with geometric altimetry are chosen in a way that the resulting barometric altitude is as close as possible to the barometric cruise flight level of the original flight.

Position of Step climbs/Descents

In case that during the cruise flight step climbs or step descents have been performed, the simulation with geometric altimetry uses the same positions for step climbs. Following the assumption on the geometric cruise flight level as described above, it can be assumed that the position of the step climbs

[6] Source: Statistisches Bundesamt (Federal Statistical Office of Germany)

/ descents remains constant even with geometric altimetry. Nevertheless, a real flight planning (and optimisation) using geometric altimetry would have come up with different step climbs / descents. This, however, cannot be evaluated in the frame of this exploratory research project.

D.3.2.3.2.2 Flight Data

For the evaluation of real flights, a single Lufthansa A320 is chosen. The flight data have been collected for this specific aircraft between 25 June 2024 and 19 October 2024. Altogether, the set of evaluated flight data comprises 617 consecutive flights. The specific aircraft is based at Frankfurt/Main airport and always performs pairs of returning flights from and back to Frankfurt. Figure 33 depicts the tracks of all evaluated flights.

Figure 33: Overview of the tracks of all evaluated flights

It must be mentioned that a low number of flights was not possible to be evaluated as the flight data were corrupted in some way and not usable for the evaluation. In those cases, the related second flight to/from the destination was omitted as well, in order to avoid any bias in the results. For example, if a flight from Frankfurt to Paris was not evaluated, the related returning flight back to Frankfurt was not used for the evaluation, too.

D.3.2.3.2.3 Atmospheric Data

Atmospheric data are essential for this kind of evaluation. The following parameters are required for the evaluation:

Air pressure
Air density

Wind speed
Wind direction
Temperature
All parameters are given as a function of the geopotential height.

The atmospheric data are publicly available, provided by the ECMWF through its Climate Data Store[7][4].

D.3.2.3.2.4 Modelling

The basic idea behind the modelling approach that the limited set of parameters describing the flight is completed by simple flight physical calculations. So, in a first step, the flight is analysed the way it was performed. For this, the ground track, described by the time history of latitude, longitude and altitude is kept untouched. As described above, for each data point, at first only the latitude, longitude, altitude, track and ground speed are available, together with a time stamp. As one basic information for the evaluation the aircraft mass is required. Unfortunately, this parameter is not available in the flight data. Therefore, the take-off mass is estimated based on the length of the flight. From the ground speed, together with wind information, the true airspeed and with additional atmospheric information on air density and temperature, the indicated airspeed and Mach number are calculated. Based on the geometric altitude the flight path angle is calculated and with this together with the ground speed, the track speed is calculated. The derivative of the track speed is essential for the evaluation of the fuel flow, as it influences the required thrust. Basically, the algorithm evaluates the required thrust setting in order to meet the acceleration observed in the flight data. Having evaluated the fuel flow for each data point the analysis of the flight data is finished.

The analysis of the flight data is then used to identify cruise flight segments, their related cruise Mach number and flight level as well as step climbs or descents (if any). Based on this a cruise schedule is derived for the simulation of the same flight with geometric altimetry. The geometric cruise flight level to be used is chosen as the flight level (following the same definition as the current definition of flight level, but using geometric instead of barometric altitude) at which the average barometric altitude during the specific cruise segment is the nearest to the geometric flight level that was flown in the real flight. The cruise Mach number was kept the same as in the real flight. Also, the position of step climbs or descents (if any) are kept the same for the flights with geometric altimetry. As the used type of altimetry does not change the climb or descent performance of the aircraft, climb and decent segments are copied without changing the data. Only at the transition between climb/descent and level flight altitudes are added or clipped, where necessary.

As the use of a constant cruise Mach number (in contrast to the sometimes slightly changing Mach number in the real flight data) can result in a slightly different ground speed in comparison to the real flight data, the time at each data point is adapted. This way, it is ensured that the latitude and longitude of each data point remain the same. Otherwise, new latitude and longitude values had to be calculated

[7] https://cds.climate.copernicus.eu/

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in case that the time signal should have been untouched. So, the adaptation of the time signal was much simpler than the adaptation of the latitudes and longitudes.

Following the identification of the aforementioned cruise flight parameters, the flight is simulated using the same algorithms with barometric and geometric altimetry. The reason, why the barometric flight also simulated (not using the real flight data for the comparison) is that by doing so, some fluctuations in the speed, stemming from atmospheric turbulence, that is not covered by the wind data, are neglected. This way, a fair comparison between flight with barometric and geometric altimetry can be made. Otherwise, the thrust fluctuations due to atmospheric turbulence, which is included in the real flight data, would falsify the evaluation of fuel consumption as these fluctuations are not included in the simulation with geometric altimetry.

D.3.2.3.2.5 Results

For each flight the difference in fuel consumption is evaluated. Figure 34 depicts an exemplary flight. The altitude is zoomed to cruise flight levels in order to be able to better distinguish between barometric and geometric altitude. One can clearly observe the changing geometric altitude for the barometric flight (blue lines) and the barometric altitude for geometric flight (red lines). For this specific flight the evaluation results in a difference in fuel consumption of 36 kg, meaning that in this case the flight with geometric barometry consumed more fuel than the flight with barometric altimetry. Also, the flight time of the flight with geometric altimetry was 2 seconds shorter than the flight with barometric altimetry.

Figure 34 depicts that in the original flight data (black lines) the cruise Mach number slightly varies during cruise flight, which results in fluctuations of the throttle. The re-simulation of the flight with barometric altimetry (blue lines) uses the average value of the Mach number during cruise as cruise Mach number, for which reasons the throttle signal is much smoother during cruise as well. By comparing the simulation with geometric altimetry against the re-simulated flight with barometric altimetry, it is ensured that the comparison is not biased by the thrust fluctuations of the real flight analysis.

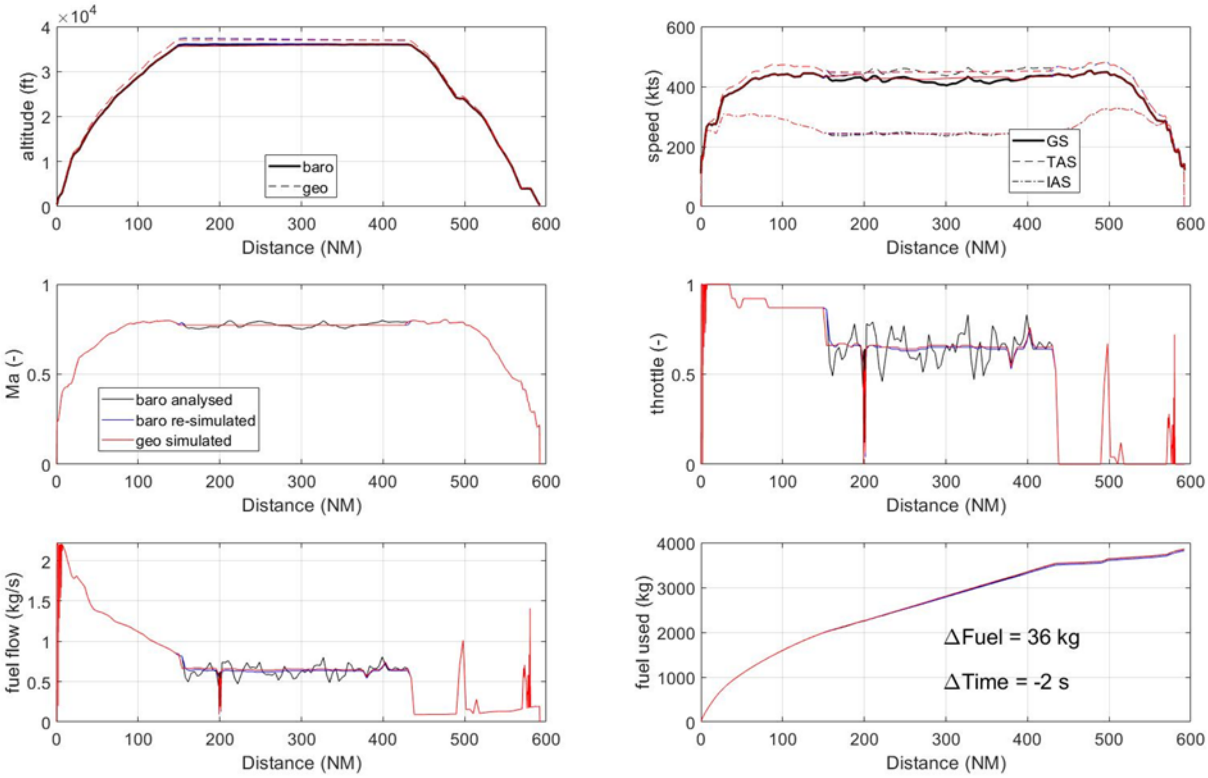

Figure 34: Exemplary results from re-simulation of a single flight with barometric and geometric altimetry

Figure 35 shows the altitude plot from Figure 34 zoomed to the cruise flight levels. In Figure 35 one can better observe the differences between barometric and geometric altitudes with barometric and geometric altimetry. In case of the flight with barometric altimetry (blue lines), the barometric altitude is kept constant at FL360 (36,000 ft), while the geometric altitude decreases because of the decreasing air pressure during cruise. Here, the maximum difference between barometric and geometric altitude is almost 1,500 ft. For the simulation with geometric altimetry the geometric altitude is kept constant during cruise. The cruise altitude is chosen in a way, that the barometric altitude is as close as possible to the barometric flight level from the flight with barometric altimetry. Therefore, the resulting cruise altitude with geometric altimetry is 37,000 ft (geometric altitude).

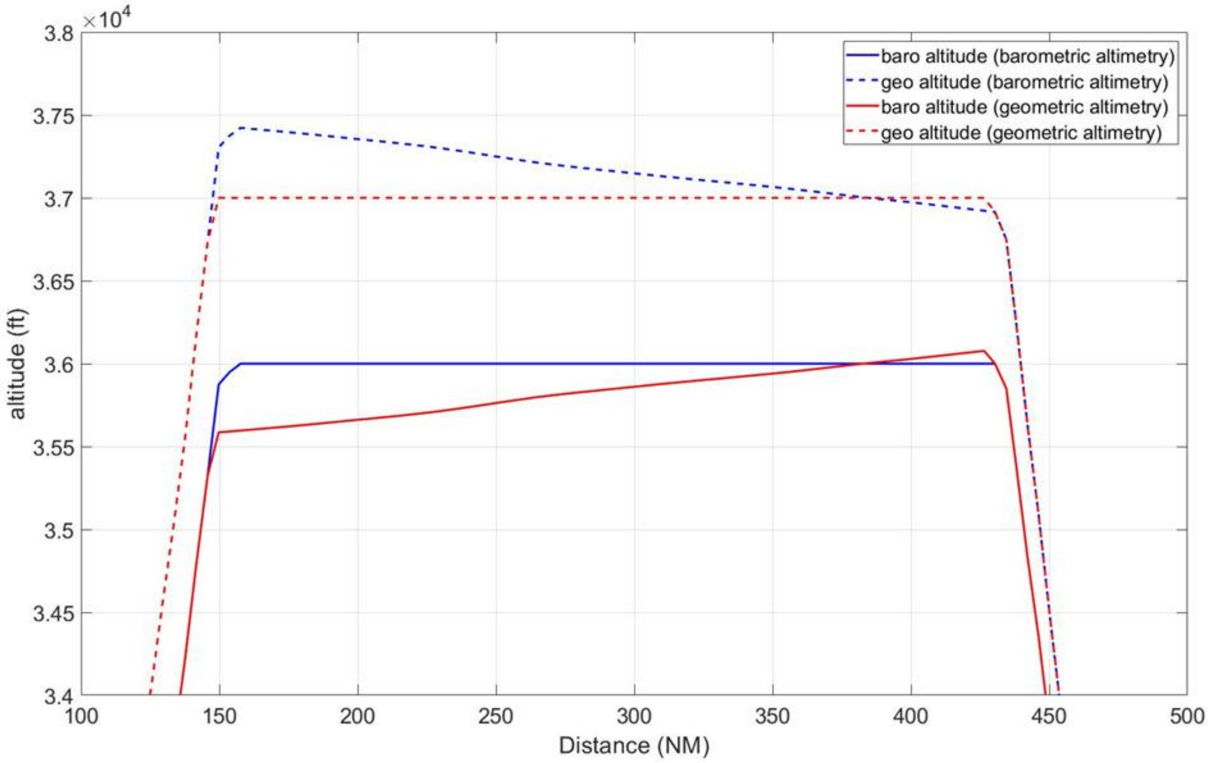

Figure 35: Exemplary results from re-simulation of a single flight with barometric and geometric altimetry (cruise altitudes only)

The evaluation of all 617 flights gives a good indication on the accumulated effects of the use of geometric altimetry. The values for the average change of the fuel consumption converges relatively quick towards a value of about 6 kg of the trip fuel. It must be noted that the relatively low numbers for absolute fuel consumption stems from the fact that only short-range flights are evaluated here.

For the evaluation of accumulated values, the number of evaluated flights is crucial, as it needs to be a statistically significant number. Figure 36 shows how the average change of the fuel consumption converges with increasing number of evaluated flights. One can observe that after ca. 200 flights the average difference in fuel consumption converges at a value of about 6 kg. Therefore, Figure 36 clearly shows that the number of evaluated flights is statistically significant.

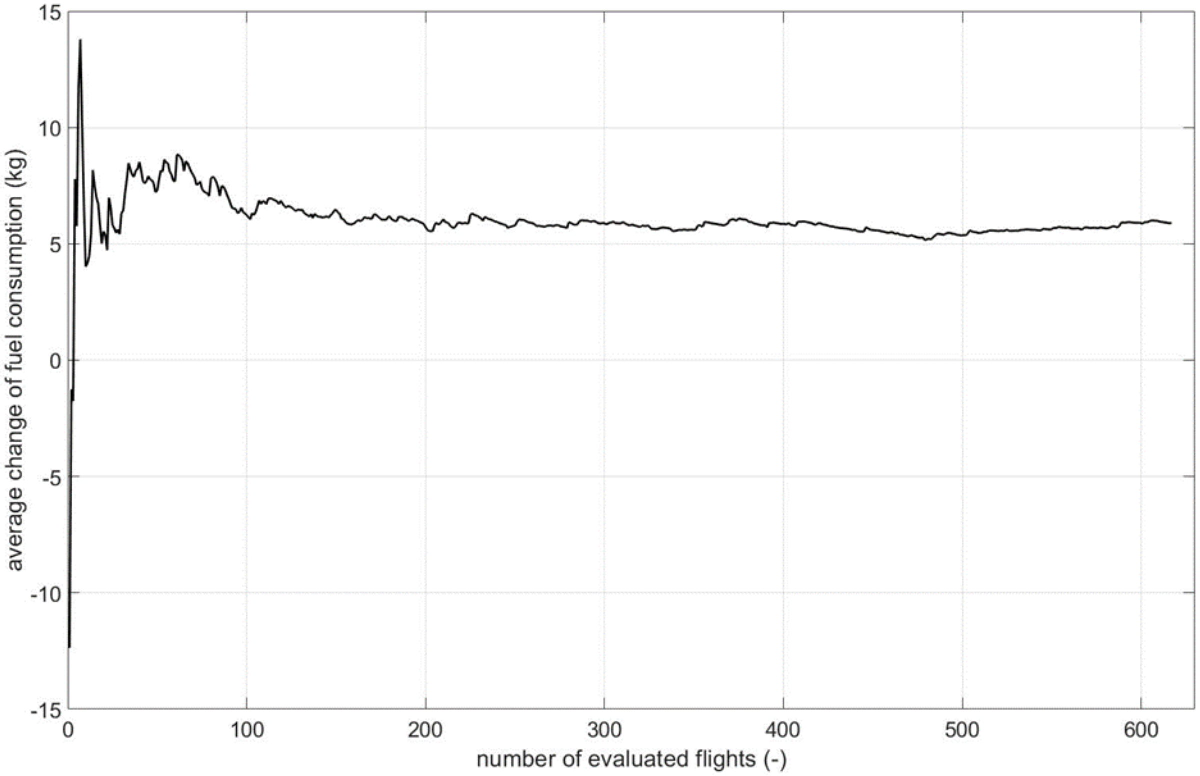

Figure 36: Convergence of average fuel consumption change

The simulations of the 617 flights revealed that none of the evaluated flights exceeded the maximum barometric operating altitude of the aircraft of 40,000 ft[8]. This is, however, only an indication that the risk to exceed the maximum operating altitude using geometric altimetry may not be large. From the results of the simulation, it cannot be concluded that exceeding the maximum operating altitude cannot occur. This needs to be observed in any case when using geometric altimetry to prevent an unintended exceeding of the maximum barometric operating altitude.

For the following interpretation of the simulation results, the reader should keep in mind that a positive change of fuel consumption means that the respective flight with geometric altimetry consumed more fuel that the same flight with barometric altimetry. Hence, a negative sign denotes a fuel saving by using geometric altimetry.

The simulations of the 617 flights show a minimum change of fuel consumption of -50.7 kg, which translates into -2.3 % of the trip fuel. The maximum change of fuel consumption is 89.8 kg or 6.6 % of the trip fuel. The average change of fuel consumption over all 617 flights is 5.9 kg or 0.2 % of the trip fuel. Thence, for all 617 flights the accumulated change of fuel consumption is 3.6 t (0.2 % of trip fuel).

[8] The evaluation performed for cruise was not able to detect all cases where the performance limit of the aircraft would have been exceeded in case that the REC MAX is below 40,000 ft.

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The distribution of changes in fuel consumption are shown Figure 37. One can clearly observe a slight shift of the whole distribution towards positive fuel changes, which is also indicated by the average value of about 6 kg.

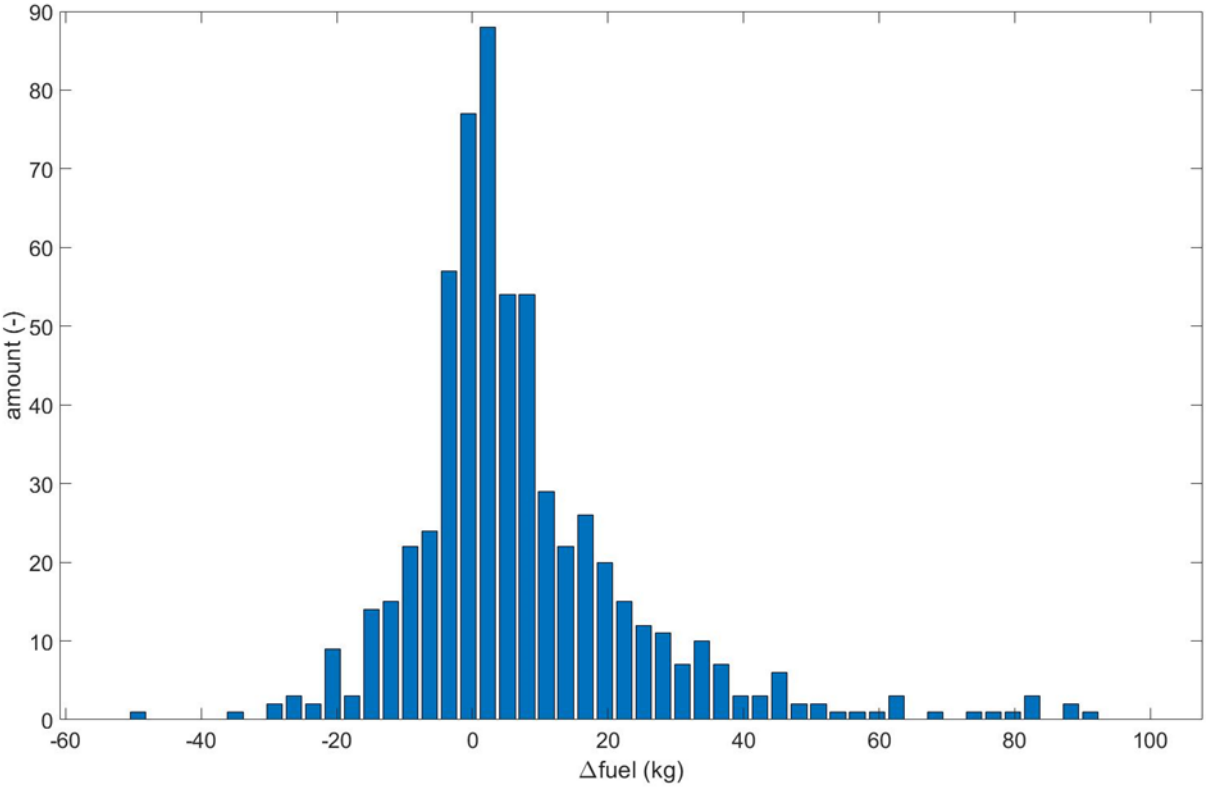

Figure 37: Results on fuel consumption from cruise flight simulations

Another parameter that is influenced by the use of the type of altimetry is the flight time. Using the same cruise Mach number the flight at a different geometric altitude (also resulting in a different air temperature) results in a different ground speed. For this reason, the flight time is also affected.

The simulations reveal a minimum change of the flight time of -31.3 s and a maximum change of the flight time of 136.1 s. The average change of flight time is 5.9 s. With a maximum increase in flight time of slightly more than 2 minutes, the influence of the geometric altimetry can be considered as negligible.

The distribution of changes in the flight time are shown in Figure 38. One can clearly observe that the vast majority of flight time changes are in the range of only a few seconds, which is also indicated by the average value of about 6 s.

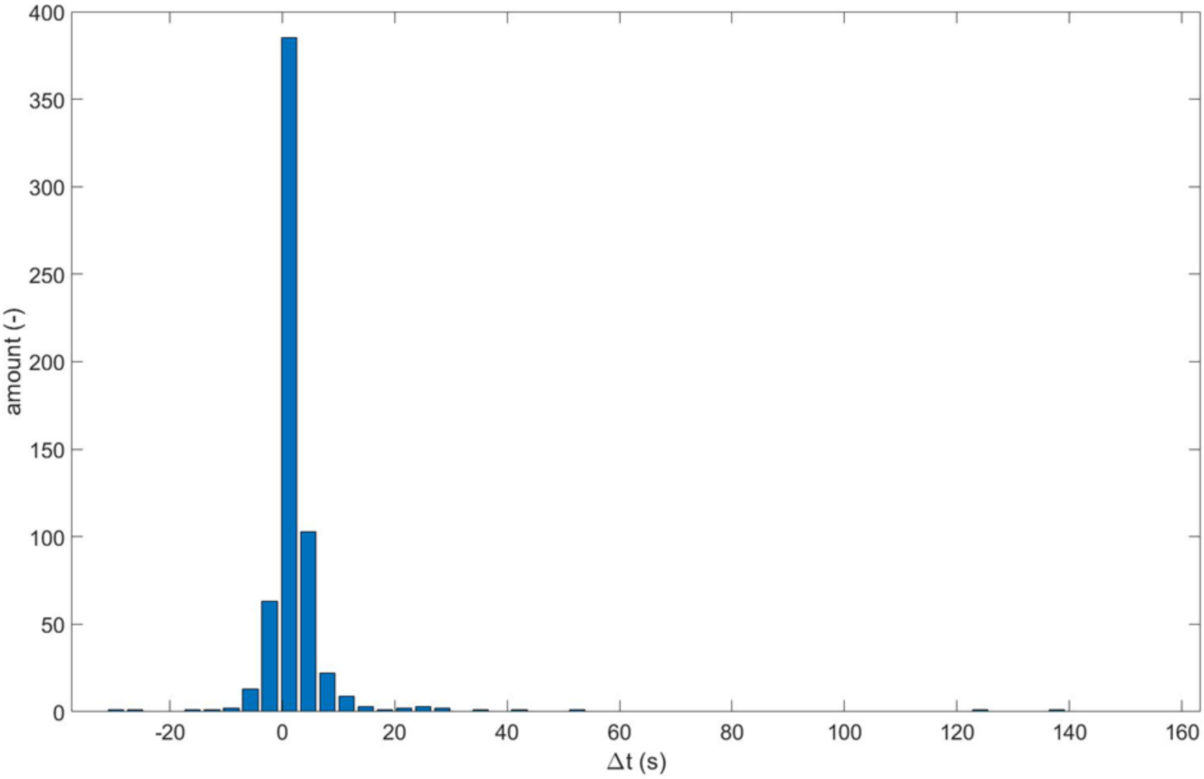

Figure 38: Results on flight time from cruise flight simulations

D.3.2.4 OBJ-GreenGEAR-0406-TRL2-ERP-ENV3 Results

The results from fuel consumption can be directly transferred to CO_2 emissions.

D.3.3 Unexpected behaviours/results

There are no unexpected behaviours or results obtained in this validation exercise.

D.3.4 Confidence in results of validation exercise #04

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

The results obtained in this validation exercise are considered representative in general. For the analysis in the TMA (climb and descent) a case study was conducted. The results, however, are representative and it is assumed that they can be extrapolated in terms of the general effect. For the cruise study the results are representative as well. The cruise study indeed only covered one single aircraft over a longer period of time. However, the chosen aircraft is able to represent typical short- and medium range operations of European airlines. The cruise results are considered to be also representative for long-range flights in general, although the quantitative results cannot be directly transferred to long-range flights. It is expected that the general tendency of the results is comparable for long-range flights, but that the quantitative results would be larger.

D.3.4.2 Quality of validation exercises results

The quality of the results obtained in this validation exercise is considered sufficient for the envisaged TRL. The used models are considered accurate enough for the purpose of the study. Even though differences in fuel flow between the used model and the real aircraft might occur, these possible differences would apply both for simulations with barometric and geometric altimetry in the same way. Hence, the evaluation of the differences of both kinds of altimetry can be considered as independent from possible modelling errors, at least regarding their general trend (sign and order of magnitude of fuel flow difference).

D.3.4.3 Significance of validation exercises results

A statistical evaluation was only performed for the cruise evaluation. Here, the number of considered flights is large enough to be statistically significant, as was shown in the result section. As for the TMA (climb and descent) a case study was performed, statistical significance is not applicable there. Nevertheless, the results of the TMA evaluation appear plausible and are considered significant enough to represent the situation in the TMA well enough and to give a good indication of the general effects.

D.4 Conclusions

D.4.1 Conclusions on concept clarification

The validation exercise did not show any evidence that the use of geometric altimetry is not operationally feasible in general.

D.4.2 Conclusions on technical feasibility

No evidence was found in the validation exercise that the use of geometric altimetry would not be technically feasible in general.

D.4.3 Conclusions on performance assessments

In the results of the descent analysis, several different effects are visible. The change of the altimetry type influences the fuel savings by a very small amount and can be positive or negative depending on the QNH. In an optimised descent scenario, the differences would not cancel out each other in a long-term scenario with varying weather conditions, but a noticeable advantage for the geometric altimetry would remain. For the shown example scenario, the change from the baseline descent profile to the solution descent profile results in fuel savings of approximately 23 kg, which is about 6.6% of the fuel consumption for this scenario. Even though these fuel savings are mostly not a direct result of the geometric altimetry, if the optimised descent profile in the solution scenario is considered to be enabled by the usage of geometric altimetry, then the change of the altimetry type indirectly enables these fuel savings. Also, the usage of geometric altimetry reduces the variance of the fuel consumption and therefore improves the predictability.

In the climb scenario, the influence of the altimetry type on the fuel savings is similar to the influence in the descent scenario: it can be positive or negative depending on the QNH. For the shown example scenario, the change from the baseline climb profile to the solution climb profile results in fuel savings of approximately 2 kg, which is only about 0.25% of the fuel consumption for this scenario and therefore much lower than the benefit in the descent scenario. The reasons for the only very low or in some cases even negative fuel savings are the two counteracting effects in the optimisation of the climb profile: the removal of the level-off segment in the solution scenario has a positive influence on the fuel savings while forcing the aircraft to fly a fixed climb gradient has a negative influence on the fuel savings. It should be noted that the usage of several altitude constraints and even level-off segments in the departure procedures in the London TMA is not the normal case in most other TMAs in Europe. At most airports in Europe, the departure procedures contain only a few or even no altitude constraints along the routing at all. Therefore, when applying the same principle how the departure procedures have been optimised here to other TMAs, the positive effect of the optimised altitude constraints would be much smaller and therefore the negative effect of the fixed climb gradient would be more prominent. For the shown scenarios in the London TMA in total, a small positive benefit remains. Even though these fuel savings are not a direct result of the geometric altimetry, if the optimised climb profile in the solution scenario is considered to be enabled by the usage of geometric altimetry, then the change of the altimetry type indirectly enables these fuel savings. In contrast to the descent scenario, the usage of geometric altimetry in the climb scenario increases the variance of the fuel consumption and therefore decreases the predictability.

For the TMA analysis, it can be concluded that geometric altimetry has a direct positive effect on the fuel consumption because, in contrast to barometric altimetry, the flight level constraints are at fixed geometric altitudes and are therefore not moved away from the optimal profile when the QNH is changing. This direct effect, however, only exists when flying an optimised profile. Also, geometric altimetry has an indirect positive effect on the fuel consumption by enabling an optimisation of the climb and descent profiles. The optimisation of the climb profile in the solution scenario results in small fuel savings but leaves potential for further improvement while the optimisation of the descent profile in the solution scenario already results in significant fuel savings of about 6.6% of the fuel consumption from the top of descent until the ILS intercept.

For cruise flight one can conclude that the use of geometric altimetry instead of barometric leads in average to a slight increase of the fuel consumption of about 0.2% of the trip fuel. The maximum increase in consumed fuel observed in the simulation is about 90 kg. However, it can be expected that in some extreme cases these values might also be even higher. The flight time is only affected in a negligible way.

D.5 Recommendations

In case that geometric altimetry is used in cruise flight, it must be assured that the maximum barometric altitude of the aircraft, which is aerodynamically the more relevant parameter for the service ceiling, is not exceeded. If so, a step descent has to be performed in order to stay within the admissible flight enveloped defined by barometric altitudes.

The cruise flight evaluations revealed a slightly increased fuel consumption by using geometric altimetry in cruise flight. Even though this increase is relatively small (increase of 0.2 % of trip fuel), it accumulates to large numbers of fuel burn increase over a whole aircraft fleet. For this reason, it is recommended not to use geometric altimetry in cruise flight, but to stick with barometric altimetry instead. The evaluation in the TMA revealed possible benefits from the use of geometric altimetry. It has been shown that the optimisation of the vertical profiles (i.e. removal of level-off segments and shifting the altitude constraints to higher altitudes) can result in positive fuel savings but it also has been shown that forcing the aircraft to fly a fixed climb gradient has a negative influence that partially counteracts or in some cases even outweighs the positive benefits. A fixed descent gradient does not have a significantly negative effect as long as a gradient is chosen that can be flown without the usage of spoilers, therefore the optimised descent profiles with geometric altimetry can be considered as a viable solution to enable fuel savings. However, for an optimisation of the climb profiles, it could be a feasible solution to use geometric altimetry without level-off segments but without enforcing a fixed climb gradient or only enforcing it where it is absolutely necessary for the separation of the aircraft. Because the usage of geometric altimetry only showed positive benefits in the TMA but a negative effect in cruise, it could be a feasible solution to use geometric altimetry in the TMA (or at least below a certain altitude threshold) and to use barometric altimetry using the ISA standard pressure of 1013.25 hPa for cruise flight. This would, however, still require some kind of transition altitude/layer in between, but would at least omit the use of the local pressure (QNH) at low altitudes and therefore omit this possible cause for mistakes by selecting a wrong QNH value. Also, this new kind of transition could be performed at a higher altitude to avoid the congested airspace in the TMA.

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