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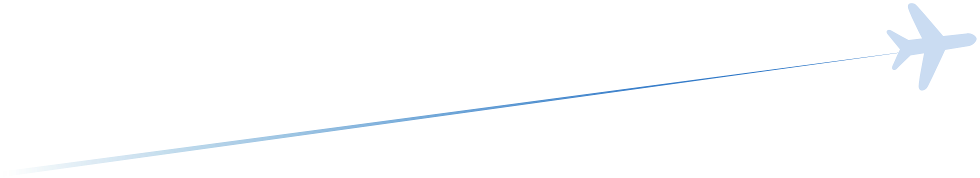

ICARUS Concept Definition: State-Of-The-Art, Requirements, Gap Analysis

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Copyright Statement

ICARUS

INTEGRATED COMMON ALTITUDE REFERENCE SYSTEM FOR U-SPACE

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Abstract

The present document is the first draft release of deliverable D3.1 “ICARUS Concept Definition: State-Of-The-Art, Requirements, Gap Analysis” of the ICARUS project. It has been produced under Work Package WP3 “ICARUS Concept Outline Definition” led by E-Geos.

The main objective of WP3 is to collect all the necessary information and analysis to be used for the identification and definition of the services suitable for the ICARUS Common Altitude Reference (CAR) system, through an in-depth analysis of the requirements of users and all stakeholders, as well as an analysis of the state of the art of each technological component.

In this document, the ICARUS concept is established, an analysis is undertaken of the state-of-the-art in height systems, digital terrain models (DTM) and geospatial products relevant to the problem, the requirements of the system/service are derived, and a gap analysis is undertaken on the components to be developed. This wide range analysis is a necessary input for prototyping the system/service.

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1 Introduction

The ICARUS project responds to the challenge of finding a Common Altitude Reference System (CARS) for drones (or Unmanned Aircraft Systems – UAS) and manned aviation flying in very low-level (VLL) airspaces. It proposes an innovative solution with a Global Navigation Satellite System (GNSS) altimetry-based approach and the definition of a geodetic-barometric transformation algorithm, implemented by a dedicated U-space service.

ICARUS proposes the use of GNSS receivers with suitable requirements for a common UAS-UAS vertical reference, and the definition of a new U3 U-space service for altitude transformation for a common UAS-Manned-aircraft reference, tightly coupled with the interface of existing U-space services (e.g. Tracking, and Flight Planning services). Finally, the terrain model information above the ellipsoid datum used in GNSS receivers, including ground obstacle information, is also an important element of the study.

1.1 Purpose of the document

The objective of this document is to perform a critical review of past and present projects, starting with the results obtained by previous and current studies and an analysis of the state of the art of the technological solutions necessary for defining ICARUS concept services. The outcomes collected from other studies are not sufficient to fill the gap of the problems encountered. In fact, the possible solution of this challenge involves a multidisciplinary approach (Geodesy / Geomatics / Navigation / Air Traffic Management (ATM) research) not always present in current studies.

This document defines the requirements affecting both a Global Navigation Satellite System (GNSS)-based altimetry approach in terms of accuracy, precision, continuity and integrity of the service and the requirements applicable to the Digital Terrain Model (DTM) (including ground obstacles) in terms of the necessary resolution and accuracy.

To enforce these actions, the U-space community of Unmanned Aircraft Systems (UAS) Pilots, drone operators, Unmanned Traffic Management (UTM) service providers, general aviation (GA) pilots has been involved through a dedicated on-line survey (web questionnaire) aimed at assessing the operational needs related to common altitude reference issues.

The requirement analysis in this phase, with the help of the survey and Advisory Board (AB), identified:

- Navigation requirements for GNSS-based altimetry;
- Requirements for accuracy and resolution of the DTM / digital surface model (DSM);
- Navigation Performance (e.g. need for a GNSS Performance monitoring service)
- Operational Requirements;
- Safety requirements.

These requirements have been taken into account in specific use cases of particular interest to highlight the ICARUS concept and its added value (e.g. two UAS flying over a city with different home points – top of a building, ground, one GA flight entering a Geometric Altitude Mandatory Zone (GAMZ), etc.) to provide a preliminary safety assessment addressed using state-of-the-art methodologies (i.e. SORA, MEDUSA) and finally to identify the gaps (technological, operational, procedural, safety, etc.) that need to be filled for full elicitation of the service.

The main outputs of this phase are therefore: the overall concept definition, through a requirement analysis for the service envisaged; the identification of gaps to be filled for implementation of the solution; and a preliminary safety assessment of the use-cases envisaged, including a check for compliance with current EU regulations.

1.2 Acronyms

Acronym	Meaning
AB	Advisory Board
ABAS	Airborne Based Augmentation Systems
API	Application Programming Interface
ARAIM	Advanced RAIM
ATC	Air Traffic Control
ATM	Air Traffic Management
ATZ	Aerodrome Traffic Zone
BVLOS	Beyond Visual Line of Sight
CAN	Controller Area Network
CARS	Common Altitude Reference System
CTR	Control zone
DAA	Detect And Avoid
DEM	Digital Elevation Model
DIODE	D-Flight Internet of Drones Environment
DOP	Dilution Of Precision
DREAMS	Drone European Aim Study
DSM	Digital Surface Model
DTM	Digital Terrain Model
EASA	European Union Aviation Safety Agency
ECEF	Earth-Centered, Earth-Fixed

EDAS	EGNOS Data Access Service
EGNOS	European Geostationary Navigation Overlay Service
EGNSS	European Global Navigation Satellite System
EO	Earth Observation
FL	Flight Level
FTE	Flight Technical Error
GA	General Aviation
GAMZ	Geometric Altitude Mandatory Zone
GBAS	Ground Based Augmentation System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HAS	High Accuracy Service
HPL	Horizontal Protection Level
IAB	ICARUS Advisory Board
ICAO	International Civil Aviation Organization
ISA	International Standard Atmosphere
KPI	Key Performance Index
LPV	Localizer performance with vertical guidance
MCMF	Multi-Constellation Multi-Frequency
NSE	Navigation System Error
NTRIP	Networked Transport of RTCM via Internet Protocol
PL	Protection Level
PPP	Precise Point Positioning
PVT	Position-Velocity-Time
QFE	Query Field Elevation
QNH	Query: Nautical Height

RAIM	Receiver Autonomous Integrity Monitoring
RNP	Required Navigation Performance
RTCM	Radio Technical Commission for Maritime Services
RTK	Real Time Kinematics
SBAS	Satellite Based Augmentation System
SIS	Signal In Space
SISE	Signal In Space Error
SOL	Safety Of Life
SORA	Specific Operations Risk Assessment
TSE	Total System Error
TTA	Time-To-Alert
UA	Unmanned Aircraft
UAS	Unmanned Aircraft System
UEE	User Equipment Error
UERE	User Equivalent Range Error
URA	User Range Accuracy
URE	User Range Error
USSP	UTM service providers
UTM	Unmanned aircraft system Traffic Management
VLL	Very-Low-Level
VLOS	Visual Line Of Sight
VPL	Vertical Protection Level

Table 1-1: List of acronyms

2 Overall ICARUS Concept Definition

The task is dedicated to the design of ICARUS concept and to its description through fundamental and perceptive characteristics, including benefits and justification of the idea, in the frame of the U-space ecosystem and GNSS services.

2.1 Previous Projects and Inputs

ICARUS will exploit the outcomes of past U-space exploratory research projects, considering their findings and recommendations, as well as the lessons learned from U-space demonstrators. The CARS document issued by EUROCONTROL will be used as the starting point for the ICARUS concept definition, in combination with other relevant documentation identified below.

In particular the following documents and outcomes will be considered as input for ICARUS project:

- **UAS ATM Common Altitude Reference System (CARS) [1]**: This discussion document published by EUROCONTROL in 2019 represents one of the main inputs for ICARUS project. To maintain separation between all users of VLL airspace, it is essential that the altitudes of all of these aircraft be known unambiguously. However, whereas conventional manned aviation uses pressure altitude obtained from barometric readings, UAS often use other systems such as satellite-derived altitudes. While each of these different systems can enable safe separation on its own, they can each furnish different altitude values from each other. A common altitude reference system needs to be established. This document provides a basis for discussion on such a system, following a workshop and a series of webinars organised by EUROCONTROL in collaboration with the European Aviation Safety Agency (EASA). The study concludes with three options:
    - **Option 1:** barometric measurements for all operations at VLL, no U-space services;
    - **Option 2:** GNSS measurements for all operations at VLL, no U-space services;
    - **Option 3:** Mixed approach; each airspace users will use its approved altimetry system, U-space services will be used for translation.

  ICARUS will follow up the CARS study, starting from option 3, with the focus on GNSS altimetry requirements for a common UAS-UAS vertical reference, a UAS-manned-aircraft translation service, and UAS ground obstacle information provided by U-space services.

  Final CORUS project ConOps [2]: The Concept of Operations (ConOps) for European Unmanned Traffic Management (UTM) Systems (CORUS) project encompassed two years of exploratory research to adopt a harmonised approach to integrating drones into VLL airspace. CORUS outcomes represent another important input for the ICARUS project. In particular, in CORUS, it is recognised that small drones commonly use altitudes based on GNSS for practical and cost reasons, while existing aviation makes use of barometric altitudes. As the CORUS CONOPS was written, work on the UAS ATM Common Altitude Reference System was ongoing, therefore the problem was taken into account in the study, but not investigated in detail. However, the project recognised that a GNSS-based approach for vertical UAS separation from the ground requires a calculation of the height above ground, possibly achieved by a look-up table (or map), to give the height of the ground at the current location relative to the same GNSS ellipsoid. Such look-up tables trade-off accuracy against size, and potentially cost.

Moreover, the project assumed that this ground-level calculation was performed inside the UAS (UAS = vehicle + remote piloting station), however the accuracy may vary.

ICARUS will take into account the final CORUS ConOps, considering the possibility of providing such calculation on the ground. Moreover, ICARUS will be following CORUS ConOps for:

- **New airspace classifications** (X, Y, Z_a, Z_u) to be used in ICARUS for the definition of the Use cases;
- **U-space service classification** (updated with respect to the initial SJU Blueprint). In particular, ICARUS will consider the new services added to be existing services with their own interfaces and high-level definition. The services listed below will be helpful for a harmonised integration of the altitude translation service offered by ICARUS. A possible collocation of the service will be proposed in the overall list of U-space services, as well as possible interactions with other U-space services needed to provide input data to feed the altitude translation service.

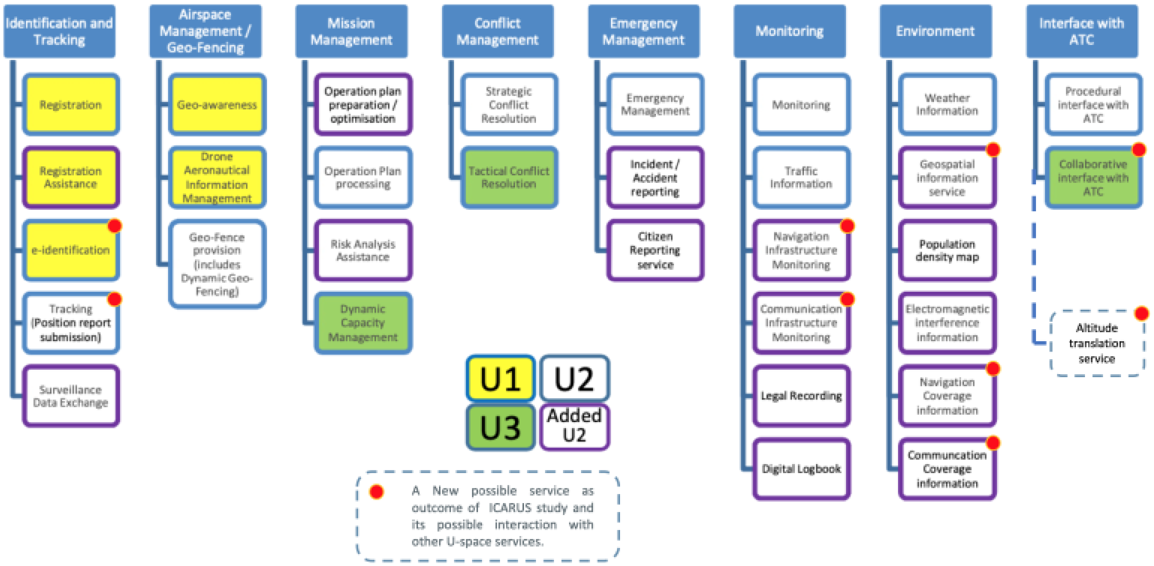


Figure 2-1 – U-space services refined by the final CORUS ConOps and possible collocation of ICARUS altitude translation service

- **SJU Exploratory Research projects 2016:** The exploratory research projects focusing different aspects of the U-space ecosystem (with both a "top-down" and "bottom-up" approach), produced a list of requirements with particular reference to the following excel files (available to the ICARUS consortium on the STELLAR platform):
  - *PROJECT U-space requirements ER4 update (based on B3).xlsx*
  - *U-space requirements_Baseline3 (1_1).xlsx*

The list of requirements produced in these studies is analyzed in the Requirement analysis (chapter 6) to identify a possible set of initial requirements applicable to ICARUS, with respect to the main objectives of the project. Such an analysis avoids "reinventing the wheel", in case the Consortium was not aware that some of the requirements of the initial CARS problem assessment had already been addressed in previous studies. In any case, the definition of new requirements is expected in ICARUS, especially in terms of GNSS-based navigation for altimetry measurements for UAS-UAS separation.

- **2019 U-space Demonstrators:** The main outcomes of SJU U-space Very Large-Scale demonstrators will be considered, especially during the validation stage of the ICARUS concept, in terms of "lessons learned". The projects that will be considered are mainly DIODE and GOF, because of the direct or indirect involvement of many ICARUS consortium partners.

- **Concurrent studies and other parallel initiatives:** Other initiatives and projects (not only funded by SJU) will be taken into account during the lifetime of the project. In particular, the following projects are considered at this stage:
    - **The SJU DACUS and BUBBLES projects** will be monitored to harmonise the progress of the research activities and results achieved with a common roadmap. The link between these projects has been already established through project coordinators and ICARUS consortium members. These "sibling" project members will also be invited to the International Advisory Board foreseen in ICARUS.
    - **GSA projects**: The European Global Navigation Satellite Systems Agency [3] has funded several application projects fostering the use of Galileo and EGNOS. Some of these concurrent studies in both the aviation and the U-space/drone domains will be taken into account during the life of the ICARUS project so that it is always updated about Galileo and EGNOS added value and differentiators for GNSS based altimetry. At this stage, two projects are identified for monitoring:
        - H2020 Ampere project [4]: Drones for electric infrastructure monitoring (ICARUS interest: Added value of MCDF Galileo Receiver installed on drones for BVLOS operations, ground obstacle and terrain model awareness);
        - H2020 Delorean Project [5]: Drones with EGNSS Receivers in Urban VLL airspaces in the context of Urban Air mobility (ICARUS interest: validation report about the performance of EGNSS receivers in an urban environment, in presence of strong multipath, scattering or interference)

      A direct contact with these projects' coordinators will be established by the ICARUS coordinator or Consortium members. The consortium understands that other projects of particular interest for ICARUS may start later. The ICARUS technical coordinator will establish direct contact with GSA to ensure both that ICARUS knows about these projects, and that they are aware of the ICARUS initiative.

    - **EC projects:** Other projects funded directly by the EC will be considered for cross fertilisation and mutual interaction. In particular, the following projects are identified at this stage:
        - H2020 5G!drones [6]: 5G technology in support of drone operations through different use cases. ICARUS interest is about the reliability of the 5G network for U-space services;
        - SUGUS project [7]: accelerating the use of the European GNSS (EGNOS and Galileo) in the UAS market. ICARUS interest is about the E-GNSS added value introduced for U-space services.

Other projects and initiatives of a particular interest for the project can be also taken into account during the progress of ICARUS.

2.2 U-Space Description and Objectives

The rapid evolution of Unmanned Aircraft System (UAS) technology is making these suitable aircraft for a plethora of different applications in the civil environment, spanning from infrastructure surveillance to environment monitoring, from goods delivery to emergency services, as well as other non-professional recreational uses. Many of these applications work in operational scenarios in Very Low Level (VLL) airspace below 120 m of altitude. This requires that UASs be:

- compliant with stringent reliability, safety and security requirements,
- compliant with avionic standards and procedures,
- fully integrated into non-segregated airspace.

The growing European drone market shows significant potential: it is estimated that this market will represent €10 billion p.a. by 2035 and over €15 billion p.a.by 2050. The impact of civil missions (either for governments or for commercial businesses) is expected to generate the majority of this value as related services are anticipated to represent a value of more than €5 billion p.a. by 2035, showing their importance in the market.

There is strong pressure on VLL operations, where the market is driven by new business opportunities (e.g. data services and mobility) and Europe is helping drive what is becoming a global industry by introducing the U-space concept.

The European Union has developed the U-space vision to facilitate the phased introduction of procedures and “a set of services designed to support safe, efficient and secure access to airspace for large numbers of drones”, to encourage the growth of the UAS industry and the use of these aircraft in Europe [8].

U-space is an enabling framework designed to facilitate any kind of routine mission, in all classes of airspace and all types of environment - even the most congested – while addressing an appropriate interface with manned aviation and air traffic control (ATC).

The delivery of U-space relies upon the following key principles:

- Ensure the safety of all airspace users operating in the U-space framework, as well as people on the ground.
- Provide a scalable, flexible and adaptable system that can respond to changes in demand, volume, technology, business models and applications, while managing the interface with manned aviation.
- Enable high density operations with multiple automated drones under the supervision of fleet operators.
- Guarantee equitable and fair access to airspace for all users.
- Enable competitive and cost-effective service provision at all times, supporting the business models of drone operators.
- Minimise deployment and operating costs by building, as much as possible, on existing aeronautical services and infrastructure, including GNSS (Global Navigation Satellite System), as well as those from other sectors, such as mobile communication services.

- Follow a risk-based and performance-driven approach when setting up appropriate requirements for safety, security (including cyber-security) and resilience (including failure mode management), while minimising environmental impact and respecting the privacy of citizens, including data protection.

U-space services will evolve and scale up as the level of automation of UAS increases [9]. The progressive deployment of U-space is foreseen in an incremental manner: each new phase will propose a new set of services while including an upgraded version of the services already existing from the previous phase (Figure 2-2).

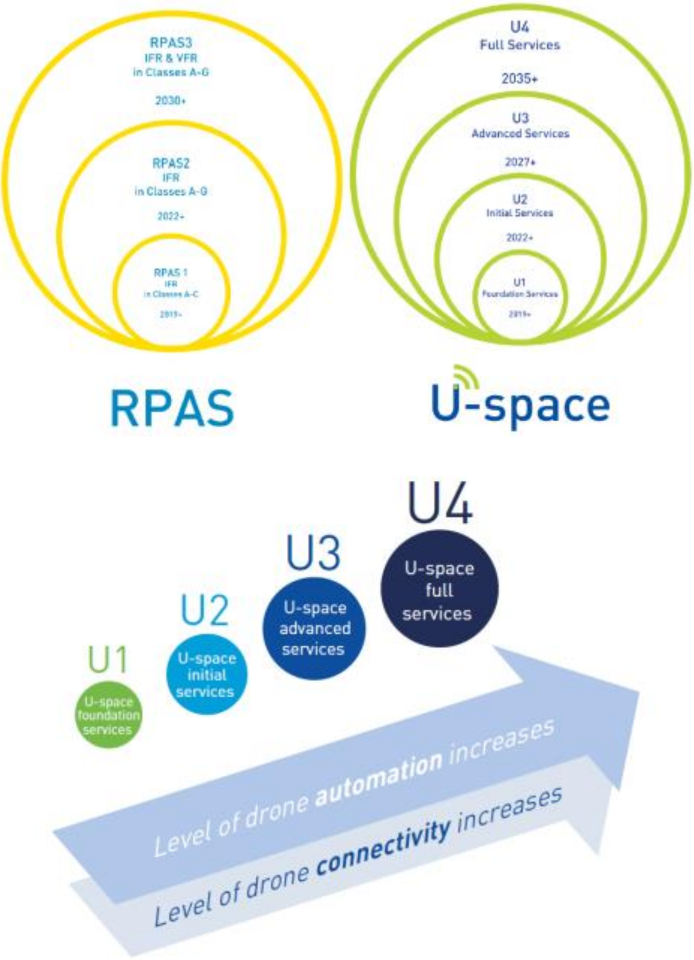


Figure 2-2: Evolution of U-space

- **U1**: U-space foundation services provide e-registration, e-identification and geo-fencing.
- **U2**: U-space initial services support the management of drone operations and may include flight planning, flight approval, tracking, airspace dynamic information, and procedural interfaces with air traffic control.

- **U3**: U-space advanced services support more complex operations in dense areas and may include capacity management and assistance for conflict detection. Indeed, the availability of automated 'detect and avoid' (DAA) functionalities, in addition to more reliable means of communication, will lead to a significant increase of operations in all environments.
- **U4**: U-space full services, particularly services offering integrated interfaces with manned aviation, support the full operational capability of U-space, and rely on a very high level of automation, connectivity and digitalisation for both the drone and the U-space system.

ICARUS proposes the definition of a new U-space service (U3) for transformation of geodetic height measurement to the barometric reference system and vice-versa, based on the introduction of GNSS-based altitude measurement for drones, tightly coupled with the interface of existing U-space services (e.g. Tracking, and Flight Planning services). Icarus is considered a U3 service because it will allow complex operations to be supported in dense areas, giving assistance for obstacle conflict detection and avoidance, and leading to a significant increase in operations in all environments including the most challenging ones e.g. those in urban areas. The users of the ICARUS service will be remote pilots competent to fly VLOS or BVLOS UAS operations in the Specific category, ultralight and GA pilots potentially sharing the same VLL airspace and the drone itself, considering the increased level of automation and connectivity expected at U-space level 3. ICARUS may also enhance the capacity of the airspace, while giving a common altitude reference for airspace users, especially in an urban environment where such promising businesses as package delivery and drone taxi applications could be seen in Europe in the coming years.

The CORUS U-space Concept of operations (ConOps) divides the whole VLL airspace into three different volumes, called X, Y, and Z that differ for the services being offered, and their access/entry requirements. The services offered limit the types of operation that are possible. In particular, the provision of conflict resolution services is the most significant difference between the volumes. In particular (see Figure 2-3):

- In X volumes, no conflict resolution service is offered and the remote pilot has full responsibility for ensuring safe operation.
- In Y volumes, only pre-flight ("strategic") conflict resolution is offered, which means, in essence, that the operation plans are coordinated to avoid collision.
- In Z volumes, in-flight ("tactical") conflict resolution is offered in addition to strategic resolution, meaning that information about the positions and motions of other aircraft is used to guide the drones to avoid conflict.

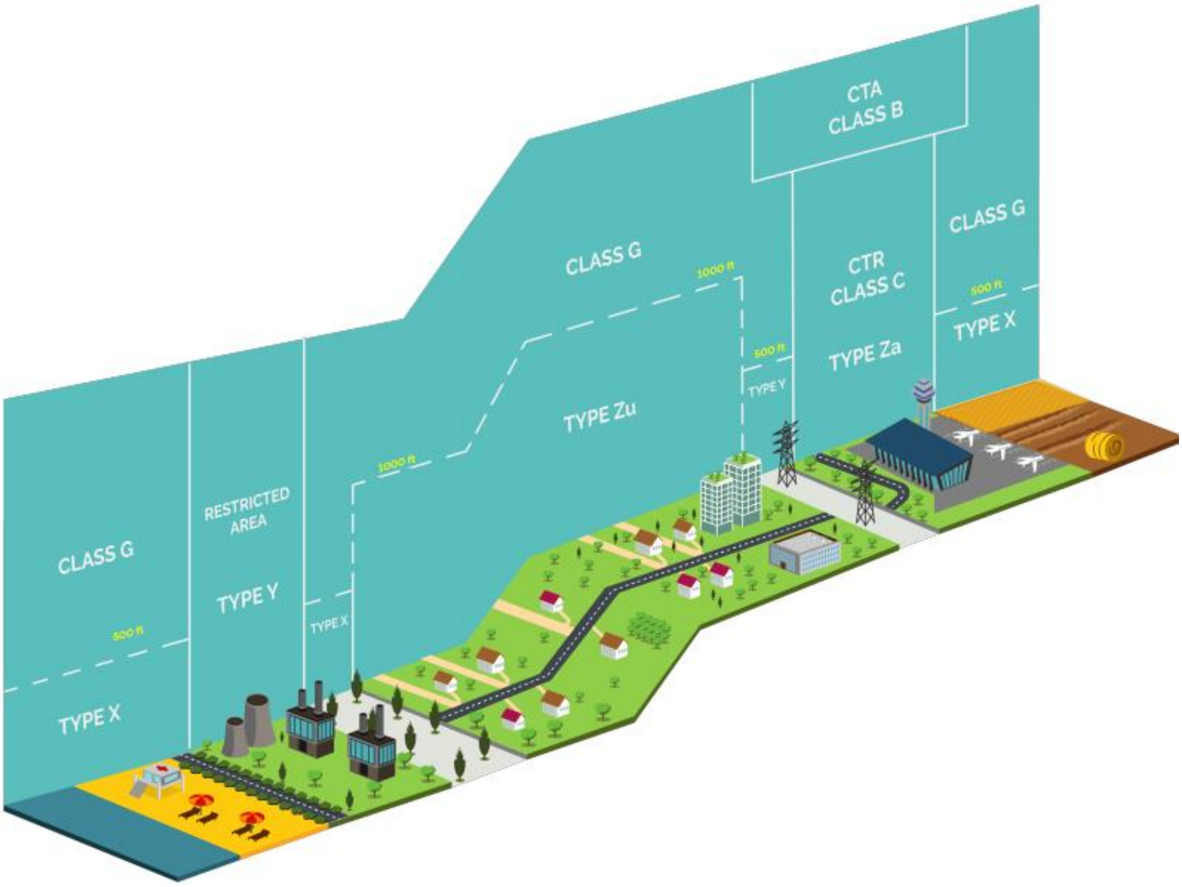


Figure 2-3: VLL Airspace types

This difference has a large impact on how drones should fly in these airspaces. The national aviation authorities, or delegated entities, will be in charge of defining the volumes and their limits. Different services will be available in different types of airspace from different U-space phases. Some of these are mandatory, or at least strongly recommended, while others are offered if needed.

SERVICE	U-SPACE PHASE	X	Y	Z
Registration	U1	Mandated	Mandated	Mandated
e-identification	U1	Mandated	Mandated	Mandated
Geo-awareness	U1	Mandated	Mandated	Mandated
Drone Aeronautical Information Publication	U2	Mandated	Mandated	Mandated
Geo-fencing provision	U2	Mandated	Mandated*	Mandated
Incident / accident reporting	U2	Mandated	Mandated	Mandated

SERVICE	U-SPACE PHASE	X	Y	Z
Weather information	U2	Mandated	Mandated	Mandated
Position report submission sub-service	U2	Recommended	Mandated*	Mandated
Tracking	U2	Optional	Mandated*	Mandated
Drone operation plan processing	U2	Optional	Mandated	Mandated
Emergency management	U2	Optional*	Mandated*	Mandated
Monitoring	U2	Optional	Mandated*	Mandated
Procedural interface with ATC	U2	Optional+	Mandated+	Mandated
Strategic conflict resolution	U2	No	Mandated	Mandated
Legal recording	U2	Optional+	Mandated*	Mandated
Digital logbook	U2	Optional+	Mandated*	Mandated
Traffic information	U2	Optional	Mandated	Offered
Geospatial information service	U2	Optional	Optional	Mandated*
Population density map	U2	Optional	Optional	Mandated*
Electromagnetic interference information	U2	Optional	Optional	Mandated*
Navigation coverage information	U2	Optional	Optional	Mandated*
Communication coverage information	U2	Optional	Optional	Mandated*
Collaborative interface with ATC	U3	Optional+	Mandated+	Mandated
Dynamic capacity management	U3	No	Mandated*	Mandated
Tactical conflict resolution	U3	No	No	Mandated

Table 2-1: U-Space Services and VLL Airspace

+ when needed   * where available

2.3 Problem statement and project purposes

The ICARUS project has the ambition of proposing an innovative and feasible solution to address the challenge of using a common altitude reference inside VLL airspaces, with the definition of a new U-space service and its validation in a real operational environment.

Traditionally in manned aviation there are currently three acknowledged methods of determining the altitude of an aircraft using a pressure difference with respect to a known datum, using standard equipment, within the International Standard Atmosphere (ISA); see Figure 2-8.

- QFE - is the atmospheric pressure at a specified datum such as an airfield runway threshold (height above the local airport "home point", the HEIGHT is the vertical distance of an aircraft above whatever SURFACE (buildings, mountains, a lake, etc.))

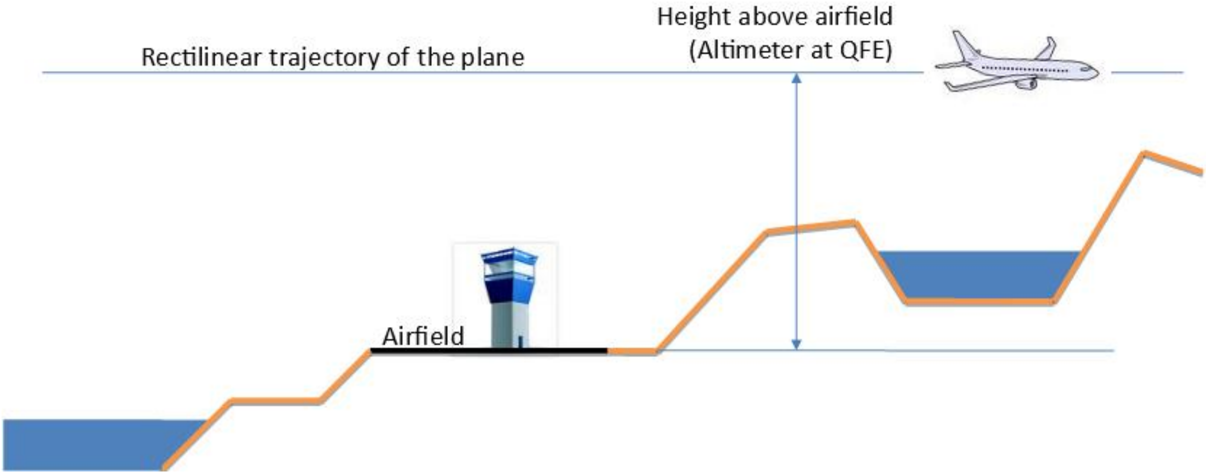


Figure 2-4: QFE reference calculation

  By setting the QFE value of an airport, the altimeter will show, all the time, the HEIGHT above that airfield. On the ground at the airfield, the altimeter will show 0 ft (zero). The higher the airport elevation is, the lower is the QFE;

- QNH - is the atmospheric pressure at mean sea level (may be either a local, measured pressure or a regional forecast pressure (RPS)). When set on the altimeter it reads altitude above a given reference mean sea level (MSL). Altitude (ALT) is the vertical distance of an aircraft above the MSL. For objects and obstacles on the surface of the earth, the word ELEVATION (ELEV) is used instead of altitude.

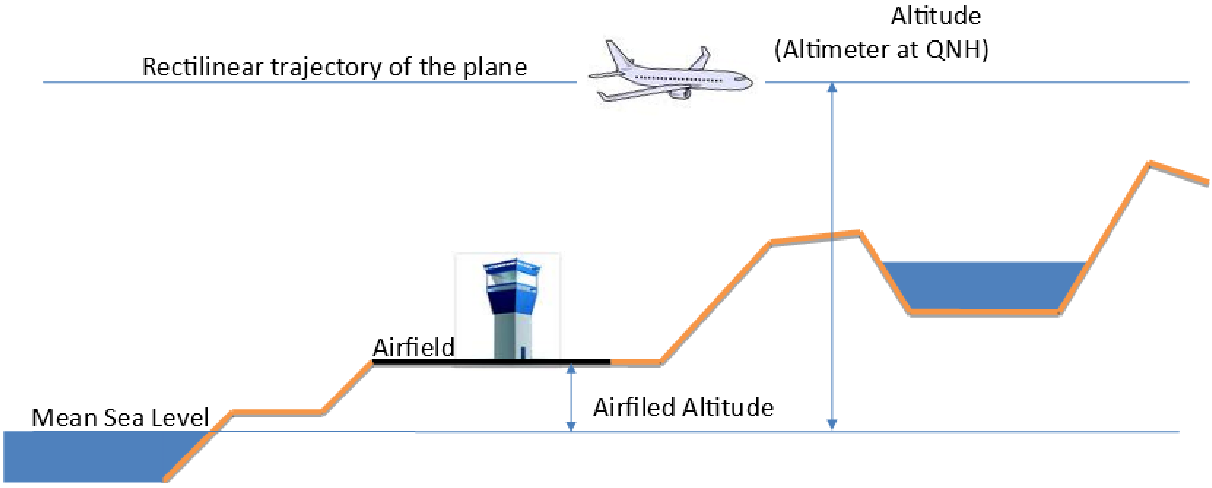


Figure 2-5: QNH reference calculation

- Flight Level (FL) - A Flight Level (FL) is the vertical distance of an aircraft above the ISOBARIC SURFACE of 1013.25hPa (hectopascals) or 29.92 inHg (inches of mercury). A surface of constant atmospheric pressure relative to a specific pressure datum, 1013.2hPa (defined as 0FL), and separated from other such surfaces by specific pressure intervals. One FL is the pressure differential of a 100ft altitude change in the International Standard Atmosphere [ISO, 1975].

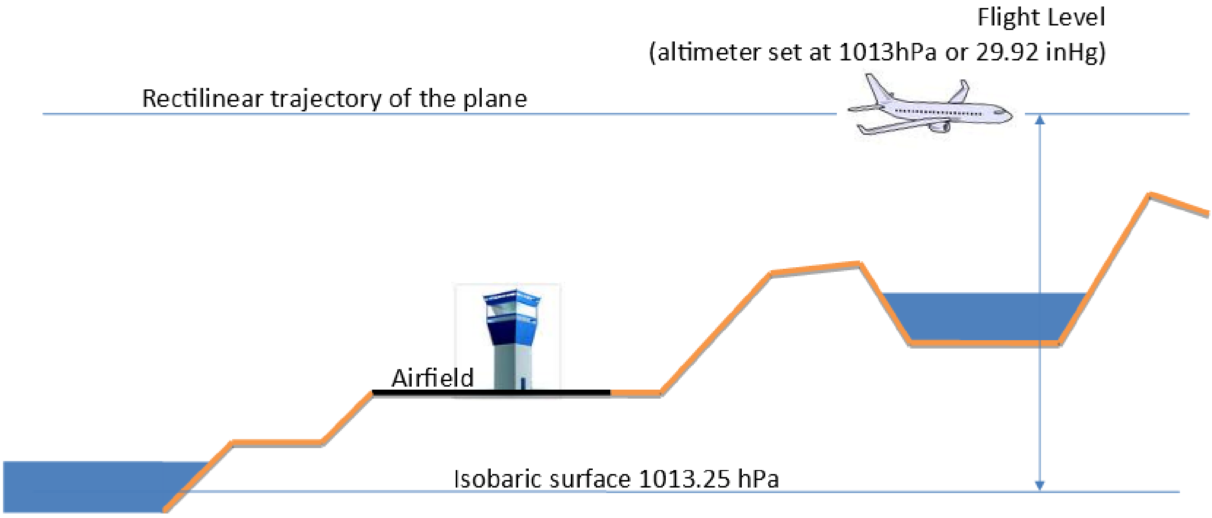


Figure 2-6: FL calculation

When maintaining a flight level, all aircraft have the same reference in order to maintain separation between them with that same reference, but you must know that the aircraft altitude (when following a flight level) changes slowly in conjunction with the local QNH.

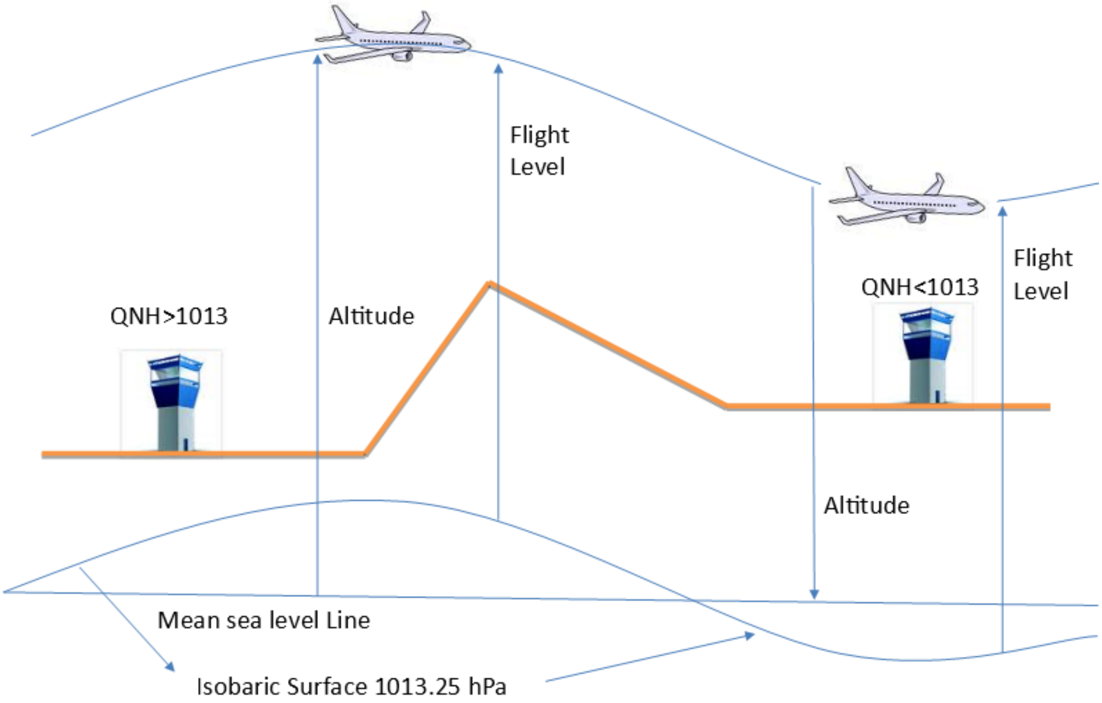


Figure 2-7: FL changes

These approaches cannot be used for UAS because:

- a small drone may take off and land almost from everywhere ("Home Point"), reducing in this way the original significance of QFE settings;
- barometric pressure altitude is not very accurate in VLL airspace, atmospheric pressure is difficult to measure over cities due to high temperature gradients: buildings generally radiate heat, in particular when there are large air-conditioning units on top of them, whereas nearby parks and lakes could be cool. This could considerably affect the measurement of barometric altitude on UAs/aircraft;
- air pressure is not constant but changes over time, so the (regional) QNH does as well. If air pressure is used for de-confliction between different airspace users, UAs may need to be able to change their QNH-setting in-flight;
- the certified resolution of the barometric measurement in airplanes is 25ft, which is very coarse for use in VLL;
- in a normal aircraft the sensors are far away from the propellers, while in a drone the rotors could be quite close to the pressure sensors causing constant changes in pressure and thus difficulties in measuring air pressure.

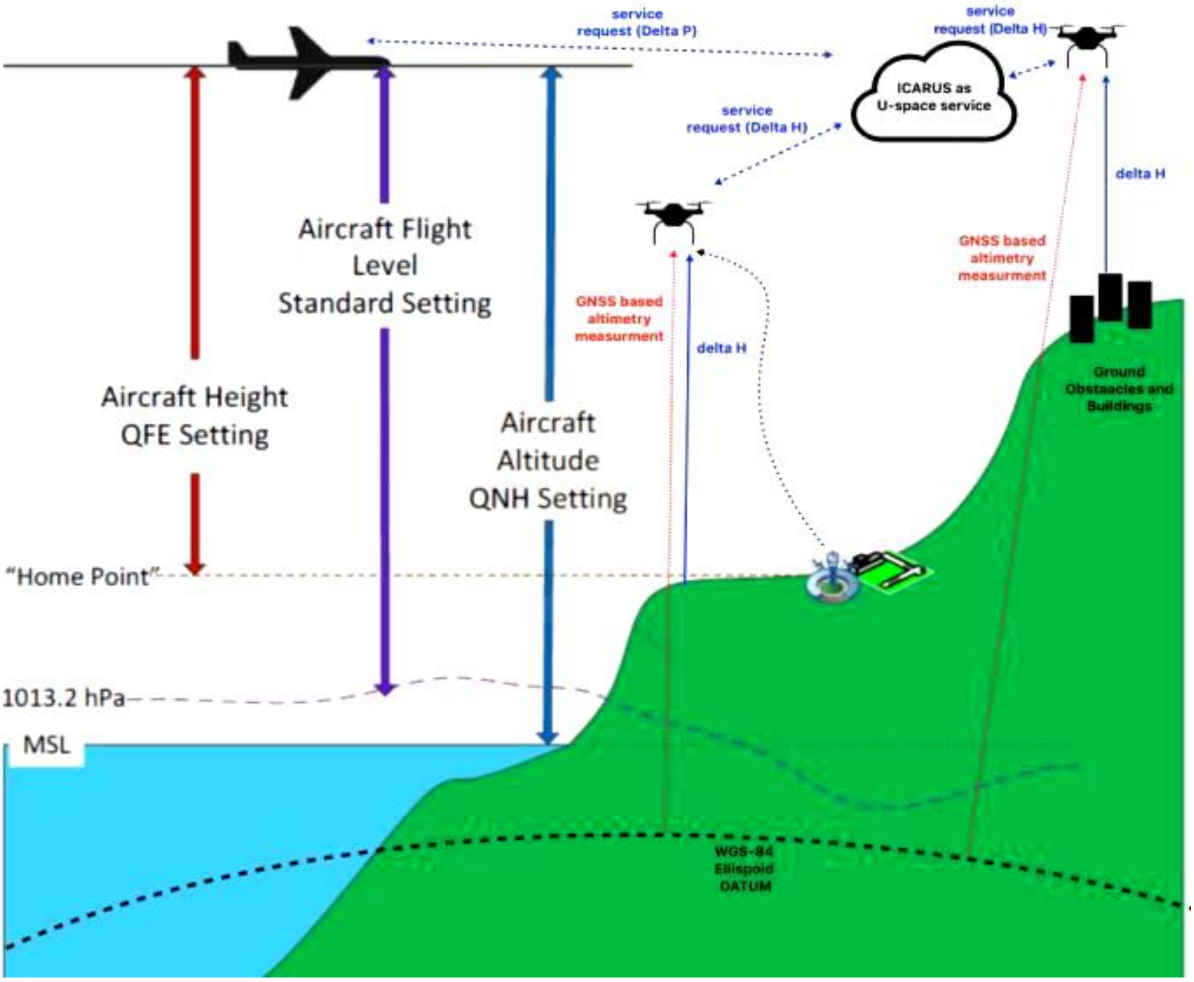


Figure 2-8: different height/altitude measurement options

Taking these considerations in mind, the ICARUS project aims to answer the following questions:

- which technology should be used to measure the altitude at which a UA is flying, and to what precision, accuracy and integrity values?
- which procedural mitigations can be put in place to harmonise the common altitude reference problem for drones, and other users of the same VLL airspace?
- which reference datum should be used to ensure that every user of a given airspace is flying in the same altitude/height reference system?

ICARUS aims to address this challenge by proposing a new approach based on GNSS-based altimetry, providing information to UAS pilots and GA pilots on the actual vertical distance to ground, barometric/GNSS-based altitude translation and flight planning information with regard to ground obstacles and buildings.

ICARUS provides the answer to the previous questions with a service is based on:

- the introduction of GNSS-based altitude measurement for the challenge of a UAS / RPAS vertical common reference datum;

- the provision of a tailored U-space service for ground obstacle mapping and terrain profile information;

- the provision of a height transformation service (geodetic measurement to barometric reference system and vice-versa) as a possible solution for UAS-GA flight integration in VLL airspace.

How will ICARUS work?

- providing remote pilots or drones with the detailed terrain model (DTM) underneath their planned trajectory (Strategic phase-U-Space Flight Planning);

- providing remote pilots or drones with the actual vertical distance from ground (DTM, including buildings and obstacles);

- sharing common altitude datum with other flying drones, in combination with the U-space Tracking service;

- warning general aviation /ultralight pilots flying in VLL airspace about the presence of new “geocentric mandatory zones” (GMZ, i.e. zones where it will be mandatory to set the altimeter in accordance with a geodetic datum, though ONLY outside ATZs and CTRs);

- providing a barometric/geodetic translation service for general aviation/ultralight pilots flying in the GMZ.

ICARUS moves from the possibility of determining height using GNSS in multi-constellation/ multi-frequency/ SBAS mode, with sub-metric accuracy and good performance on the vertical axis. In civil aviation, for example, RNP approaches using EGNOS have their vertical guidance based on the outputs of a GNSS receiver that assures the required vertical protection level, representing a promising opportunity for integration between manned and unmanned aircraft, especially with drones that rely on GNSS for navigation during nominal operations.

Drones for the mass market are developed taking into account the availability of inexpensive GNSS receivers that provide satisfactory performance and are widely adopted in the Open category. The majority of these drones, including low-cost ones, make use of GNSS/SBAS dual constellation receivers as primary navigation sensors, reaching an NSE accuracy in vertical and horizontal position determination of a couple of metres [10]. The majority of GNSS receivers adopt the WGS84 ellipsoid datum (in multiple constellation receivers, PZ-90 for GLONASS and GTRF for GALILEO are generally translated internally by the GNSS receiver firmware) as the standard reference system that will be used to provide the common reference zero altitude to all drones, especially when involved in BVLOS operations. However, the main drawback of this approach for drones comes from the lack of adequate accuracy in the vertical distance from ground, since WGS84 and similar references are based on geometric distance not from surface, but from the Earth’s centre of gravity. The gap is filled thanks to the introduction of cartographic services that can return Detailed Terrain Model (DTM) and ground obstacle data with accepted accuracy and resolution.

The approach proposed in ICARUS foresees the realisation of a DTM service embedded in an Application Program Interface (API) that can be queried by a UAS pilot or operator (or by drone itself) based on the present geographic coordinates of the UA along its trajectory, calculated by the (E)GNSS receiver during the tactical phase (i.e. during the flight). In addition, the DTM service may also be queried in the strategic phase (i.e. flight preparation) if the UAS operator defines the intended trajectory and uploads it with the Flight Plan. The output of the DTM service will provide important information on distance from the ground (including from fixed ground obstacles) in combination with the common altitude reference.

ICARUS services will be made available to third parties (e.g. U-space service providers) through a specific Application Programming Interface (API) and open and interoperable protocols with the following main elements:

- ✓ GNSS-based altimetry as a common reference datum for vertical UAS separation in VLL airspace;
- ✓ In strategic and tactical phases**,** a U-space service capable of providing
    - information on the vertical distance to the ground (terrain, ground obstacles, buildings) and warnings to the manned-aviation pilots near "Geometric Altitude Mandatory Zones";
    - conversion of reference systems for general aviation users;
    - acceptable Information latency (near real time for the tactical phase);
    - cartographic tool integration, 3D terrain model for flight planning;
    - DTM / DSM in the neighbourhood of the planned route with acceptable accuracy and resolution, including buildings in cities and ground obstacles in rural sites, for obstacle and terrain avoidance during the tactical phase.
- ✓ GNSS Integrity service reporting to UAS pilots or drones.

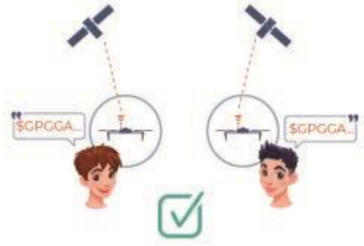
European GNSS technology (Galileo/EGNOS), in combination with the proposed U-space service, can play an important role in terms of accuracy, integrity, availability and continuity to guarantee the Required Navigation Performance (RNP) needed to address this challenge.

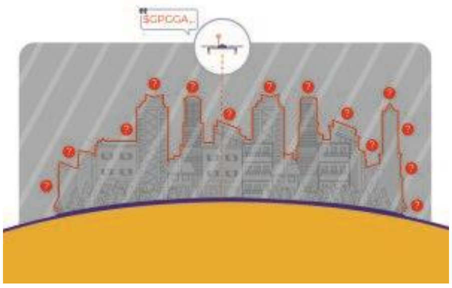
Even if most on-board UAS GNSS receivers implement multi-constellation/dual-frequency Galileo or SBAS positioning algorithms, they are not able to assess the maximum level of GNSS errors that actually affect the Navigation System Error (NSE) during the flight. Thus, they are not able to provide the integrity "protection levels" that are fundamental in safety operations. For this reason, a ground service able to address integrity provision will be implemented in the ICARUS project. This solution empowers low-cost GNSS receivers with EGNOS, providing users with higher levels of positional accuracy and, more important in safety environments, corresponding GNSS integrity values. Using this ground-based augmentation, it is possible to provide a common referenced UAS altitude with a level of error for horizontal and vertical protection to be assessed in the study. Drone operators and U-space actors might use this additional information during operations, for example for obstacle avoidance, thus greatly improving the level of safety, ensuring that drones are maintained, vertically, inside the containment area as defined in the SORA methodology.

2.3.1 High-level ICARUS objectives

ICARUS proposes the use of GNSS receivers with suitable requirements for the common UAS-UAS vertical reference, and the definition of a new U3 U-space service for altitude transformations for common UAS-manned-aircraft reference, tightly coupled with the interface of existing U-space services (e.g. Tracking, and Flight Planning services). Finally, the terrain model information above the ellipsoid datum used in the GNSS receivers, including ground obstacle information, will also be an important element of the study. The users of the ICARUS service will be remote pilots competent to fly UAS operations in VLOS or BVLOS in the Specific category, ultralight and GA pilots potentially sharing the same VLL airspace, and also the drone itself, considering the increased level of automation and connectivity expected at U-space level 3

The high-level objectives of the project can be summarised as follows:

<table>
<tr><td colspan="2">OBJ 1. To define the technical requirements for high accuracy GNSS-based altitude measurement for drones, to enable a reliable and accurate common vertical datum (UAS-UAS).</td></tr>
<tr><td>
</td><td>a. MFMC GNSS receiver requirements (stand-alone or in combination with other technologies - LIDAR, IMUs, radio altimetry, etc.) for the definition of the main navigation indicator figures for determining the vertical component in different operational environments, including cities (integrity, accuracy, continuity, availability of PBN, ICAO 9613 5th edition)
b. To identify possible strategies with respect to GNSS signal integrity, (on-board / U-space service-oriented) for the monitoring of GNSS signal performance, compliant with the economic viability of drones and new business opportunities
c. To explore the added value and differentiators offered by the European GNSS constellation (authentication service and cyber security issues, high accuracy figures on the vertical axis)</td></tr>
</table>

<table>
<tr><td colspan="2">OBJ 2. To investigate the vertical accuracy and resolutions achievable by the current Digital Terrain Model (DTM/DSM) services for ground obstacles clearance (UAS-Ground Obstacles).</td></tr>
<tr><td>
</td><td>a. a GNSS-based approach for vertical separation of UAS from the ground requires a calculation of the height above ground, possibly achieved using a look-up table, or map (U-space mapping service, strategic phase). Trade-off accuracy against size, cost, on-board calculation.
b. Survey about actual available DTM/DSM models (Global DEMS, Regionals, European, etc.) including aeronautical ground obstacles</td></tr>
</table>

	c. Gap analysis: investigation of possible standardisation activities related to new sources of information (different public/ private databases) for ground obstacles outside airports, and data models to feed a U-space mapping service.

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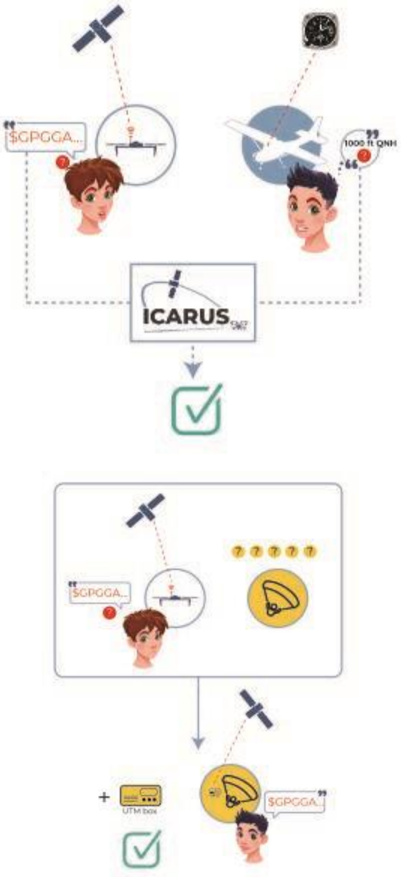
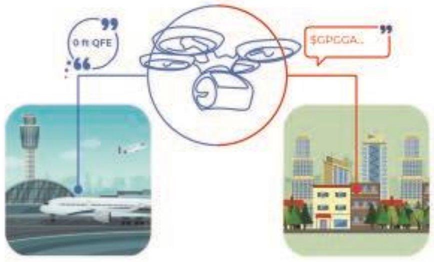
OBJ 3. To design a tailored U-space service for height transformation: geodetic measurement to a barometric reference system and vice-versa for UAS and manned aircraft (UTM/ATM interface, Class G Airspace)	
	a. Define the input and output parameters of the proposed service for the different actors (drone, drone pilot, GA pilot, ultralight pilot) and the additional information needed by the service for real-time optimal performance (METAR stations, GNSS ground geodetic and monitoring network) b. Identify possible ways for altitude translation service delivery with respect to class of the Airspace (X, Y, Zu, G, D) and the airspace actors expected (i.e. 5G for drones, VHF for GA pilots) c. Investigate and define the concept of “Geometric Altitude Mandatory Zones”: VLL Zones where it will be mandatory for airspace users - of manned and of unmanned aircraft - to set the altimeter to a geodetic altitude rather than barometric (no translation service is needed in these zones) d. Propose a mechanism for defining a common altitude reference system for ultra-light users as well, through the exploitation of U-space services (tracking service) and GNSS technology (common altitude reference)

OBJ 4. To Foster the safest possible system for a common altitude reference system to address the needs of UAS, manned flights and new Urban Air Mobility actors (i.e. air taxis), paving the way for the enhancement of the VLL capacity and UAS separation for future BVLOS applications.

	a. Propose possible solutions to the common altitude reference system in ATZ / Zu airspaces as well, through the help of use cases considering the new air taxis b. Propose a final ConOps for the CARS concept.

The high-level objectives identified will be investigated with the help of five use cases (chapter §6), envisaged to emphasise the very specific aspects of each project objective.

As already said Icarus will be conceived with a micro-service architecture where the main services are:

- Accurate cartography, DTM / DSM, 3D model of the ground obstacles in the strategic phase of flight (Flight planning service) and during the execution of flight (tactical phase), to provide real-time information of vertical distance to the ground
- Information service: warning to a manned aviation pilot when crossing (or near) the limit of a new "Geometric Altitude Mandatory Zone" and related advice (Automatic translation and readings of barometric height to altitude), in combination with conversion of reference systems (barometric to geodetic and vice-versa) to address the harmonisation of general aviation users
- Vertical alert service over the common reference system defined alerting drones on actual vertical distance from ground
- GNSS Signal Monitoring and Positioning and Integrity service reporting enhanced accuracy, performance estimation and integrity to UAS pilots or drones

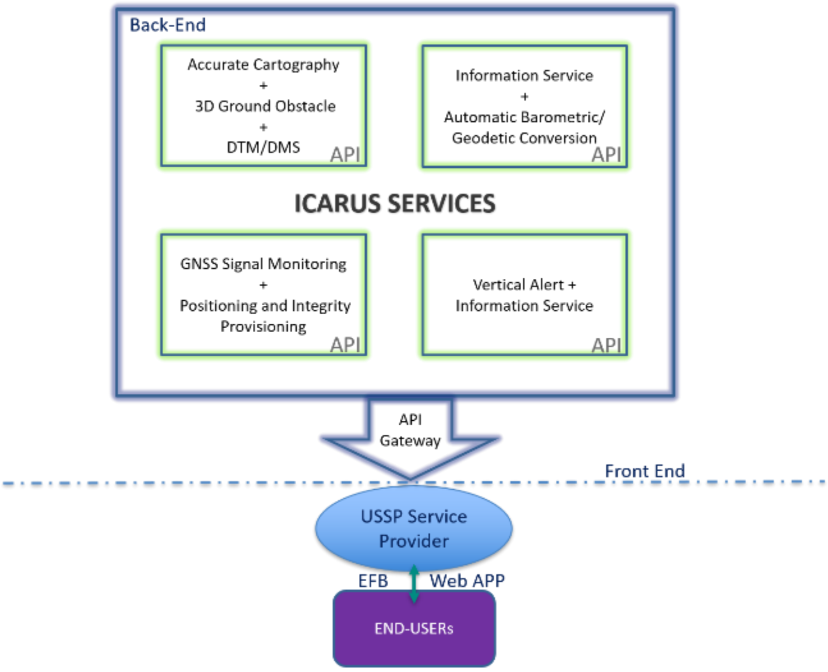


Figure 2-9: High Level Microservice architecture scheme

The proposed approach in ICARUS foresees the realization of DTM service embedded in an Application Program Interface (API) that can be queried by UAS pilot or UAS Operator (or by drone itself) based on the present geographic position coordinates of the UA along its trajectory, calculated by the (E)GNSS receiver during the tactical phase (i.e. during the flight). In addition, DTM service may be queried also in the strategic phase (i.e. flight preparation) having the UAS operator defined the intended trajectory and uploaded it, with the Flight Plan). The output of the DTM service would provide valuable information on distance from ground (including from fixed ground obstacles) in combination with the common altitude reference.

The GNSS Services providing users higher levels of accuracy in the position solution and, more important in safety environments, related GNSS integrity values will help drone operators and UTM actors with additional information for obstacle avoidance, tactical deconfliction and other flight operations requiring a high level of safety. In the following paragraphs brief summaries of the micro services will be done.

2.4 High-level description of main ICARUS building blocks

The following chapters give a detailed analysis of the main components of the ICARUS service, in particular:

- GNSS Positioning, Integrity, and Signal Monitoring to identify the best GNSS service algorithm and architecture to guarantee the Required Navigation Performance
- Currently available digital Terrain model & Ground obstacle data service to:
    - analyse the current management of terrain models and ground obstacles in the ATM domain;
    - evaluate different available methodologies and geo-spatial data describing terrain (DTM / DSM, points clouds, 3D models)
- Currently available Precision Height Systems & frames to analyse the state of the art of the modelled height systems and frames available, as well as their connections.
- ICARUS requirements analysis to identify the requirements of the envisaged ICARUS service in terms of:
    - Navigation requirements for GNSS-based altimetry (Accuracy, Precision, Integrity, Continuity) and key enabling technologies
    - DTM / DSM requirements for accuracy and resolution of the model;
    - Performance of Navigation (e.g. need for a GNSS Performance monitoring service)
    - Operational requirements and Safety requirements.
- Gap Analysis & Gap-filling service to identify the gaps needing to be filled the between the current state of art and the future ICARUS state, from technological, operational and safety points of view.
- Preliminary Safety Assessment & compliance with EU regulations to make a preliminary safety assessment of the use-cases envisaged, including a check for compliance with current EU regulations
- Overall Error Budget: error correlation analysis and estimation regarding:
    - Digital terrain model, digital surface model, ground obstacles
    - Navigation system error
    - Height system conversion error
    - Flight technical error

Finally, the theoretical errors identified are verified through field trials.

3 GNSS Positioning, Integrity, and Signal Monitoring

The use of GNSS for drone positioning is essential, thanks to the worldwide availability and continuity of this technology in the provision of positioning services. The improvement in terms of accuracy of the consolidated constellations (GPS) [11][12], and the spatial and frequency diversity guaranteed by the new reliable and accurate constellations deployed (i.e. Galileo) [13][14], make this technology even more promising and provide better performance. Moreover, the existing augmentation technologies allow high levels of accuracy and reliability to be reached: during the execution of BVLOS operations, GNSS (possibly augmented) is the preferred choice for navigation.

Before describing the main technical solutions, some specific definitions are provided below [16]:

- **Accuracy:** The accuracy in the position of a craft at a given time is the degree of conformance of that position with the true position. Since accuracy is a statistical measure of performance, a statement of navigation system accuracy is meaningless unless it includes a statement of the uncertainty in position that applies. For instance, civil aviation requirements tend to measure accuracy at the 95th percentile. From a system performance perspective, accuracy is understood to be a global system characteristic and is evaluated in post-processing.
- **Integrity:** Integrity is the measure of trust that can be placed in the correctness of the information supplied by a navigation system. Integrity includes the ability of the system to provide timely warnings to users when the system should not be used for navigation. Integrity requirements, applied to a safety context, refer to percentiles that range between 99.999% and 99.9999999% (depending on the particular topic under consideration). Moreover, integrity requirements involve alarms being raised when a system's performance is bad enough to become risky. Unlike accuracy, integrity is rather intended as real time decision criterion for using or not using the system. Integrity is defined by a set of parameters:
    - **Alert Limit:** The alert limit for a given parameter measurement is the error tolerance not to be exceeded without issuing an alert.
    - **Time to Alert:** The maximum allowable time elapsed from the onset of the navigation system being out of tolerance until the equipment initiates the alert.
    - **Integrity Risk:** The probability that, at any moment, the position error exceeds the alert limit.
    - **Protection Level:** Statistical error bound computed to guarantee that the probability of the absolute position error’s exceeding said number is smaller than or equal to the target integrity risk.
- **Continuity:** The continuity of a system is the ability of the total system (comprising all elements necessary to maintain craft position within the defined area) to perform its function without interruption during the intended operation. More specifically, continuity is the probability that the specified system performance will be maintained for the duration of a phase of operation, presuming that the system was available at the beginning of that phase of operation.
- **Availability:** The availability of a navigation system is the percentage of time that the services of the system are usable (i.e. the performances of the system are within the requirements) by

the navigator. Availability is an indication of the ability of the system to provide usable service within the specified coverage area.

3.1 State of the art

Drones often use GNSS for positioning purposes. An increasing number of manned commercial flights also use GNSS-based information. However, they use barometric pressure to ensure vertical separation between aircraft.

The use of GNSS for the determination of altitude has several strengths:

- Accuracy is improved (see the following paragraphs for details).
- Altitude is computed in a geodetic reference frame, allowing the use of a common reference datum for all the objects sharing the same airspace. This may be a good mechanism for defining a common altitude system in VLL airspace and for assuring separation between flying objects.
- A computed position is not prone to errors due to temperature or pressure gradients.

However, the main weakness of GNSS-based technologies is the lack of a simple, low-cost assessment of the level of positioning errors that affects NSE, a relevant component of the overall Total System Error (TSE). This will be treated in more depth in the following paragraphs.

Besides classical visual and inertial techniques, the main GNSS-based technologies currently used for positioning and navigation of drones are:

1. Stand-alone GNSS
2. Augmented GNSS
3. Navigation via Signals of Opportunity, an experimental navigation technique that make use of signals coming from several different sources. This was not necessarily conceived for navigation and will not be addressed in present work.

3.1.1 Standalone GNSS

Standalone GNSS positioning is the most basic and cheapest solution. It provides free global access to solution computation; a large number of very cheap receivers can easily be found for the mass-market. In its most basic configuration, a GNSS receiver can process single-frequency measurements from a single constellation (the most widely used is obviously GPS).

The GPS SPS PS [11] states that "well-designed GPS receivers have been achieving horizontal accuracy of 3 metres or better and vertical accuracy of 5 metres or better 95% of the time". The Performance Analysis Reports [12], based on the measurements of a network of reference stations, assures even better figures: the report of April 2020 observes an average vertical accuracy of 4 metres and an average horizontal accuracy of 2 metres (95th percentile). In the same report, the availability of the positioning solution is 100% of the time. On the other hand, these promising figures have several drawbacks:

1. GPS is a USA military service, that can be switched off or its performances can be intentionally degraded if USA DoD considers it necessary.

2. Its geometry – and hence its performance – can be heavily degraded, especially in low visibility conditions (presence of obstacles, urban canyons, etc). In fact, the promising figures mentioned above are obtained by fixed stations with calibrated receivers and supposedly optimum sky visibility.
3. Computation of the single frequency solution is prone to disturbance (e.g. ionospheric delay).
4. The GPS SPS PS does not provide guarantees that allow reliable solutions. In fact, the performance bounds are so loose (8 m horizontal accuracy, 13 m vertical accuracy, 95% of the time), that it could be defined a "best effort"; moreover, there are no actual guarantees regarding satellite failure: so far, satellite/constellation failure probabilities have been extrapolated from historical data series.

The means of improving the performance of the standalone GNSS solution, without involving augmentation systems, are:

1. Including other GNSS constellations (Galileo, Beidou, Glonass) to increase the number of visible satellites (and hence the solution availability, especially in a harsh environment) and improve the Dilution of Precision (and hence the accuracy). Multi-constellation receivers are required for this.
2. Processing dual-frequency observables (ionosphere-free combination) to improve the accuracy of solution (but this kind of processing degrades the accuracy, since the combination increases the noise). Dual frequency receivers are required.
3. Processing carrier phase observables to reduce the impact of noise, thereby improving the precision and the accuracy), with the cost of an initial unavailability of the solution (convergence time of the filters in case of smoothing application, ambiguity resolution for PPP/RTK methods). Receivers that provide continuous, reliable, and stable carrier phase measurements are required.

In particular, the inclusion of the Galileo constellation brings the following advantages:

1. As previously stated, the geometry and the availability of signals is improved, both in terms of satellite and frequency diversity. (The satellites in the Galileo constellation broadcast signals on four frequencies: E1, E5a, E5b, E6).
2. Galileo is a civilian and Europe-controlled system with no political issues, free access, and worldwide coverage.
3. Even if relatively young, Galileo has promising performances [14] and guaranteed results [13]: in the last performance report (January-March 2020), the average 95th percentile of the positioning error for dual frequency processing was slightly more than 1.6 metres for the horizontal component and about 3 metres for the vertical component. Fewer than 0.01% were outliers exceeding 20 metres of error.
4. In the short-medium terms, two additional Galileo services will be available to the user community:
    - High Accuracy Service (HAS): this should bring the positioning performance close to those reached by Precise Point Positioning (PPP) processing (< 20 cm, 95% error – see section 3.1.2.2), including an Authentication Service. It will be necessary to have qualified and enabled receivers on the E6 band, and the service will be free of charge.

In the current state, the provisioning of the initial HAS is envisaged after the end of the testing and experimenting phase that will begin by the end of 2020.

- Open Service Navigation Message Authentication (OS NMA): this will provide a guarantee to the user regarding the received and demodulated navigation message, protecting against certain kinds of malicious attack (spoofing, meaconing). The authentication codes will be included in the I/NAV navigation message on the E1 band, in an expressly reserved field.

However, the use of standalone, non-augmented GNSS for drone positioning and navigation should be discouraged, since it has many disadvantages and weaknesses:

1. GNSS signals, if used without precaution, are vulnerable to malicious actors: jamming, spoofing, meaconing, etc.;
2. GNSS signals are vulnerable to multipath and unintentional interference;
3. Vulnerability to system faults (ground segment faults, satellite failures, signal generation failure) or Signal in Space propagation errors (e.g. adverse space weather that generates ionospheric storms, anomalous troposphere) without provision of timely warning to the user;
4. Loose guarantees for Signal in Space accuracy

There are no indications regarding the integrity of such a solution, and the guaranteed accuracy is too low, at least for safety-critical and liability-critical applications.

3.1.2 Augmented GNSS

3.1.2.1 Real-Time Kinematics (RTK)

Real Time Kinematics is a differential GNSS method that uses carrier-phase measurements and provides high levels of accuracy (a few centimetres) when near to a reference station whose position is well known. This station provides corrections to the “observation space representation”. Since the goodness of these differential corrections is related to the distance between reference station and the moving receiver, the service is offered at a local level.

The service is generally offered by private providers (Trimble, Topcon, Fugro) or public authorities (IGN, CUZK): the payment of a fee is required. Autonomous and expensive in-situ base station installation (requiring long set-up) are available. Many drones are equipped with RTK-ready receivers.

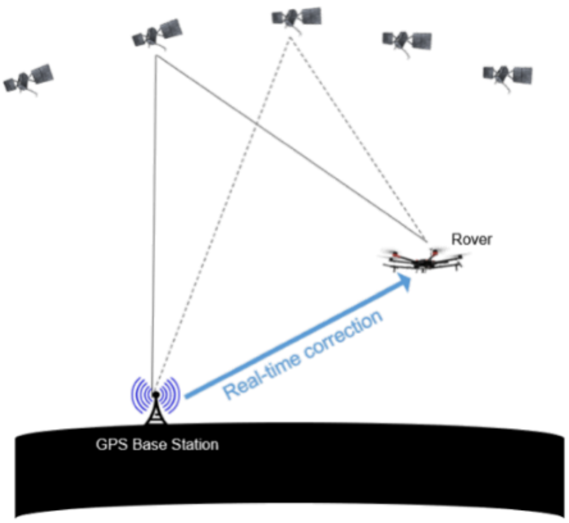


Figure 3-1: RTK architecture

The main weaknesses of RTK techniques are the necessity of a real-time data link between the base station and the drone to receive the corrections, and the geographic limitation of the solution. Moreover, pricing and convergence time can be an obstacle to its use. However, the most important problem is that no integrity can be provided (although there has been some scientific research in this direction), therefore there is no warranty nor quantification on the correctness of the positioning solution.

3.1.2.2 Precise Point Positioning (PPP)

Precise Point Positioning is a method of achieving high-accuracy positioning solution, in the order of tens of centimetres. Unlike RTK, the corrections of PPP are in the "state space representation": the broadcast navigation message is replaced with precise data timely provided by an external source (requiring a fee) with global coverage. The receiver then models and estimates the residual errors (usually related to local effects). Hence, there is no need of a base or reference station.

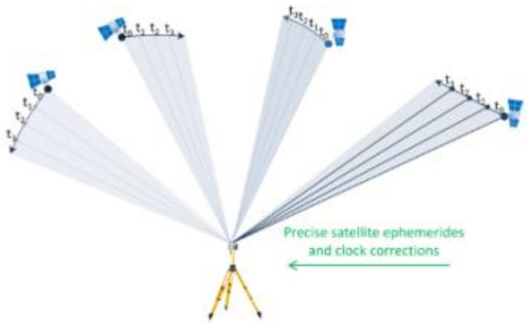


Figure 3-2: Precise Point Positioning (PPP)

PPP uses carrier phase measurements, and Kalman filters for the estimation of several parameters. Since it has a long convergence time, PPP is usually used for post-processing in batch mode or with a receiver with low dynamics, and its use in real-time dynamic applications is discouraged. As with RTK, its main disadvantages, besides its long convergence time, are its cost and its lack of provision of integrity parameters.

3.1.2.3 Satellite-Based Augmentation Systems (SBAS)

Satellite-based Augmentation Systems (SBAS) are systems that support wide-area or regional - even continental scale - augmentation using geostationary Earth-orbit (GEO) satellites that broadcast the augmentation information. These systems have been developed to provide safety-critical augmentation to civil aviation. An SBAS augmentation consists of:

1. GEO ranging measurements (on the L1 frequency);
2. correction information (satellite's clock and ephemeris, ionosphere, etc.);
3. integrity information.

While the main goal of SBAS is to provide integrity assurance, it also increases the accuracy with position errors below 1 metre (1 sigma). SBAS systems are standardised at International Civil Aviation Organisation (ICAO) level to ensure interoperability; standards, requirements and specifications are described in ICAO Standards and Recommended Practices (SARPS) [17] and Radio Technical Commission for Aeronautics (RTCA) Minimum Operational Performance Standards (MOPS) / Minimum Aviation System Performance Standard (MASPS) [18][19]. See also [20].

SBAS is composed of:

1. Space segment, comprising one or more geostationary satellites with navigation payloads broadcasting:
    a. Ranging signal
    b. Wide Area Differential corrections
    c. GNSS/Ground Integrity Channel
2. Ground segment, comprising all the components necessary for the monitoring and processing of the GNSS signal to generate the corrections and the integrity messages, and the facilities for uploading the navigation content to the GEO satellites:
    a. Monitoring Station Network - tens of reference stations carefully distributed on the service region
    b. Processing Facility Centre – a centralised centre that computes the corrections and the integrity parameters
    c. GEO Satellite Control Centre - centralised centre that generates the signal with the message provided by the Processing Facility Centre and up-linking it to the GEO satellites
    d. Communication Layer – interconnects the different elements of the Ground Segment
3. User Segment, comprising all the craft equipped with SBAS-certified receivers.

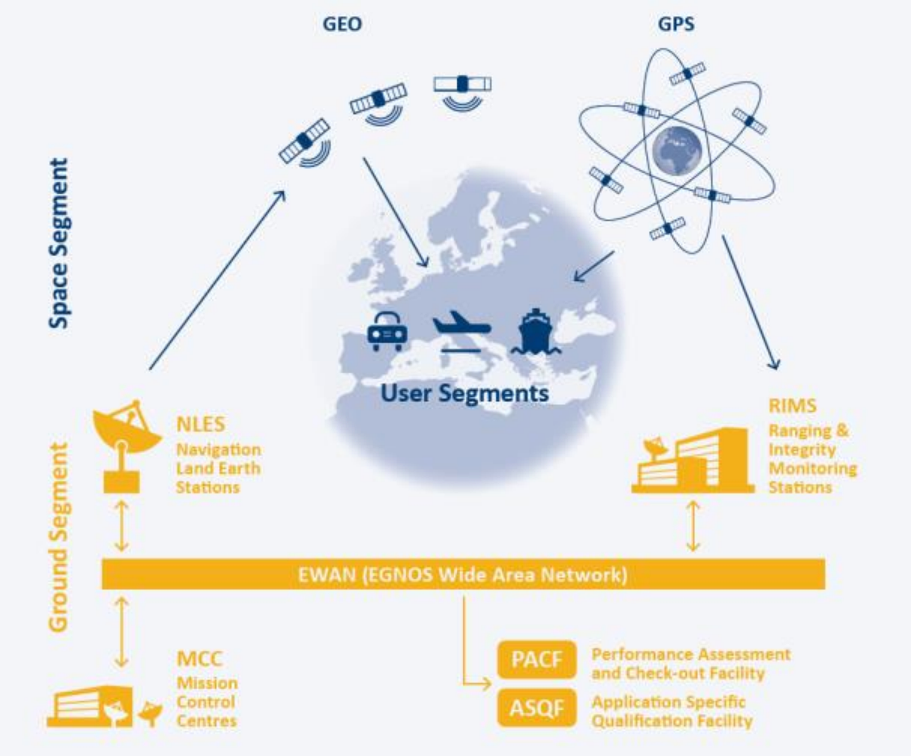


Figure 3-3: SBAS architecture (EGNOS case)

Currently, there are five operational SBAS systems available, each covering a different region (EGNOS over Europe, WAAS over North America, MSAS over Japan, GAGAN over India, and SDCM over Russia).

In the following, the focus is obviously on European SBAS (EGNOS). Currently, the EGNOS footprint covers Europe, providing APV-1 required performance with availability more than 99% of the time [21].

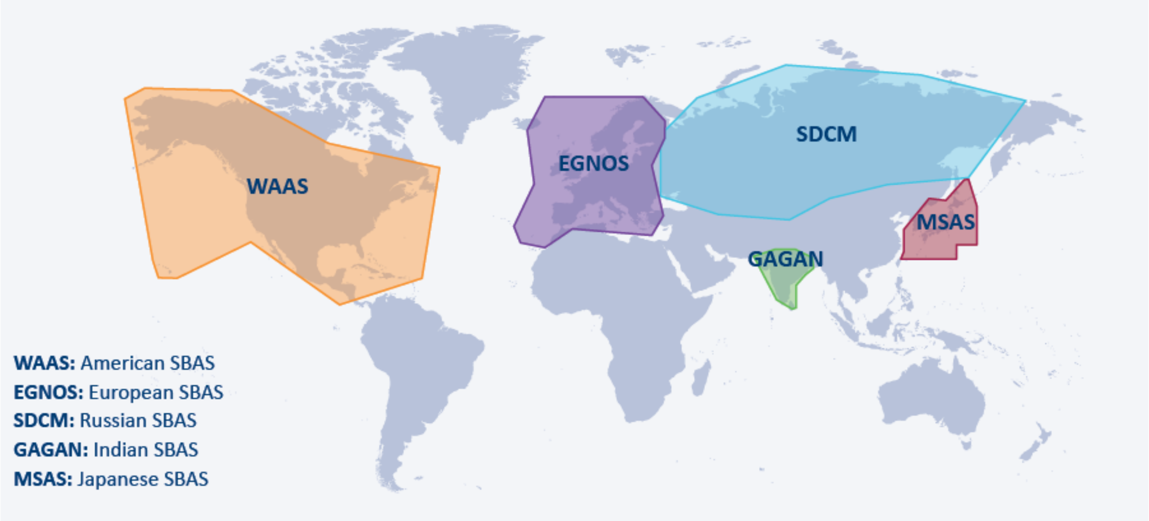
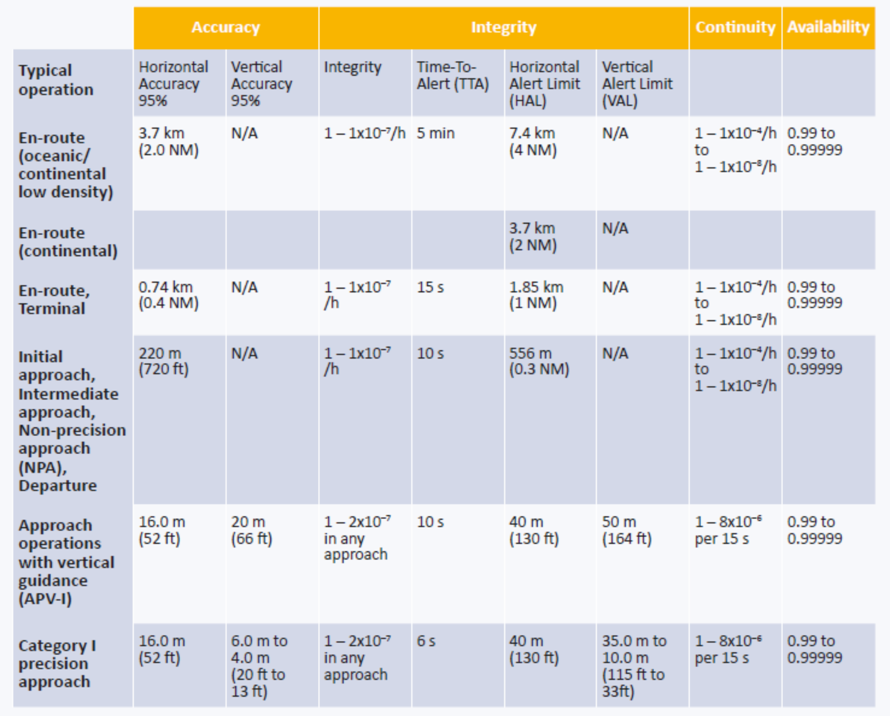
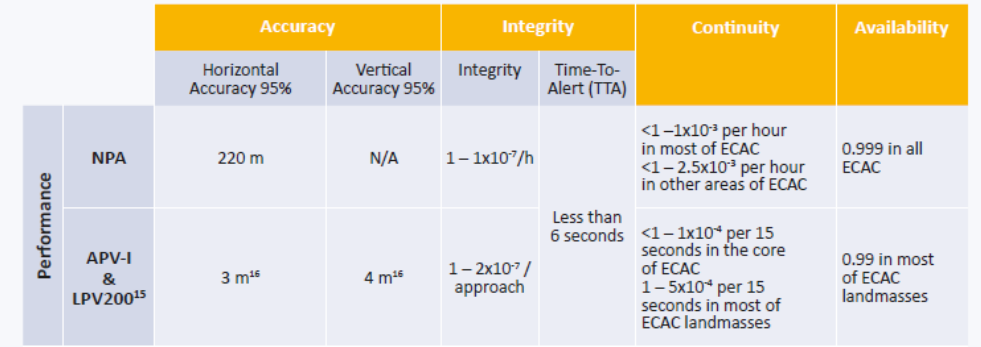


Figure 3-4: Existing SBAS systems



	Accuracy		Integrity				Continuity	Availability
Typical operation	Horizontal Accuracy 95%	Vertical Accuracy 95%	Integrity	Time-To-Alert (TTA)	Horizontal Alert Limit (HAL)	Vertical Alert Limit (VAL)		
En-route (oceanic/ continental low density)	3.7 km (2.0 NM)	N/A	$1 – 1x10^{-7}$/h	5 min	7.4 km (4 NM)	N/A	$1 – 1x10^{-4}$/h to $1 – 1x10^{-8}$/h	0.99 to 0.99999
En-route (continental)					3.7 km (2 NM)	N/A		
En-route, Terminal	0.74 km (0.4 NM)	N/A	$1 – 1x10^{-7}$ /h	15 s	1.85 km (1 NM)	N/A	$1 – 1x10^{-4}$/h to $1 – 1x10^{-8}$/h	0.99 to 0.99999
Initial approach, Intermediate approach, Non-precision approach (NPA), Departure	220 m (720 ft)	N/A	$1 – 1x10^{-7}$ /h	10 s	556 m (0.3 NM)	N/A	$1 – 1x10^{-4}$/h to $1 – 1x10^{-8}$/h	0.99 to 0.99999
Approach operations with vertical guidance (APV-I)	16.0 m (52 ft)	20 m (66 ft)	$1 – 2x10^{-7}$ in any approach	10 s	40 m (130 ft)	50 m (164 ft)	$1 – 8x10^{-6}$ per 15 s	0.99 to 0.99999
Category I precision approach	16.0 m (52 ft)	6.0 m to 4.0 m (20 ft to 13 ft)	$1 – 2x10^{-7}$ in any approach	6 s	40 m (130 ft)	35.0 m to 10.0 m (115 ft to 33ft)	$1 – 8x10^{-6}$ per 15 s	0.99 to 0.99999

Figure 3-5: SoL service performance requirements (ICAO)



		Accuracy		Integrity		Continuity	Availability
		Horizontal Accuracy 95%	Vertical Accuracy 95%	Integrity	Time-To-Alert (TTA)		
Performance	**NPA**	220 m	N/A	$1 – 1x10^{-7}$/h	Less than 6 seconds	$<1 –1x10^{-3}$ per hour in most of ECAC $<1 – 2.5x10^{-3}$ per hour in other areas of ECAC	0.999 in all ECAC
	APV-I & LPV200[15]	3 m[16]	4 m[16]	$1 – 2x10^{-7}$ / approach		$<1 – 1x10^{-4}$ per 15 seconds in the core of ECAC $1 – 5x10^{-4}$ per 15 seconds in most of ECAC landmasses	0.99 in most of ECAC landmasses

Figure 3-6: EGNOS SoL Service performance values

Moreover, the EGNOS Data Access Service (EDAS) offers ground-based access to EGNOS data through the internet on a controlled access basis. EDAS is the point of access for the data collected and generated by the EGNOS ground infrastructure. EDAS provides the same data that is broadcast by the EGNOS satellites (EGNOS Message) in near real-time, together with the raw data, and allows users to plug into EGNOS ground infrastructure to receive the data collected, generated and delivered by the EGNOS system. In this way, EDAS delivers EGNOS data to users who cannot always view the EGNOS satellites (such as those in urban canyons) or to support a variety of other value-added services, applications and research programmes.

The first drawback of an SBAS system is the cost of the receiver. There are low-cost receivers on the market capable of acquiring an SBAS signal and applying some corrections: nevertheless, the safety-enabled receivers, that allow the integrity messages to be processed and are capable of generating integrity parameters, are expensive (because of the necessary MOPS certification).

A second weakness is that current SBAS systems only provide augmentation services for single-frequency (L1) GPS signals: the possibilities offered by frequency and constellation diversity are not exploited. There are evolutions in progress, but since SBAS is related to aeronautics safety applications, its development strictly controlled and regulated, and hence it has to be considered in a long-term perspective.

3.1.2.4 Ground Based Augmentation Systems (GBAS)

A Ground-Based Augmentation System (GBAS) is a civil-aviation safety-critical system that supports local augmentation at the airport level by providing enhanced levels of service that support all phases of approach, landing, departure and surface operations. While the main goal of GBAS is to provide integrity assurance, it also increases accuracy, with position errors below 1 m (1 sigma), reached by processing differential corrections received by the aircraft through a dedicated VHF channel. As SBAS, GBAS systems are standardised at ICAO level; standards, requirements and specifications are described in ICAO SARPS [17] and RTCA MOPS and MASPS [22][23]. See also [24].

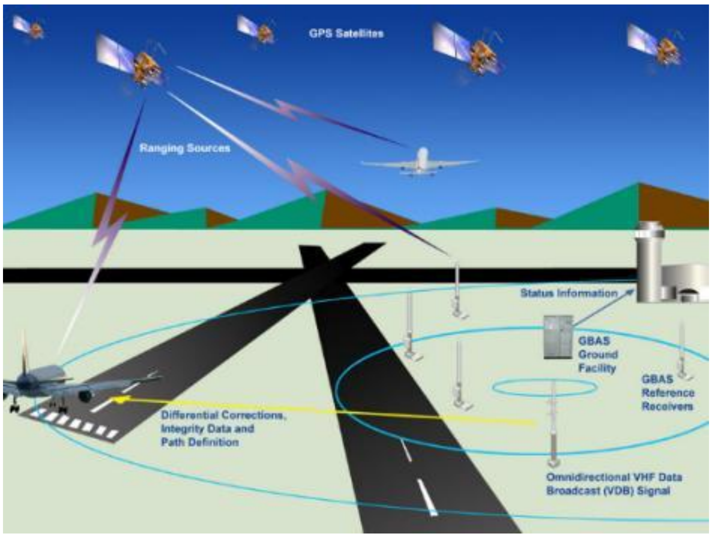


Figure 3-7: GBAS architecture

Like SBAS, currently deployed GBAS systems only provide augmentation services for single-frequency (L1) GPS signals, although several experimental multi-constellation, multi-frequency GBAS systems are under deployment in different US and European airports: the possibilities offered by frequency and constellation diversity is not exploited. There are evolutions in progress, and the development has to be considered in a medium/long-term perspective.

Moreover, there are no mass-market receivers that support GBAS, a technology tightly linked to the aeronautics world; the installation of the system (2-4 reference receivers + master station + VHF data transmitter) is very expensive and long, and limited to the perimeter of airports.

3.1.2.5 Airborne Based Augmentation Systems (ABAS)

Airborne Based Augmentation Systems (ABAS) are avionic solutions that process GNSS signals together with other on-board sensor information to provide integrity and/or improve accuracy. The main strength of such systems is that they do not need the implementation of complex or expensive architectures or to wait for the slow deployment of new systems from other external providers (as is the case for GBAS/SBAS).

The most widely used techniques belong to Receiver Autonomous Integrity Monitoring (RAIM) family. The underlying idea is to use measurement redundancy to compute integrity parameters and perform "Fault Detection and Exclusion", i.e. to identify and exclude faulty satellites from the Position-Velocity-Time (PVT) solution. There are many different kinds of RAIM algorithm, with tens of implementations: range-comparison RAIM, parity-method RAIM, least-square-residual RAIM, solution-separation RAIM, etc.

The introduction of new frequencies and constellations makes the research move towards promising Advanced RAIM (ARAIM) techniques, allowing exploitation of the advantages of diversity to improve accuracy and availability, and provide integrity. The ARAIM technique belongs to the "Multiple Hypothesis Solution Separation" methods family. Unlike traditional RAIM methods, conceived for single-frequency (L1) GPS measurements, ARAIM uses dual frequency and multi-constellation inputs, and requires some external data provisioning. The Integrity Support Message (ISM), whose rate, channel and provider are not yet defined, is still under discussion. In its current state, the content of the ISM is foreseen to change slowly, and therefore it could also be experimentally pre-loaded just before the flight. It should be underlined that ARAIM is tailored to the manned aviation domain, with stringent safety requirements, but it is not yet standardised, so it can be still tailored (easily, compared with other techniques) to other domains.

The main strength of ARAIM is that it is the first "available" and "ready" technique that allows integrity parameters to be computed, exploiting low-cost multi-constellation, multi-frequency receivers, without the need for implementing complex or expensive architectures. At the same time, its performance still needs to be evaluated extensively in an operational context (especially in harsh environments). For more details regarding the algorithm, refer to [25][26][27][28][29][30].

3.2 Objectives

From a navigation point of view, the main objective of the project is to provide an adequate reliable, accurate and timely drone positioning service to the entities that interact in the operational scenario. In this way, the ICARUS service will guarantee the ability to have full situational awareness, and reliable and accurate control and tracking, providing height measurements through a common altitude reference system (WGS84). Rather than focusing on extreme accuracy improvements, the system will provide a reliable positioning service, hence an integrity computation (i.e. protection levels) becomes essential, to guarantee the requested RNP.

Independently from the architecture implemented (see proposed architectures in chapter 3.2.1), two algorithmic solutions can be installed in Telespazio's Computing Unit (see chapters 3.2.2 and 3.2.2.2).

3.2.1 Proposed solution: possible architectures

Depending on the use cases and specifically on the hardware capabilities of the drone equipment (i.e. whether a reliable stable data communication channel can be established and whether the drone's receiver can provide raw GNSS measurements), four different architectures can be implemented.

In case 1, the drone's GNSS receiver is able to provide raw GNSS measurements in real-time. These measurements are sent to Telespazio's Computing Unit, that also collects the EDAS data and the raw measurements from a trusted network of sensor stations (ASI, IGS, EUREF). The Computing Unit will then compute the drone's PVT solution, together with its integrity parameters. At the same time, the Unit will evaluate the GNSS performance of the monitoring stations nearby. The possible system states are given in Table 3-1.

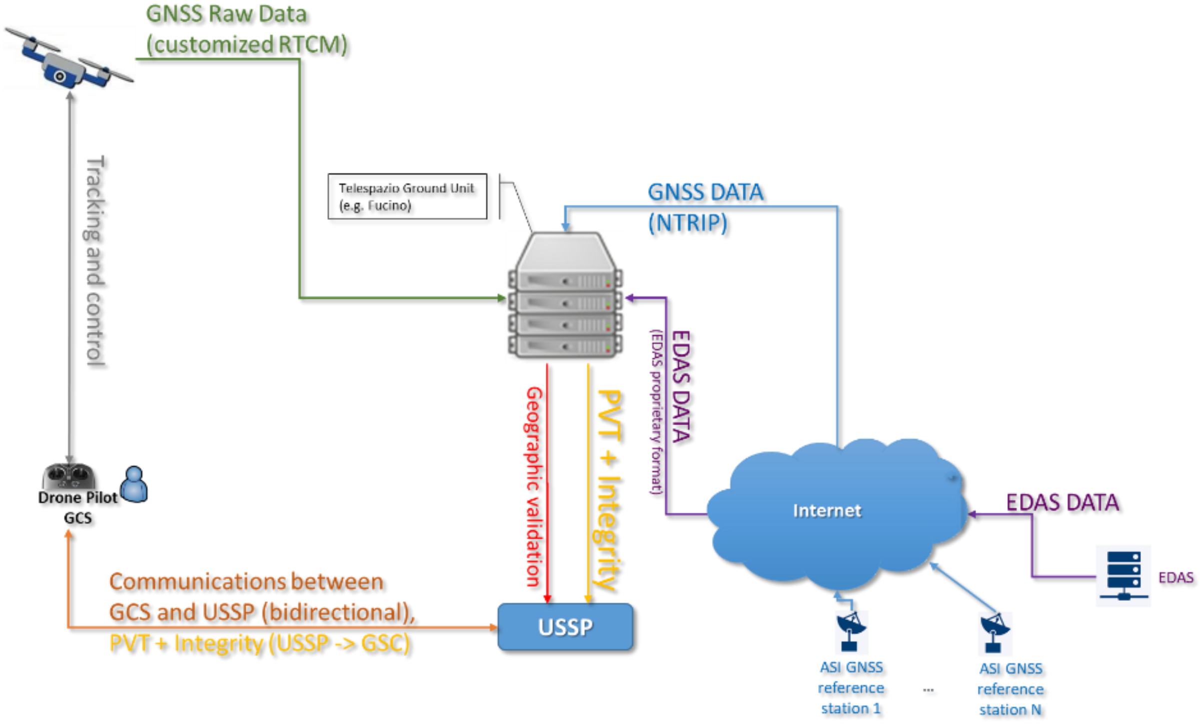


Figure 3-8: case 1 - receiver providing raw GNSS measurements

Status nr.	PVT + integrity solution status (drone)	Monitored parameters status (regional)	GNSS solution status (overall)
1	OK	OK	OK Normal condition
2	OK	Not OK • integrity estimation raises alert, and/or • SiS problems in area	WARNING Working without guarantees (should never happen)
3	Not OK • no PVT provided, or • integrity alert raised	OK	ALERT Local problem: • Obstacles blocking signal • Multipath • Interference • Spoofing • Meaconing • Receiver failure
4	Not OK • no PVT provided, or • integrity alert raised	Not OK • integrity estimation raises alert, and/or • SiS problems in area	ALERT Not working, as expected

Table 3-1: Possible status of the solution (case 1)

In case 2, the drone's GNSS receiver is not able to provide raw GNSS measurements in real-time, and therefore it computes its PVT solution independently, providing it autonomously to the system or through the pilot's cockpit interface. Telespazio's Computing Unit then collects the EDAS data and the raw measurements from the same trusted network of sensor stations. The Computing Unit will only compute the integrity parameters, extrapolating them from the reference stations, evaluating the GNSS performance nearby at the same time. The possible system states are given in Table 3-2.

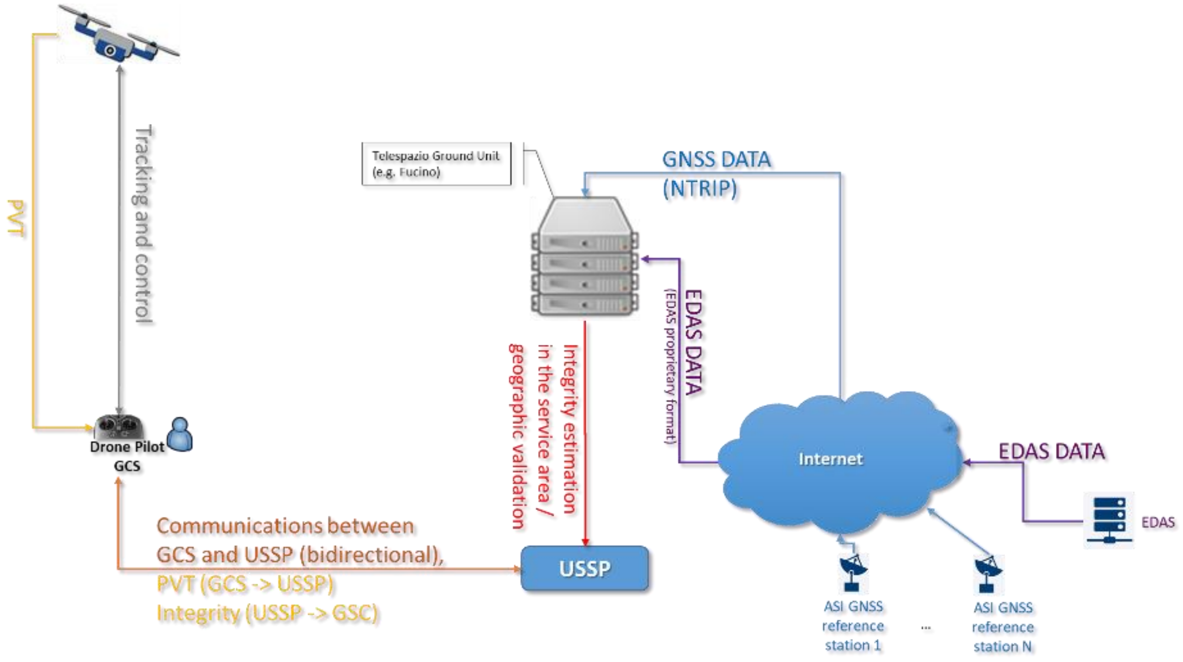


Figure 3-9: case 2 - receiver not providing raw GNSS measurements

Status nr.	PVT solution status (drone)	Monitored parameters status (regional)	GNSS solution status (overall)
1	OK	OK	OK Normal condition (unless there is an undetected local failure)
2	OK	Not OK • integrity estimation raises alert, and/or • SiS problems in area	ALERT The PVT solution has not to be used!
3	Not OK does not provide PVT	OK	ALERT Local problem: • Obstacles blocking signal • Multipath • Interference • Spoofing

			• Meaconing • Receiver failure
4	**Not OK** does not provide PVT	**Not OK** • integrity estimation raises alert, and/or • SiS problems in area	**ALERT** Not working, as expected

Table 3-2: Possible status of the solution (case 2)

In case 3, the drone's GNSS receiver is part of an "evolved" box, consisting of an embedded microcomputer (e.g. Raspberry Pi) connected with communication and positioning modules. In this case, the drone is able to host part of the software developed for Telespazio's Computing Unit, becoming capable of providing GNSS-based positioning and integrity. At the same time, the external unit will host the software dedicated to the evaluation of the GNSS performance of the monitoring stations nearby. The possible system states are given in Table 3-3.

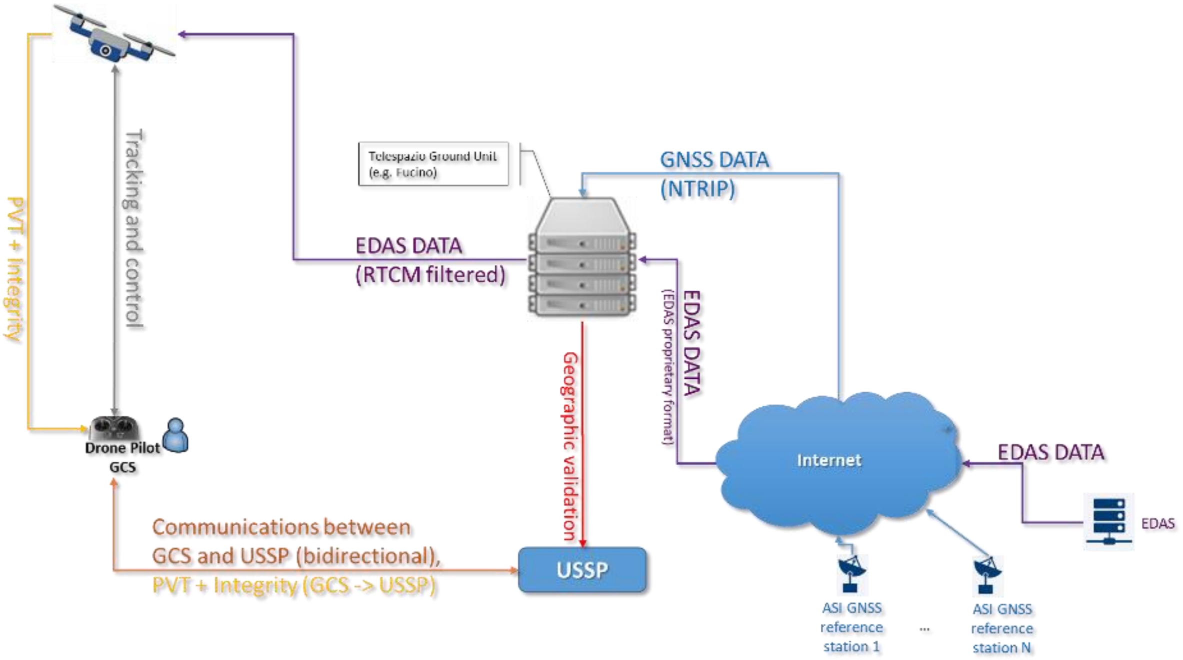


Figure 3-10: case 3 – receiver connected to an embedded microcomputer

In case 4, the part of Telespazio's Computing Unit that performs the computation of PVT and integrity is hosted on the pilot's cockpit. The external unit will host the software dedicated to the evaluation of the GNSS performance of the monitoring stations nearby. The possible system states are given in Table 3-3.

The four proposed architectures provide a common UA altitude with defined protection levels: drone operators and UTM actors can use this additional information for obstacle avoidance, tactical deconfliction and other flight operations requiring a high level of safety.

Since the solution is calculated by an entity external to the drone operator, using public and certified data (i.e. EDAS), an implicit anti-tampering functionality should be guaranteed.

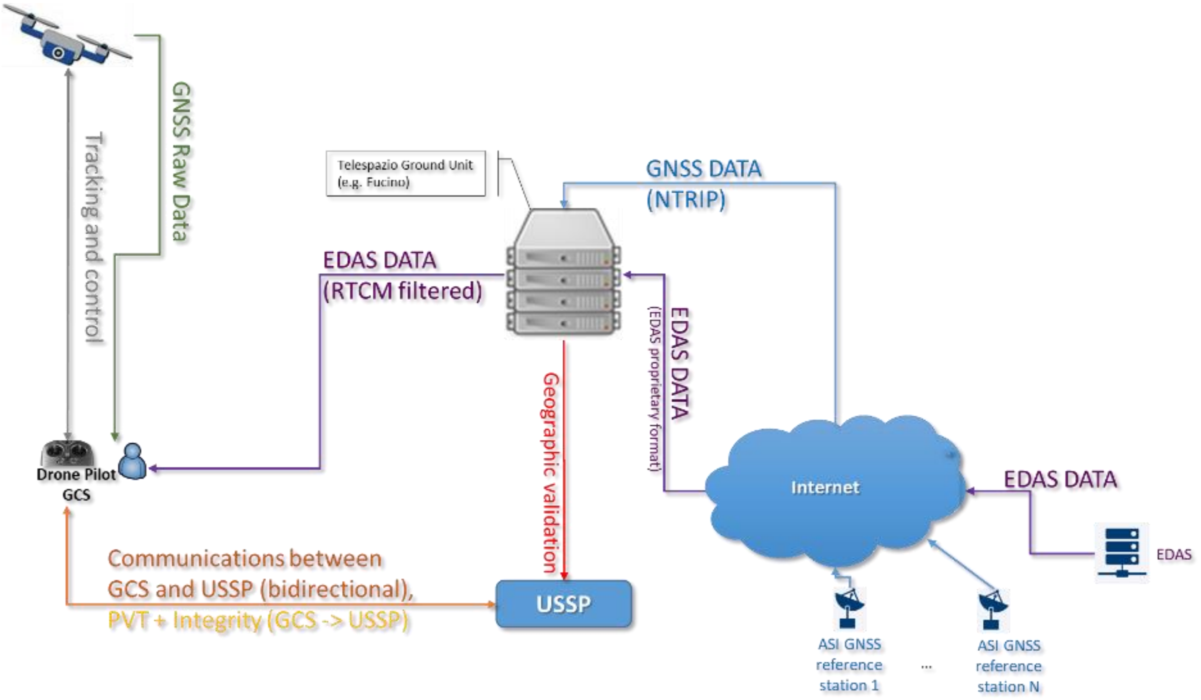


Figure 3-11: case 4 – pilot's cockpit hosting PVT + integrity computation

Status nr.	PVT + integrity solution status (drone)	Monitored parameters status (regional)	GNSS solution status (overall)
1	OK	OK	OK Normal condition
2	OK	Not OK • SiS problems in area	WARNING Working without guarantees (should never happen)
3	Not OK • no PVT provided, or • integrity alert raised	OK	ALERT Local problem: • Obstacles blocking signal • Multipath • Interference • Spoofing • Meaconing • Receiver failure
4	Not OK • no PVT provided, or • integrity alert raised	Not OK • SiS problems in area	ALERT Not working, as expected

Table 3-3: Possible status of the solution (case 3 and 4)

3.2.2 Proposed solution: possible algorithms

3.2.2.1 GPS + EGNOS

In the first proposed solution, a single frequency GPS computation with application of EGNOS is applied. This solution allows the accuracy to be enhanced to sub-metre levels, providing the aeronautic-certified protection levels as well. The external computation in the unit would also make it applicable to low-cost receivers, even the simplest ones.

The disadvantages of this solution are that is would not exploit the Galileo constellation (for integrity, at least), limiting availability and improvement of the accuracy from diversity of frequencies and satellites, leading to a weakness in the case of harsh environments. Moreover, the integrity parameters would not be adaptable to application domains other than manned aircraft, leading to overestimated protection levels. Some of the disadvantages implied in the use of this algorithm will be overcame with the complete deployment of new generation EGNOS v3, foreseen in 2025 [32], that will allow SBAS-augmented dual-frequency, multi-constellation processing.

3.2.2.2 GPS + Galileo + ARAIM

In the second proposed solution, a dual-frequency, dual-constellation computation is performed, using the ARAIM algorithm to provide integrity. The external computation in the unit would also make it applicable to low-cost receivers. A dual-frequency ionosphere-free combination would be used, eliminating one of the principal error sources. In addition, the use of Galileo satellites would improve availability. Aeronautical protection levels would be provided; however, fine-tuning can be performed, and some requirements could be relaxed (since it is not a safety-related application).

The disadvantages of this solution are that it does not use explicit external augmentation systems to further enhance the accuracy, the need to assess performance in an urban environment, and for an additional process to establish and verify the truthfulness of the ISM parameters that are, in any case, loaded before the flight.

3.2.3 Selected solution and justification

To enable the solution that best fits the addressed objectives to be chosen, some theoretical and practical considerations about the two main issues regarding navigation in the present context, i.e. accuracy and integrity, are considered.

Firstly, evaluating the effective actual accuracy of the navigation solution is a long and complex procedure, involving different aspects. To address this, the navigation error budget will be assessed later (see §9.3.2). However, the architectures and algorithms given in paragraphs above are not the best solutions in terms of accuracy: it is necessary underline that the nominal 95th-percentile error cannot be the only driver of the implementation. Therefore, even if there are feasible techniques that show better performance from this point of view (such as RTK), a trade-off analysis between cost and benefit can lead to a different choice.

In our proposal, the most important driver (given the need to satisfy accuracy requirements, see §0 and §9.3.2) is the provision of integrity to a low-cost receiver mounted on a drone: in fact, the major drawback of the RTK solution, besides the cost of the service and the set-up and convergence times, is that no effective, EGNOS-Safety-of-Life-service (SoL)-compliant, integrity parameters (i.e. protection levels) are calculated.

Since the proposed solutions all guarantee the provision of integrity parameters, the architecture selected is the one described in “case 1”, previously depicted in Figure 3-8 and Table 3-1.

The raw measurements collected by the GNSS receiver mounted on the drone are sent to Telespazio’s Computing Unit (TCU), that simultaneously collects the EDAS data and the raw measurements from a trusted network of sensor stations (e.g. ASI, IGS, EUREF). The Computing Unit will then compute the drone’s PVT solution, together with its integrity parameters. At the same time, the Unit will evaluate the GNSS performances of the monitoring stations nearby. The possible statuses are represented in Table 3-1. This architectural implementation can host the computation of integrity parameters according to the algorithms foreseen by SBAS processing or according to the ARAIM algorithm. Both the application of algorithms based on SBAS (using EGNOS/EDAS data) and that based on ARAIM processing have been designed to ensure the provision of GNSS augmentations that allow LPV-200 approach performance specifications to be respected. These specifications are compliant with the requirements foreseen for the U-Space (see §0). These requirements are listed in the following table.

Parameter	ICAO LPV-200 requirements
95% Horizontal Accuracy	16 m
95% Vertical Accuracy	4 m
Fault-Free Accuracy1	10 m, 10-7 per 150 s in nominal conditions
Effective Monitoring Threshold (EMT)2	15 m, 10-5 per 150 s in degraded conditions
Horizontal Alert Limit (HAL)	40 m
Vertical Alert Limit (VAL)	35 m
Continuity Risk	8 x 10-6 per 15 s
Integrity Risk	2 x 10-7 per 150 s
Time-to-alert	6 s
Availability	99% to 99.999%

Table 3-4: ICAO LPV-200 requirements

It must be underlined that, besides the accuracy values (which have very conservative requirements - in the practice the accuracy is much higher, with significantly lower navigation system errors - see §9.3.2), the most important parameters provided by the system are the protection levels defined at the beginning of present chapter. Generally speaking, the Alert Limits are at a value of between 4 and 6 sigma of the Navigation System Error distribution (guaranteed by the Integrity Risk probability), while the 95th percentile accuracy represents the 2-sigma value (statistically computed and without guarantee).

The architecture described above preferred for the following reasons:

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[1] The Fault-Free Accuracy is defined in this way: Pr(Vertical Error > FFA) < 10^{-7}/150s in nominal conditions

[2] The Effective Monitoring Threshold is defined in this way: Pr(Vertical Error > EMT) < 10^{-5}/150s in degraded conditions (faults of the GNSS system not large enough to ensure detection)

1. Simplicity of equipment on-board the drone: only a communication module is needed (e.g. 4G/LTE).
2. Relatively low throughput needed for communication between the drone and the TCU, generally characterised by low latency (if a 4G/LTE link is used): the data sent are basically the raw GNSS measurements; the throughput and the latency experienced so far have not exceeded 2 kbit/sec and 1 msec, respectively, and in these conditions there are only minor communications issues.
3. The installation of the SBAS state machine on a centralised entity, directly connected to the Internet through a wired, stable, wide-band connection, guarantees that the EGNOS messages, provided by the EDAS data centre are always delivered on time: in this way, (a) there is no need for initialisation time (except that for the smoothing filters) and (b) the risk of missing or delayed messages (that would lead to much inflation of the protection levels) is negligible: in the SBAS processing, the timeliness availability of EGNOS messages is crucial for minimising protection levels.
4. The installation of the developed software on a ground system allows potentially unlimited hardware resources, which have no problems in terms of resources allocated (RAM, CPU, etc.), and which are easily scalable and upgradable when correctly dimensioned.
5. Any change in the algorithm or in the processing standard will need just one central entity to be upgraded with validated or certified software, instead of updating the on-board firmware of all drones flying. At the same time, the processing applied on the raw observables might be used to certify positioning data (implicit anti-tampering function and guarantee of application of required aeronautics standards).

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4 Currently available Digital Elevation Model & Obstacle data products

4.1 Introduction

This chapter, after general definitions, illustrates the features of the presently available, free and commercial, global and European, regional/local Digital Elevation Models, including both Digital Surface Models (DSM) and Digital Terrain Models (DTM) and ground obstacle data products.

Information on free resources (public repository) and commercial services are also given.

The following principal questions are addressed:

- Which Digital Elevation Models and obstacle data products are available?
- What are their main features and their accuracy?
- Are there any services that already provide Digital Elevation Models and obstacle data products?
- Are these free or paid services? Are they certified services?
- Which are the most relevant use cases, and which Digital Elevation Models and obstacle data products should be used?

Finally, first references are given.[3*]

4.2 Definitions

4.2.1 DEM, DSM, DTM

DEM - Digital Elevation Model is a generic term, without a particular specification (Digital Height Model (DHM) is sometimes used), to indicate the discrete representation of the surface of the Earth using points generally placed on a regular grid (GRID data format) or, sometimes, irregularly (TIN data format). For each point its position is known in a chosen reference frame (globally WGS84, in Europe ETRF2000) and represented through a chosen coordinate system (horizontal coordinates: geographic (latitude, longitude) or cartographic (East, North); height: orthometric (H) with respect to a chosen geoid model (usually EGM96) or ellipsoidal (h)).

Digital Surface Model (Figure 4-1) is the term indicating the discrete representation of the surface of the Earth visible from space, therefore including vegetation, buildings, infrastructures and generally all man-made objects.

Digital Terrain Model (Figure 4-1) is the term indicating the discrete representation of the surface of the bare ground, that is the surface of the Earth visible from space (DSM) filtered (Figure 4-2) to remove

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[3*] The opinions expressed herein reflect the authors' view only. Under no circumstances shall the SESAR Joint Undertaking be responsible for any use that may be made of the information contained herein.

vegetation, buildings, infrastructure and generally all man-made objects. Therefore, DTM is obtained filtering DSM. It should be stressed that filtering is dependent on the algorithm adopted and generally degrades the vertical accuracy of the original DSM.

(References [1], [2], [3], [4], [5])

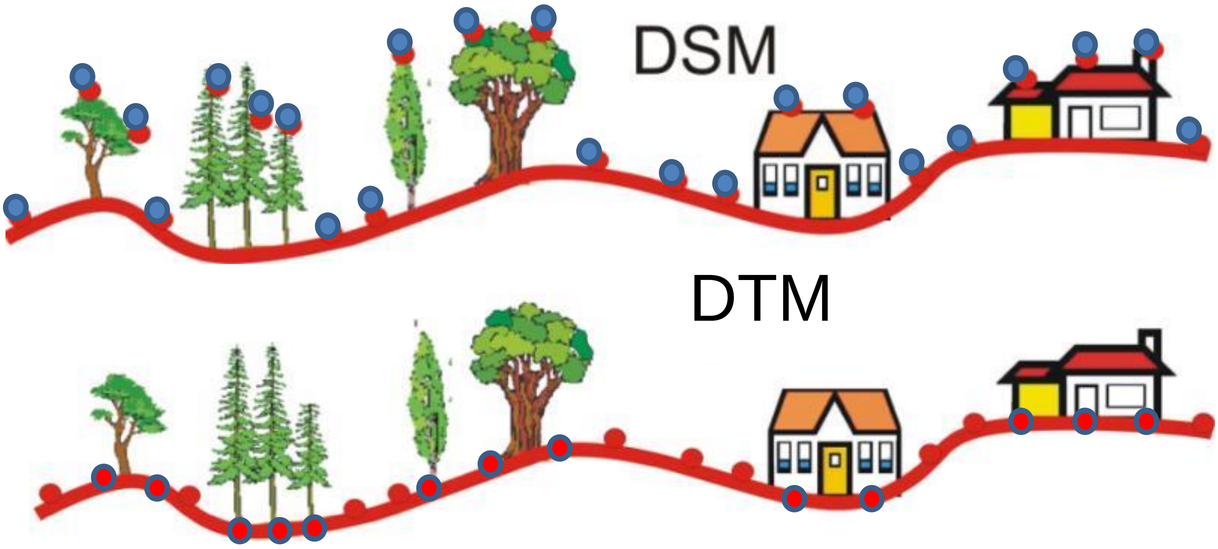

Figure 4-1: DSM vs. DTM - (after K. Jacobsen, 2018 [1])

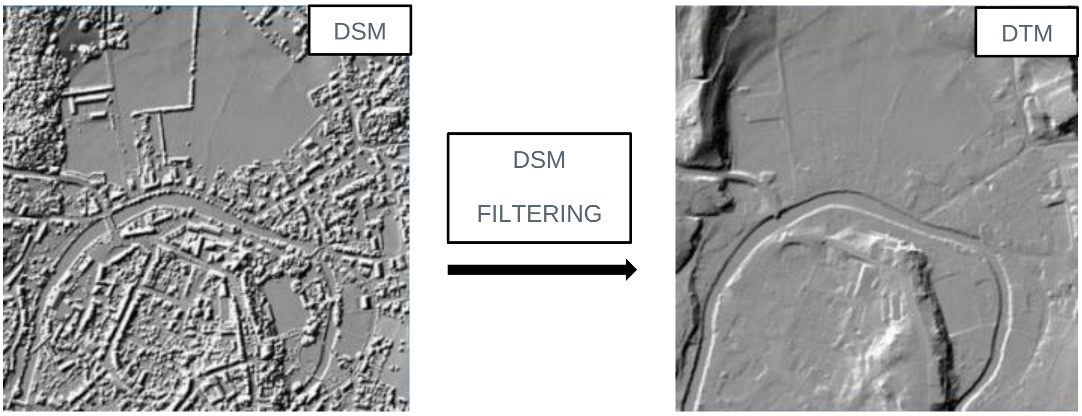

Figure 4-2: DSM filtering to derive DTM - (after K. Jacobsen, 2018 [1])

4.2.2 Obstacles

Obstacles in aviation terms of features with a vertical significance compared with the surrounding terrain or surrounding features which constitute a potential hazard to aircraft operations.

According to ICAO, obstacles are fixed (whether temporary or permanent) and mobile objects, or parts thereof, that:

- are located on an area intended for the surface movement of aircraft; or
- extend above a defined surface intended to protect aircraft in flight; or
- stand outside those defined surfaces and that have been assessed as being a hazard to air navigation

For many years, it was a requirement for states to publish obstacle data in their Aeronautical Information Publication (AIP). However, the requirement was to provide this information in a simple, textual form, classified in one of three ways:

- obstacles that affect the en-route phase of flight;
- obstacles at an aerodrome that affect the circling area;
- obstacles at an aerodrome that affect the approach/take-off phases of flight

Information relating to terrain was only required in a very limited form, for runways for which Category (CAT) II/III operations are approved. This terrain information was provided graphically in the Precision Approach Terrain Chart (PATC), specified by ICAO Annex 4.

Digital data are required now, so that the information may be automatically incorporated into procedure design tools.

According to [7], obstacle data must comprise the digital representation of the vertical and horizontal extent of the obstacles (e.g. eTOD [10]). Obstacles must not be included in terrain datasets, that is in the DSM, but obstacle data elements are features that must be represented in separate data sets by points, lines or polygons. In an obstacle dataset, all defined obstacle feature types must be provided and each of them must be described according to the list of mandatory attributes provided in [6] - Appendix 8, Table A8-4.

(References [6], [7], [8], [9], [10])

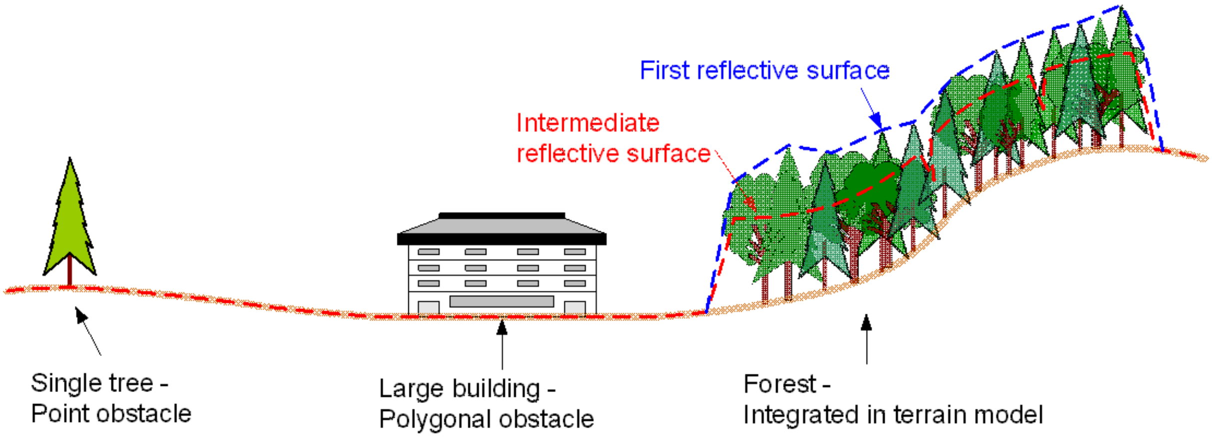

Figure 4-3: Different kinds of obstacles - (after EUROCONTROL, 2019 [6])

4.2.3 DSM and obstacles

DSM is therefore the discrete representation of the surface defining the physical boundary for aeronautic purposes.

A routinely updated DSM at the highest detail (generally realized with airborne LiDAR technology) contains the majority of the obstacles, at least those that are permanent.

(References [11])

4.2.4 Main features of DEM and obstacles

The main features of DEM and obstacles are:

- availability (free, commercial)
- DEM type (DSM, DTM)
- reference frame (datum, geoid, height type: ellipsoidal, orthometric), coordinate system (geographic, cartographic)
- GRID resolution
- coverage (latitude/longitude ranges)
- accuracy (horizontal, vertical) in term of 90% or 95% Circular Error (CE90, CE95) and 90% or 95% Linear Error (LE90, LE95) (see paragraph 4.6 for definitions - note that vertical accuracy decreases with terrain slope)
- repository (public)/service (commercial)

These features are summarised for each DEM in the following format:

DEM name - official web site - availability (free, commercial)
DEM type (DSM, DTM) - reference frame, coordinate system, height type - grid resolution (coverage)
horizontal accuracy - vertical accuracy
Repository (public)/service (commercial) official web site

For obstacles, refer to the cited documents.

4.3 Global DEMs

4.3.1 SRTM DEM

DSM generated from NASA's Shuttle Radar Topography Mission (SRTM) in 2000.

SRTM was a joint project of NASA, the German and Italian space agencies, and the US National Geospatial-Intelligence Agency. It was managed by NASA's Jet Propulsion Laboratory (JPL), Pasadena, California, for NASA's Science Mission Directorate, Washington, D.C.

SRTM flew aboard the Space Shuttle Endeavour in February 2000, mapping Earth's topography between 56 degrees south and 60 degrees north of the equator. During the 11-day mission, SRTM used an imaging radar to map the surface of Earth numerous times from different perspectives. These combined radar data were processed at the JPL to produce a global topographic map created by bouncing radar signals off the Earth's surface and back to the shuttle.

The 1” (30-metres) topographic data products with worldwide coverage (except Middle East) were released in 2014 and are publicly distributed by the U.S. Geological Survey (USGS) along with the previous 3” (90-metres) topographic data products with worldwide coverage that have been distributed since 2003.

SRTM DEM - https://www2.jpl.nasa.gov/srtm/ - Free
DSM - WGS84+EGM96 geoid - geographic - (H_{EGM96}) - 1’’ (56°S-60°N, no Middle East) - mean CE90 10 m - LE90 4-16 m (mean LE90 8 m)
Repository: USGS EROS Data Centre - see Public Data Distribution for details

4.3.2 ASTER GDEM3

DSM generated from processing of 2.3 million scenes taken since February 2000 by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (15 meters GSD).

ASTER is one of five instruments aboard NASA's Terra spacecraft (launched in 1999), built in Japan for the Ministry of Economy, Trade, and Industry (METI). A joint U.S./Japan Science Team is responsible for instrument design, calibration, and data validation.

Version 3 of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) is available from NASA's Land Processes Distributed Active Archive Center (LP DAAC) since 2019. The ASTER GDEM covers land surfaces between 83°N and 83°S.

The first ASTER GDEM was released in 2009, with Version 2 being released in 2011. The ASTER GDEM Version 3 maintains the GeoTIFF format and the same gridding and tile structure as in previous versions, with 30-metres spatial resolution and 1°x1° tiles.

Version 3 also features a new global product: the ASTER Water Body Dataset (ASTWBD). This raster product identifies all water bodies as either ocean, river, or lake, and each GDEM tile has a corresponding Water Body tile.

ASTER GDEM3 and ASTWBD - https://asterweb.jpl.nasa.gov/gdem.asp - Free
DSM - WGS84+EGM96 geoid - geographic - (H_{EGM96}) - 1'' (83°S-83°N) - mean CE90 25 m - LE90 8-18 m (mean LE90 12 m)
Repository: NASA's LP DAAC Data Pool - LP DAAC's Application for Extracting and Exploring Analysis Ready Samples (AppEEARS)

4.3.3 AW3D30 - AW3D Standard

DSM generated from processing some 3 million data images taken from January 2006 to May 2011 by Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) on-board the "DAICHI" Advanced Land Observing Satellite (ALOS) (2.5 metres GSD).

The Japan Aerospace Exploration Agency (JAXA) processed the imaged and produced the global digital 3D map. This digital 3D map compiled is claimed to have the world's best detail, enabling terrain all over the world to be shown at 5 metres spatial resolution with a 5-metres height accuracy (ALOS World 3D - 5m (AW3D Standard)).

The compilation and service provision was performed by NTT DATA Corporation and Remote Sensing Technology Centre (RESTEC), Japan under a JAXA commission.

To increase the of the 3D map data, JAXA also prepared a DSM version with lower spatial resolution (of about 30 metres) to be published free of charge (ALOS World 3D - 30m (AW3D30)).

AW3D30 - https://www.eorc.jaxa.jp/ALOS/en/aw3d30/ - Free
DSM - WGS84+EGM96 geoid - geographic - (H_{EGM96}) - 1'' (82°S-82°N) - mean CE90 11 m - LE90 4-10 m (mean LE90 7 m)
Repository: https://www.eorc.jaxa.jp/ALOS/en/aw3d30/data/index.htm

AW3D Standard - https://www.aw3d.jp/en/products/standard/ - Commercial

DSM - WGS84+EGM96 geoid - geographic - (H_{EGM96}) - 0.15'' (82°S-82°N) - mean CE90 11 m - LE90 4-10 m (mean LE90 7 m)
Service - NTT DATA Corporation and RESTEC: https://www.aw3d.jp/en/

4.3.4 MERIT DEM

DTM generated by removing multiple error components (absolute bias, stripe noise, speckle noise, and tree height bias) from the existing spaceborne DEMs (SRTM3 v2.1 and AW3D-30m v1). In detail, the SRTM3 DEM (below 60°N) and the AW3D-30 m DEM (above 60°N) were used as the baseline DEMs; the unobserved areas in both DEMs were filled with the Viewfinder Panoramas DEM (VFP-DEM). VFP-DEM (http://www.viewfinderpanoramas.org/dem3.html) was developed by carefully filling the areas unobserved by SRTM using other datasets such as digitised paper topography maps, the Canadian Geobase DEM and the U.S. National Elevation Data. It covers the entire globe at 3" resolution. Though the data source, quality and effective resolution of the VFP-DEM are not consistent across the globe, its accuracy is better than other low-resolution DEMs above N60° (such as GMTED2010).

The height errors included in the original DEMs were separated from actual topography signals and removed using a combination of multiple satellite datasets and filtering techniques. After error removal, global land areas mapped with ±2m-or-better accuracy increased from 39% to 58%. Significant improvements were found, especially in flat regions such as river floodplains. Here, detected height errors were larger than actual topographic variability and following error removal, landscapes features such as river networks and hill-valley structures at last became clearly represented. This DTM will expand the possibility of geoscience applications such as terrain landscape analysis, flood inundation modelling, soil erosion analysis, and wetland carbon cycle studies that require high-accuracy elevation data.

MERIT DEM gives terrain elevations at a 3sec resolution (~90m at the equator), and covers land areas between 90N-60S, referenced to the EGM96 geoid. Hydrologically adjusted DTM is also available as a component of MERIT Hydro datasets.

MERIT DEM is available on a server of the University of Tokyo (Japan) and can be downloaded free of charge for scientific data use.

MERIT DEM - http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_DEM/index.html - Free
DSM - WGS84+EGM96 geoid - geographic - (H_{EGM96}) - 3'' (60°S-90°N) - mean CE90 11 m - LE90 similar to AW3D30 (3-10 m, but with significant improvement in flat areas; 58% of the overall DEM within ±2m or better accuracy)
Repository: http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_DEM

4.3.5 TanDEM-X DEM - WorldDEM^{TM}

DSM generated from interferometric processing of the multiple radar images of the Earth's entire land surface taken by the twin satellites TerraSAR-X and TanDEM-X between 2011 and late 2015 and completed in 2016. DTM obtained through filtering is also available.

Since 21 June 2010, the twin German TerraSAR-X (launched on 15 June 2007) and TanDEM-X radar satellites have been recording the Earth flying in close formation. As they fly over the Earth, both satellites 'see' the same land area, but from slightly different perspectives. The signal reflected by the ground arrives at the satellites with a small time offset due to the different ranges. This range difference is recorded interferometrically with millimetre precision. The distance between the twin satellites varied between 500 metres and, on occasion, just 120 metres. This made the creation of a Digital Elevation Model (DEM) of the Earth's surface on DLR computers in Oberpfaffenhofen.

The TanDEM-X DEM covers all of Earth's land surfaces, ole-to-pole, totalling over 148 million square kilometres. The elevation models generated with TanDEM-X and TerraSAR-X have the advantage of being the first to capture the Earth with uniform accuracy and no gaps.

The full-resolution data, with a horizontal sampling distance of 12 metres (WorldDEM™), also allowed the creation of versions with reduced resolutions of 30 metres and 90 metres.

While access to the 12-metres and 30-metres elevation models is subject to restrictions due to the potential for commercial exploitation, and thus requires a scientific proposal, the 90 metres DEM is now available on a DLR server and can be downloaded free of charge for scientific use.

TanDEM-X - https://geoservice.dlr.de/web/dataguide/tdm90/ - Free
DSM - WGS84 - geographic - (h_{WGS84}) - 3'' (global) - CE90 < 10 m - LE90 2-10 m (mean LE90 4 m)
Repository: https://geoservice.dlr.de/web/dataguide/tdm90/#access

WorldDEM^{TM} - https://www.intelligence-airbusds.com/ - Commercial/Free for scientific research under approved research projects submitted at TanDEM-X Science Service System DLR (https://tandemx-science.dlr.de/cgi-bin/wcm.pl?page=TDM-Proposal-Submission-Procedure)
DSM and DTM - WGS84 - geographic - (h_{WGS84}) - 0.4''-1'' (global) - CE90 < 10 m - LE90 2-10 m (mean LE90 4 m)
Service - AIRBUS: https://worlddem-database.terrasar.com/

4.4 European DEMs

4.4.1 EU-DEM

DSM of the European Environment Agency's (EEA) 39 member and cooperating countries generated as a hybrid product based on SRTM and ASTER GDEM data fused by a weighted averaging approach. Two versions are available (v1.0, v1.1).

The statistical validation of EU-DEM v1.0 documents a relatively unbiased (-0.56 metres) overall vertical accuracy of 2.9 metres RMSE, which is fully within the contractual specification of 7m RMSE (European Commission 2009). Evaluation of RMSE values by country revealed higher RMSE values for the Nordic countries of Iceland (RMSE=9.41 m), Norway (RMSE=5.75 m) and Sweden (RMSE=7.41 m), which can be explained by the absence of SRTM data north of 60°N. Further, investigations of EU-DEM elevation accuracy documented increasing elevation biases and variability in areas of variable topography and ground cover. The results are generally consistent and can be explained by the measurement characteristics and differences between the involved data sources. As a general conclusion, it can be stated that the validation of the EU-DEM dataset yields overall values within specifications (full report: [17]).

The following corrections and improvements have been implemented in EU-DEM v1.1:

- systematic correction of geo-positioning issues (found and corrected for Malta and Lampedusa islands)
- bias adjustment with ICESat

- screening and removal of artefacts, including the presence of blunders (i.e. negative or positive anomalies); more than 75,000 artefacts have been detected and corrected
- consistency with the upgraded version of EU-Hydro, in order to produce a better river network topology

EU-DEM v1.1 has not been validated yet (comments and user feedback on EU-DEM v1.1 can be provided to copernicus.land@eea.europa.eu).

EU-DEM - https://land.copernicus.eu/imagery-in-situ/eu-dem - Free
DSM - ETRS89 (GRS80) - geographic - ($H_{EVRS2000\text{ - geoid }EGG08}$) - 3’’ (EEA 39 member and cooperating countries) - mean CE90 10 m (latitude < 60°) - 25 m (latitude > 60°) - LE90 4-16 m (latitude < 60°) - 8-18 m (latitude > 60°) (mean LE90 8 m (latitude < 60°) - 15 m (latitude > 60°))
Repository: https://land.copernicus.eu/imagery-in-situ/eu-dem

4.4.2 Euro-Maps 3D DSM

DSM derived from stereo image pairs acquired by the Cartosat-1 satellite at an original 2.5 m spatial resolution.

The product has been generated by GAF AG using a highly automated processing chain developed in close co-operation with the German Aerospace Centre (DLR).

The European Space Agency (ESA), has added the Euro-Maps 3D DSM to the Copernicus Data Access Portfolio (DAP) (see latest DAP document, Annex 6), thus making it available to Copernicus Services, Union Institutions and Union Research Projects through the Copernicus Data Warehouse (DWH).

The Euro-Maps 3D DSM product comprises a digital surface model (DSM) with 5 m post spacing and an (optional) associated orthogonal layer with a 2.5 m spatial resolution.

For Europe, the product is based on stacks of up to 15 stereo pairs. The use of multiple stereo pairs acquired using different acquisition angles leads to minimal gap-filling and results in unique accuracy and reliability. During an editing process, the DSM has been further refined and water bodies exceeding certain dimensions have been hydrologically corrected, so that consistent water flow is ensured. Detailed quality and traceability layers are part of the delivery and every height value can be traced with pixel accuracy.

The Euro-Maps 3D DSM is part of the GAF Elevation Suite, which comprises also Euro-Maps 3D for Ortho products with 10 m post spacing and VHR multi-stereo DSM products. For further details about Euro-Maps 3D, please see http://euro-maps.gaf.de/products/prod_008.html.

Euro-Maps 3D DSM - https://www.gaf.de/content/euro-maps-3d-dsm-now-also-available-copernicus-data-access-portfolio - Free
DSM - WGS84 - cartographic (UTM) - (H_{EGM96}) - 5 m (EEA 39 member and cooperating countries) - CE90 5-10 m (mean CE90 7 m) - LE90 5-10 m (mean LE90 7 m)
Repository: https://spacedata.copernicus.eu/

4.5 Regional/Local DEMs

Regional/local DEMs are available worldwide through online open (off-the-shelf products) and commercial (off-the-shelf and on-demand products) portals.

4.5.1 Online Open Resources

- Open Digital Elevation Model (OpenDEM) - The Portal for sharing the 3rd Dimension (https://www.opendem.info/index.html)
- OpenTopography - High-Resolution Topography Data and Tools (https://opentopography.org/)
- European Data Portal - The European Data Portal harvests the metadata of Public Sector Information available on public data portals across European countries. Information regarding the provision of data and the benefits of re-using data is also included (https://www.europeandataportal.eu/en)
- Public Agencies – ~~Free of charge~~
  For Italy - Geoportale Nazionale 'Free' (after registration):
  LIDAR data over 1st-2nd order river watersheds
  (including some relevant urban areas: Rome, Milan, Turin, etc.)
  $H_{ITALGEO2005}$ - 1 m - LE90 40 cm horizontal, 20 cm height
  (https://geodati.gov.it/geoportale/datiterritoriali)

4.5.2 Online Commercial Services

Commercial services are offered by private companies with respect to different DEM products. The following is a (not exhaustive) list of services related to local DEMs generated on demand, and of services regarding global DEMs:

- NTT DATA Corporation and RESTEC (https://www.aw3d.jp/en/)
- Intermap - NEXTMap (https://www.intermap.com/nextmap)
- PlanetObserver (https://www.planetobserver.com/products/planetdem/planetdem-30/)
- Apollo Mapping (https://apollomapping.com/digital-elevation-models)
- Hexagon (https://hxgncontent.com/products/digital-surface-models)
- Maxar (https://www.maxar.com/products/elevation-suite)

High-resolution (GRID resolution: up to 0.1 - 0.5 metres)/ high-accuracy (LE90: up to 0.2 - 0.5 metres) DEMs generated from aerial photogrammetric and LIDAR surveys are also included in on-demand products offered by commercial services.

It must be stressed that such DEMs (generally DSMs) are intrinsically on-demand products, since they must be very up-to-date so that they include all the existing permanent objects (including obstacles) whose horizontal/vertical dimensions are significant with respect to (i.e. equal to or larger than) their resolution and accuracy.

None of these services are certified.

4.5.3 Relevant future prospects in DEM

With the rapid increase in the development of high-revisit-time constellations, governments and companies have begun to invest in making these data more accessible [16] (e.g., the Planet Labs Open California initiative [17], SpaceNet [18], IARPA CORE3D programme [19]).

Two relevant industrial projects, presently focused on 2D information only, are ongoing in the Earth Observation (EO) field:

- Planet - constellation of optical satellite sensors (https://www.planet.com/)
- ICEYE - constellation of SAR satellite sensors (https://www.iceye.com/)

Considering the potential of both constellations, it is expected that both companies will provide DEM products (maybe on-demand) in the near future.

Geospatial data providers can generate 3D-point clouds from stereo pairs and/or multiple single images taken at different times, and with different lighting and vegetation between acquisitions, selecting the best camera angles as appropriate, according to the orographic characteristics of the observed site.

With a large number of input images (at least 2 per day for Planet) 3D models will be produced that are as accurate as those obtained from a single same-day stereo pair. These companies can therefore exploit such a large archive of single-epoch images to compute the best possible 3D model with reasonable computational cost.

These constellations could be also exploited for mono-plotting and/or stereo-plotting methods to measure and digitise an updated obstacle database, according to [12] and [13].

(References [12], [13])

4.6 DEM and obstacle data accuracy assessment

The accuracy assessment of DEMs and obstacle data is based comparing them against a reference DSM/DTM whose accuracy and GRID resolution are higher (usually generated by airborne/terrestrial LiDAR or high scale/high accuracy photogrammetry) than the DEMs/obstacle data to be assessed.

The general accuracy assessment procedure must evaluate:

- the overall roto-translation 3D bias (horizontal, vertical and rotational)
- the 3D random error (horizontal, vertical)

of the DEM/obstacle-data with respect to the reference DSM/DTM.

The accuracy for DEMs/obstacle-data is usually given using the following statistical indices:

- horizontal accuracy - uncertainty in the horizontal position of a pixel with respect to the reference
  90% Circular Error (CE90) - The threshold value of 90% of the absolute values of the differences between the DEM/obstacle data and the reference; in case of normally distributed differences with equal standard deviations in two orthogonal directions ($\sigma_x = \sigma_y = \sigma$) CE90 = 2.146*$\sigma$
  95% Circular Error (CE95) – The same as CE90, with threshold value of 95%; CE95 = 2.445*σ
- vertical accuracy - uncertainty in the height of a pixel with respect to the reference
  90% Linear Error (LE90) - The threshold value of 90% of the absolute values of the differences between the DEM/obstacle and the reference; in case of normally distributed differences with standard deviation σ LE90=1.645*σ
  95% Linear Error (LE95) - Same as LE90 with threshold value of 95%; LE95 = 1.960*σ

(References [14], [15], [16], [17])

4.7 Relevant use cases

To better focus on the choice of the most suitable DEMs and obstacle data products available for managing the strategic phase (mission planning), two relevant use cases are presented, related to urban and extra-urban areas.

4.7.1 Urban areas

The main goal to be satisfied is the proper representation of the 3D urban morphology, to enable mission planning not only over but also inside urban areas, considering possible flight routes at least partially inside urban canyons.

For this, a city model is generally needed, that is a DSM including all obstacle data that describes all buildings, infrastructure, objects and vegetation that constitute the urban environment. The key point is the accuracy of this city model, which must satisfy the compromise between two contrasting needs: on one hand, the technical need to describe the 3D urban morphology accurately enough to estimate the space available to efficiently and safely plan flight routes within urban canyons; on the other hand, the budgetary requirements that will keep the accuracy within a certain level, so that costs for creating and updating the city model (which are a function of accuracy) are manageable.

A reasonable compromise is therefore a city model with an accuracy in the range 0.5-1.0 metres, reasonably higher in the case of narrower urban canyons (e.g. historical centres). To satisfy such an accuracy, DSMs from satellite imagery are not suitable, and on-demand products offered by commercial services and generated from aerial photogrammetric and LIDAR surveys must be considered.

4.7.2 Extra-urban areas

The main goal to be satisfied is the proper representation of the morphology of the 3D terrain, vegetation and possible man-made objects, to enable mission planning over these areas.

For this, a DSM is needed that includes all obstacle data, and whose accuracy is dependent on the flight goal, which could just be a transit across the area or an inspection of the area or some of its details (e.g. vegetation/forests/crops status, hydrography, structures/infrastructure).

In the case of a transit over the area, a DSM (including all obstacle data) with an accuracy in the range 5-10 metres is enough, so free products from satellite imagery such as EU DEM and Euro Maps 3D DSM (which may be complemented by free off-the-shelf regional/local products coming from online open resources, if available) are suitable.

In the case of inspection of the area or some of its details, a DSM (including all obstacle data) with an accuracy in the range 0.5-2.0 metres, or reasonably higher in case of structures/infrastructure (e.g. power lines, roads, railways, bridges, dams) is needed. To satisfy such an accuracy on-demand DSM products offered by commercial services and generated from aerial photogrammetric and LIDAR surveys must be considered.

4.8 References

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5 Currently available precision height systems & frames

In this chapter, the different height systems currently used in geodesy and surveying will be defined. The different height systems will be described, and their standard precisions will be given. Furthermore, transformation between the defined height systems will be discussed.

5.1 Introduction

Various different height definitions are commonly used in geodesy and surveying. Before the advent of GNSS, orthometric heights were mainly used, since they can be obtained by observing height increments between intervisible points through the process of spirit levelling. In fact, starting from a benchmark of a known orthometric height and summing all the observed height increments, the orthometric height can finally be estimated. The same holds for normal heights that can also be obtained from spirit levelling. With the advent of the GNSS technology in the 1990s, coherent global ellipsoidal heights have been made available to users. Ellipsoidal heights can be estimated with respect to a given geocentric reference ellipsoid in a fast and precise way using GNSS techniques. However, especially in general aviation applications, flight altitude is also determined through an atmospheric pressure observation that is usually related to the orthometric heights.

In this chapter, the definitions of orthometric, normal and ellipsoidal heights will be given. The relationships between these different heights will then be discussed. Finally, the standard precisions of these heights and of the transformation formulas are detailed.

5.2 Definitions

5.2.1 Ellipsoidal height

Ellipsoidal height is a geometric height that is derived through GNSS observations. Its definition is purely geometric and does not involve the Earth's "gravity field" (see section 5.2.2), as is the case with orthometric and normal heights (see section 5.2.2 and 5.2.3).

The GNSS method allows 3D coordinates of the surveyed points P to be estimated with respect to a given geocentric Cartesian 3D reference frame (X, Y, Z). If we couple an ellipsoid centred at the origin of the Cartesian axes to this frame, we can get the 3D ellipsoidal coordinates of point P, namely the latitude φ_P, the longitude λ_P and ellipsoidal height h_P, by inverting the following relation:

$$\begin{cases} X_P = (N_P + h_P)\cos\varphi_P\cos\lambda_P \\ Y_P = (N_P + h_P)\cos\varphi_P\sin\lambda_P \\ Z_P = (N_P(1-e^2) + h_P)\sin\varphi_P \end{cases} \quad \textbf{(1)}$$

where N_P is the east-west curvature radius and e^2 the eccentricity of the ellipsoid.

Particularly, as shown in Figure 5-1, the ellipsoidal height h_P of a point P on the Earth's surface is the length of the segment $\overline{PP_0}$, i.e. the distance along the normal to the ellipsoid from the point P to the point P_0, lying on the ellipsoid's surface.

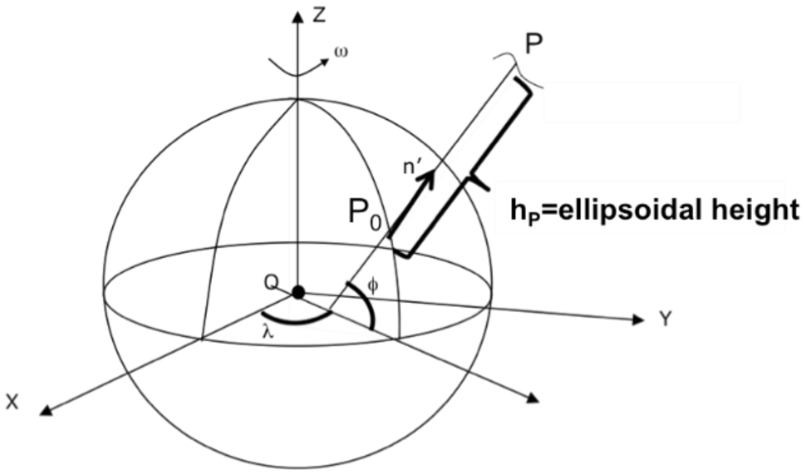

Figure 5-1: latitude, longitude and ellipsoidal height

5.2.2 Orthometric height

The definition of the orthometric height H_P of a point P is strictly related to the definition of the Earth's "gravity field".

This gravity field is the sum of the gravitational field due to the attraction of the Earth's masses and of the centrifugal field due to the Earth rotation. It can be obtained as the gradient of the gravity potential [7], which is

$$W(P) = V(P) + CP(P) = \int_{V_E} \frac{\rho(Q)}{r_{PQ}} dv_Q + \frac{1}{2}\omega^2(X_P^2 + Y_P^2) \tag{2}$$

where $V(P)$ is the gravitational potential, $CP(P)$ is the centrifugal potential, $\rho(Q)$ is the Earth mass density inside the Earth volume V_E, $r_{PQ} = |\bar{r}_P - \bar{r}_Q|$ is the distance between the computational point P and the integration point Q inside the masses, ω is the mean angular velocity of the Earth and X_P, Y_P are the cartesian coordinates of P in the geocentric 3D Cartesian reference frame, as defined in the previous section. Given the gravity potential $W(P)$, the equipotential surfaces of the field and the plumb lines can be defined. An equipotential surface is the surfaces where the gravitational potential assumes a constant value K, i.e.:

$$W(P) = K \tag{3}$$

The plumb lines are the lines orthogonal to the equipotential surfaces of the field (see Figure 5-2).

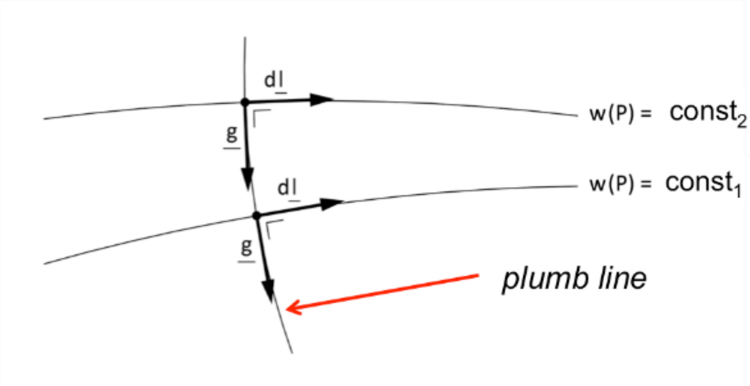

Figure 5-2*:* equipotential surfaces and plumb lines

The geoid is a particular equipotential surface of the gravity field of the Earth that coincides with the Mean Sea Level (MSL) with a maximum discrepancy of 1÷2 m at global scale. This surface is the so-called geoid and is continued over land areas by analytical methods.

The orthometric height H_P of a generic point P, e.g. lying on the Earth surface, is the length of the plumb line between P an P_0 (see Figure 5-3).

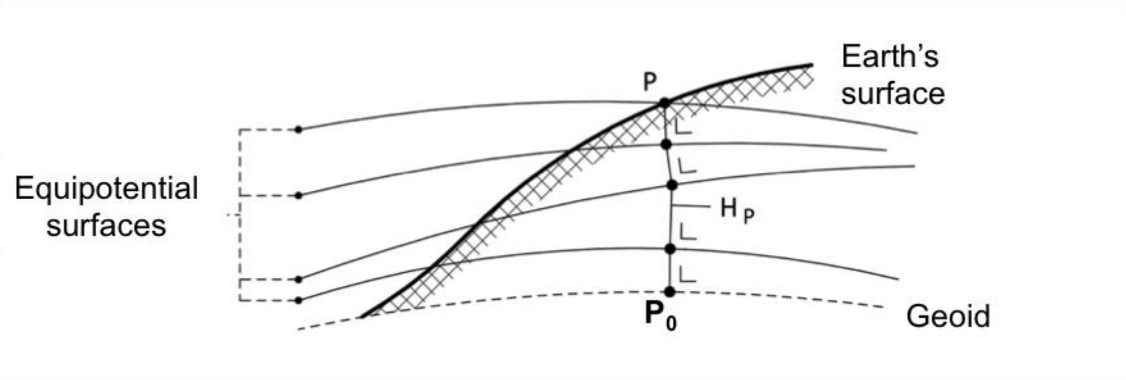

Figure 5-3: the geoid and the orthometric height

Analytically, the orthometric height can be expressed in terms of the geopotential number $C(P)$, i.e.

$$C(P) = \int_{P_0}^{P} g \, \mathrm{d}\ell = W_0 - W_P \tag{4}$$

where P_0 is the projection of point P on the geoid along the plumb line, $W_0 = W(P_0)$ is the gravitational potential associated to the geoid surface, P is the considered point, $W_P = W(P)$ is the gravitational potential at P, $g = |\nabla W|$ and the integral is taken along the plumb line ℓ from P_0 to P.

It can be proved that the orthometric height $H(P)$ is given as

$$H(P) = \frac{C(P)}{\bar{g}(P)} \tag{5}$$

where

$$\bar{g}(P) = \frac{1}{H_P} \int_{P_0}^{P} g \, \mathrm{d}\ell \tag{6}$$

5.2.3 The normal height

The normal height H_P^* of a point P can be defined following the same approach used in the definition of the orthometric height [7]. For that, we consider the normal potential U and the modulus of the normal gravity $\gamma = |\nabla U|$ of the Mean Earth Ellipsoid. We can write for a given point Q

$$\int_0^Q \gamma \, \mathrm{d}h = \int_0^Q -\mathrm{d}U = U_0 - U_Q \tag{7}$$

where U_0 is the normal potential at the ellipsoid and the integral is along the normal to the ellipsoid. If we further assume that $U_0 = W_0$ and $U_Q = W_P$ where P is on the Earth surface, we have

$$\int_0^Q \gamma \, \mathrm{d}h = U_0 - U_Q = W_0 - W_P = C(P) \tag{8}$$

Therefore, the normal height H_P^* is given as

$$H^*(P) = \frac{C(P)}{\bar{\gamma}_Q} \tag{9}$$

with

$$\bar{\gamma}_Q = \frac{1}{H_P^*} \int_0^Q \gamma \, \mathrm{d}h \tag{10}$$

Thus, we can say that the normal height of P, $H^*(P)$, is equivalent to the height of Q above the ellipsoid.

5.3 Height observations and their accuracy

Ellipsoidal height can be observed using GNSS techniques. In standard GNSS campaigns using double-frequency geodetic receivers and performing real-time or post-processing relative positioning by phase observations, or by precise point positioning, the ellipsoidal heights can be observed with a standard deviation of a few centimetres (less than 5 cm). This accuracy decreases depending on the quality of the instrument and on the processing methodology, e.g. it could reach the level of a few metres if stand-alone low-cost single frequency receivers are used.

Orthometric height of a point B can obtained through spirit levelling [3] starting from a point A of known orthometric height, as:

$$H_B - H_A = \Delta L_{AB} + \int_A^B \frac{g - \gamma_0}{\gamma_0} dl + H_B \frac{\gamma_0 - \bar{g}_B}{\gamma_0} - H_A \frac{\gamma_0 - \bar{g}_A}{\gamma_0} = \Delta L_{AB} + \Delta H^{ort} \tag{11}$$

where H_A and H_B are the orthometric height of the points A and B, respectively, ΔL_{AB} is the observed levelling increment, ΔH^{ort} is the "orthometric correction" and γ_0 is a suitable value of the normal gravity field, i.e. the gravity field of the Mean Earth Ellipsoid.

To define the reference frame, a common technique is to define a benchmark of known orthometric height using a tide gauge to estimate the Mean Sea Level. Figure 5-4 describes a modern tide gauge. This technique is used to define the reference frame at a national or continental level. Usually each country also defines a network of benchmarks linked to the tide gauge to be used as a reference for local surveys.

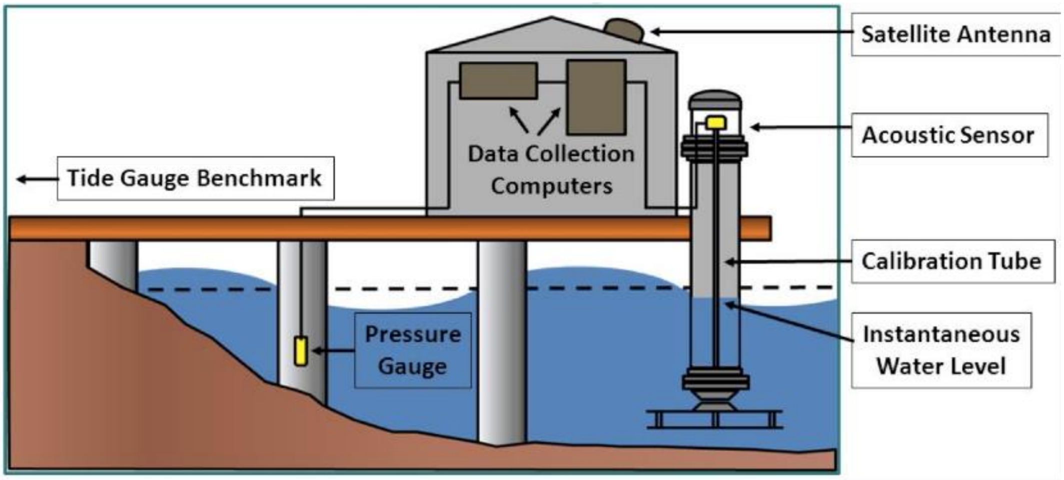

Figure 5-4: the tide gauge scheme

As for normal heights, they can also be derived starting from a spirit levelling technique [3]. In particular, observing the increments ΔL_{AB} the height increment between two points A and B can be written as

$$H_B^* - H_A^* = \Delta L_{AB} + \int_A^B \frac{g-\gamma_0}{\gamma_0} \mathrm{d}\ell + H_B^* \frac{\gamma_0 - \bar{\gamma}_B}{\gamma_0} - H_A^* \frac{\gamma_0 - \bar{\gamma}_A}{\gamma_0} = \Delta L_{AB} + \Delta H^* \quad \textbf{(12)}$$

where ΔH^* is the “normal correction”.

Orthometric and normal heights estimated from spirit levelling are usually highly precise. The standard deviation of a spirit levelling line is described according to the following rule

$$\sigma = k\sqrt{L} \quad \textbf{(13)}$$

where L is the total length of the levelling line and the constant value k depends on the chosen instrument. In particular, for very high and high precision levelling its value ranges between 0.5 mm/km and 2 mm/km, respectively.

5.4 Conversion between height systems

The transformations between two different height systems are very well established in the literature. They will be explained in the following paragraphs, with some comments on their expected precisions.

5.4.1 Orthometric height and Ellipsoidal height

The relationship between the orthometric height $H(P)$ and the ellipsoidal height $h(P)$ of a point P is defined as

$$h(P) \cong H(P) + N(P) \tag{14}$$

where $N(P)$ is the geoid undulation, i.e. the height of the geoid above the ellipsoid along the normal to the ellipsoid (see Figure 5-5).

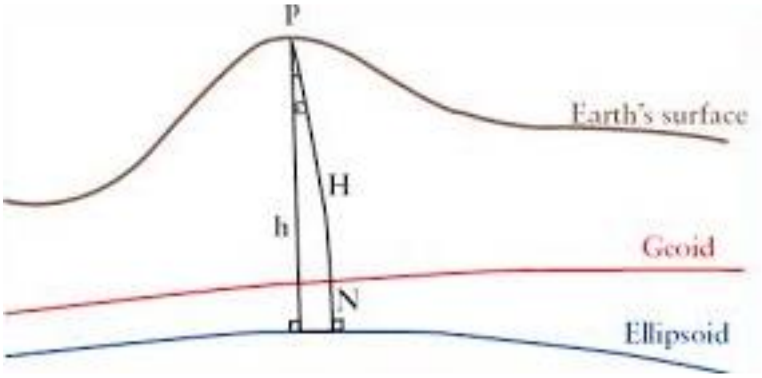

Figure 5-5: ellipsoidal height $\boldsymbol{h(P)}$, orthometric height $\boldsymbol{H(P)}$ and geoid undulation $\boldsymbol{N(P)}$

It must be mentioned that this relationship is, rigorously speaking, an approximate equation. In fact, while h and N are line segments, H is not, being measured along the plumb line that is a double curvature line. However, this equation holds up to a few tenths of a millimetre, so can virtually be considered rigorous given the actual observation accuracy of h, H and N.

The geoid undulation N can be estimated by observing the Earth's gravity field and is available at global, continental and local levels.

Global Geopotential Models (GGMs) give the geoid undulation estimate over the entire Earth. They are estimated either from dedicated satellite gravity missions (e.g. the ESA GOCE mission[16]) or from a combination of satellite and ground-based gravity data (e.g. EGM2008 [18]-[19], see Figure 5-6).

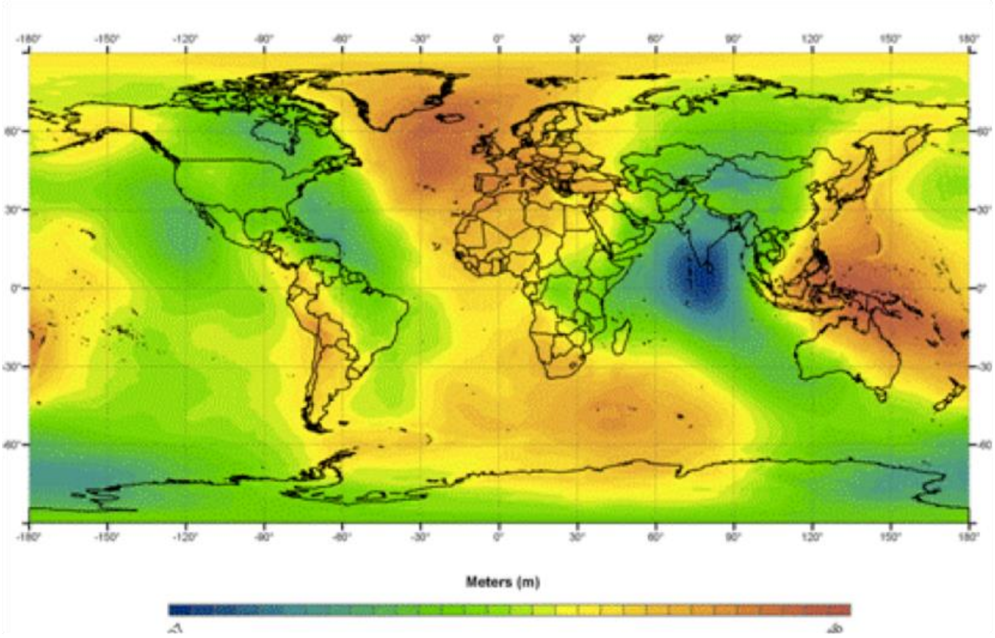

Figure 5-6: the global geoid model EGM2008 [18]-[19]

They are usually expressed as a truncated spherical harmonic expansion, i.e.

$$N(P) = \frac{GM}{\gamma_e(P)} \sum_{n=0}^{N_{max}} \left(\frac{\bar{R}}{r_e(P)}\right)^{n+1} \sum_{m=0}^{n} (C_{nm}\cos(m\lambda_P) + S_{nm}\sin(m\lambda_P))P_{nm}(\cos\vartheta_P^S) \tag{15}$$

where the point P is on the ellipsoid, $\gamma_e(P)$ is the normal gravity at the point P, $\bar{R}$ is the radius of the reference sphere associated to the global model, $r_e(P)$ is the reference ellipsoidal radius at the point P, $P_{nm}(\cos\vartheta)$ are the associated Legendre functions of degree n and order m, $\{C_{nm}, S_{nm}\}$ are the spherical harmonic coefficients of the anomalous potential $T(P) = W(P) - U(P)$ and λ_P, ϑ_P the spherical coordinates of the point P. High order GGMs can have $N_{max} = 2190$ or more and thus can have quite a high frequency content. The precision of the geoid undulation of the high resolution GGMs is between 15-20 cm in the areas where the ground gravity data coverage is dense. As already mentioned, they are available over the entire Earth and can thus be profitably used in linking the ellipsoidal and the orthometric heights at global level, according to the formula given at the beginning of this section. A detailed description of the available GGMs can be found at the International Centre for Global Earth Models (ICGEM), an official service of the International Association of Geodesy (IAG) (see ICGEM the web page: *http://icgem.gfz-potsdam.de/home*) hosted at GFZ in Potsdam [10].

An observation is necessary: λ_P, ϑ_P^S are the spherical coordinates of the point P on the ellipsoid surface and must not be confused with the ellipsoidal ones, commonly used by GNSS receivers. They can be obtained by exploiting the following relationship between the geocentric Cartesian 3D reference frame and the spherical coordinates of a generic point P:

$$\begin{cases} X_P = r_P \sin\vartheta_P^S \cos\lambda_P \\ Y_P = r_P \sin\vartheta_P^S \sin\lambda_P \\ Z_P = r_P \cos\vartheta_P^S \end{cases} \tag{16}$$

Continental geoid models are usually computed and made available to users as a map of the geoid undulation on a suitable regular grid. They are estimated using a dense local gravity dataset and they are generally more precise than the GGMs. In fact, their accuracy is usually around 8 cm. They can be used in the transformation formula $h \leftrightarrow H$ over a limited portion of the Earth's surface, e.g. only over the corresponding continent. As an example, we can mention the European (quasi)geoid EGG2015 [5] (see section 5.4.2 for the quasi-geoid definition) which holds for Europe (see Figure 5-7). It is estimated over a regular $1' \times 1'$ geographical grid in the area $25° < \varphi < 84° \quad -50° < \lambda < 70°$.

Finally, local national geoids are also available. Like the continental models, these are usually estimated over a country or a region. They can reach a precision of 2-3 cm due to the availability of denser ground gravity data. They are sometimes classified and thus not always freely available. As an example, we can mention the Italian (quasi) geoid ITALGEO2005 [2], which is estimated over a regular $2' \times 2'$ geographical grid in the area $35° < \varphi < 48° \quad 5° < \lambda < 20°$ (see Figure 5-8).

A large collection of continental/regional/local geoids is available at the International Service for the Geoid (ISG), another official service of the International Association of Geodesy (IAG) (see ISG the web page: *http://www.isgeoid.polimi.it*) hosted at DICA - Politecnico di Milano in Milan [21]. A web-based height conversion service that uses the models freely available in the collection is available, among other services offered.

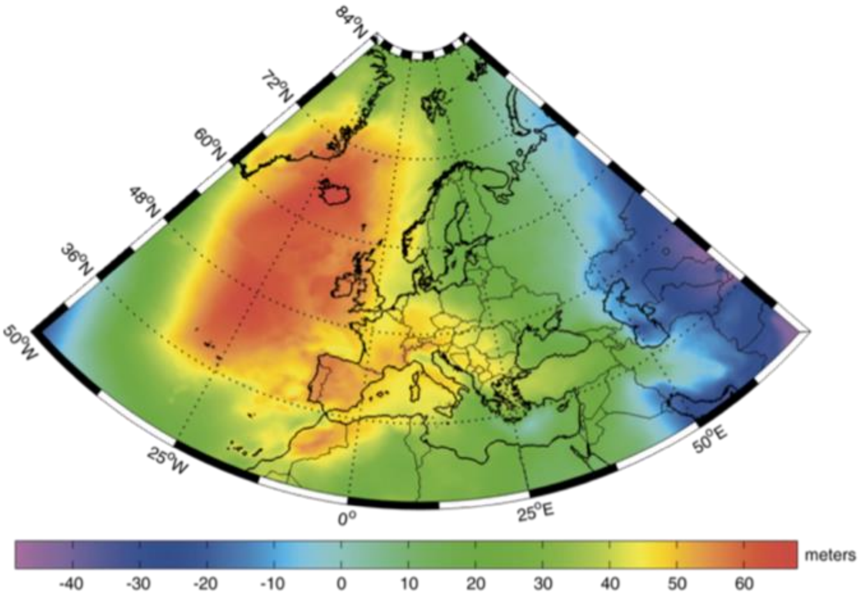

Figure 5-7: the European (quasi) geoid EGG2015 [5]

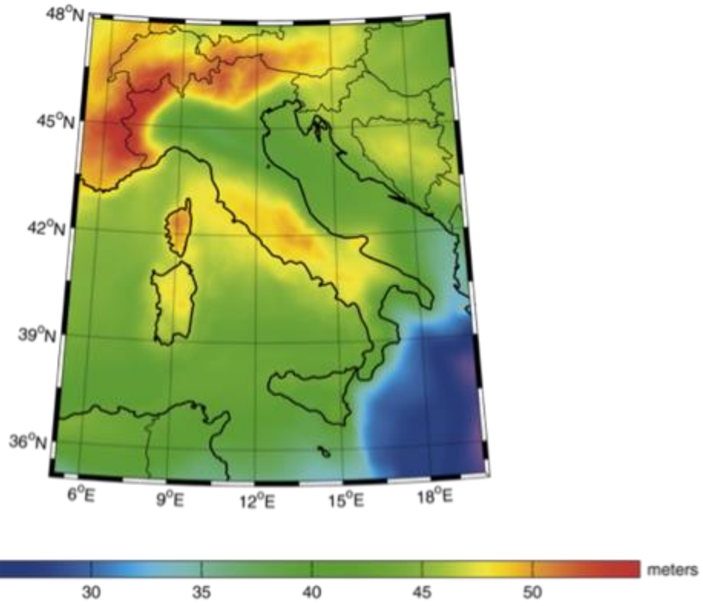

Figure 5-8: the Italian (quasi) geoid ITALGEO2005 [2]

All in all, the equation that is used for getting H from h, or viceversa, holds at a precision level that, in the worst case, is of the order of 30 cm (i.e. when GGMs are used for estimating N).

Moreover, as continental/regional/local geoids are typically provided in the form of gridded data, an interpolation is required to evaluate the geoid undulation at an arbitrary point. Typically, a bilinear interpolation among the closest four grid nodes is used through the following formula:

$$N(P) = N_{i+\xi,j+\eta} = (1-\xi)(1-\eta)N_{i,j} + \xi(1-\eta)N_{i,j+1} + \eta(1-\xi)N_{i+1,j} + \xi\eta N_{i+1,j+i} \quad \textbf{(17)}$$

where $N_{i,j}$, $N_{i+1,j}$, $N_{i,j+1}$, $N_{i+1,j+1}$ are the geoid undulations of the closest point to *P* and $\xi, \eta \in [0,1]$ are relative distances of the point *P* with respect to the grid step in the row and column directions, respectively, see Figure 5-9.

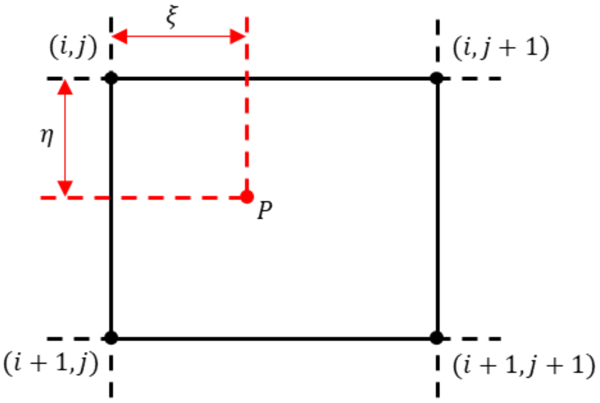

Figure 5-9: bilinear interpolation

5.4.2 Normal height and Ellipsoidal height

When considering normal and ellipsoidal heights the equation to be used is

$$h(P) = H^*(P) + \zeta(P) \quad \textbf{(18)}$$

where (P) , called the height anomaly, is the separation between the Earth's surface and the telluroid. The telluroid is a surface that mirrors the Earth's surface according to the equation $W(P) = U(Q)$ with P on the Earth's surface and Q on the telluroid (see Figure 5-10).

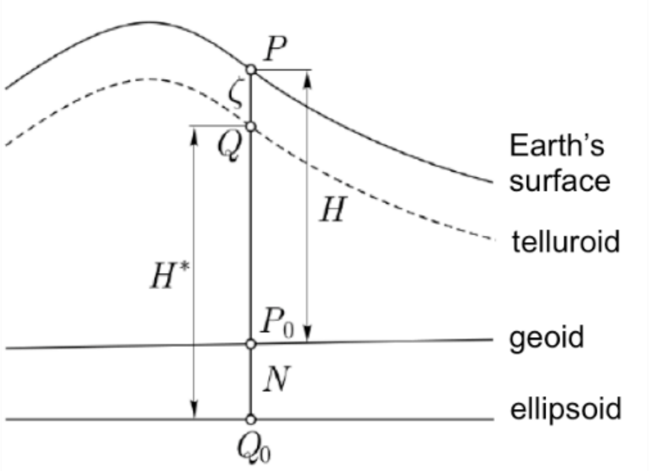

Figure 5-10: geoid and telluroid

By mapping the $\zeta(P)$ values onto the ellipsoid, one gets the quasi-geoid. It must be underlined that the quasi-geoid is NOT an equipotential surface of the gravity potential, as is evident from its definition.

All the discussion in section 5.4.1 on the geoid holds for the quasi-geoid. Quasi-geoid models are available at global, continental and regional levels and can be used to perform the conversion. Thus, the expected precisions in the formula $h \leftrightarrow H^*$ are substantially the same as described for $h \leftrightarrow H$.

5.4.3 Orthometric height and Normal height

If orthometric heights have to be calculated from normal heights (and vice-versa), the equation to be applied is derived, as shown in Figure 5-10, as:

$$\begin{gathered} h(P) = H(P) + N(P) \\ h(P) = H^*(P) + \zeta(P) \end{gathered} \tag{19}$$

which implies that

$$H(P) + N(P) = H^*(P) + \zeta(P) \tag{20}$$

For the expected precision of this conversion formula, please refer to the discussion in section 5.4.1

Furthermore, the most commonly used transformation between geoid undulations and height anomalies is given by the following approximate formula [7]:

$$N(P) = \zeta(P) + \frac{\Delta g_B(P)}{\bar{\gamma}} H(P) \tag{21}$$

where Δg_B is the Bouguer gravity anomaly, $\bar{\gamma}$ is mean normal gravity, and H is the orthometric height. In mountainous areas, this approximation can introduce errors of the order of tens of centimetres [6].

5.4.4 Orthometric height and atmospheric pressure

Strictly speaking, the relationship between atmospheric pressure and orthometric height is not a conversion between two height systems. This relationship is described here. This is a relevant equation for the ICARUS project since atmospheric pressure is used to estimate the flight altitude on both manned and unmanned aircraft, especially in general aviation. In particular, it is used to determine the QNE, QNH and QNE values that are typically used to calibrate the altimeter in general aviation.

The equation that allows the difference in orthometric height H to be estimated as a function of the atmospheric pressure can be obtained as follows:

If we consider a gas column of area S and height H, its weight F is

$$F = mg = (\rho S H) g \tag{22}$$

where ρ is the gas density and g is the acceleration due to gravity. The gas pressure P is then given by

$$P = \frac{F}{S} = \rho H g \tag{23}$$

and, by differentiating, we obtain

$$\mathrm{d}P = -\rho g \, \mathrm{d}H \tag{24}$$

where the minus sign means that the pressure decreases while the altitude increases.

Now, if we consider the ideal gas law

$$PV = nRT = \frac{m}{M} RT \tag{25}$$

where P, V, and T are the pressure, volume and temperature, n is the number of moles of gas, m is the total mass of gas, M is the molar mass and R is the ideal gas constant, we can get

$$P = \frac{m}{V}\frac{RT}{M} = \rho \frac{R}{M} T = \rho R_s T \tag{26}$$

where R_s is the specific gas constant. Thus, we have

$$\rho = -\frac{1}{g}\frac{\mathrm{d}P}{\mathrm{d}H} = \frac{P}{R_s T} \tag{27}$$

which implies

$$\frac{\mathrm{d}P}{\mathrm{d}H} = -\frac{g}{R_s T} P \implies \frac{\mathrm{d}P}{P} = -\frac{g}{R_s T}\mathrm{d}H \tag{28}$$

If T and g are considered constant, this is a first order linear differential equation and its solution is the “hypsometric equation”:

$$H = -\frac{R_s T}{g} \ln\left[\frac{P}{P_0}\right] + H_0 \tag{29}$$

where H_0 is the reference height at which the atmospheric pressure value P_0 is known. Although simple and straightforward, this is quite a rough approximation of the relationship between H and P. The assumption that T and g are constant in height is not usually satisfied. In fact, these two quantities change with height. Therefore, we should take this into account in solving the differential equation. This means that its solution has to be written as

$$\ln\left(\frac{P}{P_0}\right) = -\frac{1}{R_s}\int_{H_0}^{H} \frac{g(\xi)}{T(\xi)} \mathrm{d}\xi \tag{30}$$

If we now assume that the temperature is linearly dependent on the height H decreasing with a constant lapse rate L, i.e.

$$T(H) = T_0 + L(H - H_0) \tag{31}$$

where T_0 is the temperature at the reference point at height H_0, and that g can be approximated by its mean value $\bar{g}$ in the range from H_0 to H, we can get the improved solution

$$\ln\left(\frac{P}{P_0}\right) = -\frac{\bar{g}}{LR_s}\left[\ln\left(\frac{T_0 + LH}{T_0}\right)\right] \implies \frac{T_0 + L(H - H_0)}{T_0} = \left(\frac{P}{P_0}\right)^{-\frac{LR}{\bar{g}}} \tag{32}$$

The last equation can then be solved with respect to H, obtaining

$$H = \frac{T_0}{L}\left[\left(\frac{P}{P_0}\right)^{-\frac{LR}{\bar{g}}} - 1\right] + H_0 \tag{33}$$

Equation (33) is the one usually applied in estimating the flight altitude by observing the atmospheric pressure. The standard values of the parameters to be used are defined in the Manual of the ICAO standard atmosphere [9]. Therefore, in practice the reference system depends on the chosen height reference value H_0 and on the pressure P_0 at this height. The latter is usually defined according to the following convention:

- QFE is the atmospheric pressure measured at the airfield. If the barometric altimeter is calibrated at this pressure level it will show the altitude with respect to the airfield. In other words, to retrieve the orthometric height of a point P setting the altimeter at the QFE level, it is necessary to know the orthometric height H_A at the airfield. By exploiting the hypsometric equation, see Equation (29), we obtain:

  $$H_P = -\frac{R_S T}{g}\ln\left[\frac{P_P}{QFE}\right] + H_A = \Delta H_{AP} + H_A \tag{34}$$

  while exploiting Equation **(33)**, the result is:

  $$H_P = \frac{T_0 + LH_A}{L}\left[\left(\frac{P_P}{QFE}\right)^{-\frac{LR}{g}} - 1\right] + H_A = \Delta H_{AP} + H_A \tag{35}$$

- QNH is the atmospheric pressure at the mean sea level corresponding to the horizontal coordinates of the point A, e.g. the airfield. By setting the altimeter at QNH level, the result is therefore directly the orthometric height, i.e. starting from the hypsometric equation, see Equation (29), we obtain:

  $$H_P = -\frac{R_S T}{g}\ln\left[\frac{P_P}{QNH}\right] = \Delta H_{0P} \tag{36}$$

  or by using Equation **(33)**, the result is

  $$H_P = \frac{T_{H=0}}{L}\left[\left(\frac{P_P}{QNH}\right)^{-\frac{LR_S}{g}} - 1\right] = \Delta H_{0P} \tag{37}$$

  Note that usually the QNH value is determined by a ground barometric station by inverting Equation (33) for P_0, once the station height and the station pressure are known.

- QNE is the standard value of the atmospheric pressure equal to 1013.25 hPa. Therefore, the height computed by setting the altimeter at the QNE level does not have a physical meaning. In fact, it represents the altitude over the reference isobar line. This convention is usually adopted above the transition height (i.e. height greater than about 1000 m), thus it is not relevant for the drone flight.

Note that $T_{H=0}$, i.e. the temperature at H = 0, is equal to the constant value 15 °C according to the ICAO standard atmosphere model [9].

Since the QFE and QNH values are determined by a ground barometric station, there are two sources of error when computing the orthometric height at the generic point P: the first is the accuracy of the knowledge of the reference height, the second is related to the combination of barometer accuracy and model error in Equation (33). Supposing that the former has been observed by geodetic GNSS receiver (plus a geoid model) its errors are described in the previous sections, while the latter can be quantified only experimentally, as performed by Alberi et al. [1] that showed an RMS in the range 1 – 2.5 m.

It should also be noted that Equations (33), (34), (35), (36) and (37) are valid if the horizontal coordinates of the point P and of general reference point A where the reference pressure (QFE or QNH) is determined are the same. If this condition is not satisfied, correctly estimating the orthometric height from pressure observation requires a correction to be added depending on the lateral pressure variation, i.e. the height difference $A'A''$ in Figure 5-11.

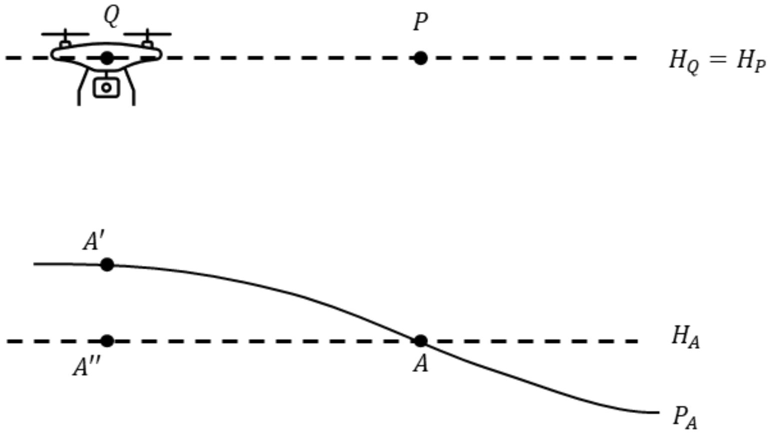

Figure 5-11: Effect of lateral pressure variations

The dashed black lines represent isolines, while solid black line represents an isobar line. Points P and Q have the same orthometric height, as do points A and A''. Point A' has the same horizontal position as Q and A'' and is the point where the pressure is equal to the pressure at A.

In Figure 5-11 the height of points P and Q is the same, as is the height of points A and A'', i.e.

$$\begin{gathered} H_P = H_Q \\ H_A = H_{A''} \end{gathered} \tag{38}$$

Starting from Equation (38) and according to Equation (33) we can therefore derive the orthometric height difference between Q and A'', i.e.

$$\Delta H_{QA''} = \frac{T_{A'}}{L}\left[\left(\frac{P_Q}{P_A}\right)^{-\frac{LR_S}{\bar{g}}} - 1\right] + \frac{T_{A''}}{L}\left[\left(\frac{P_A}{P_{A''}}\right)^{-\frac{LR_S}{\bar{g}}} - 1\right] \tag{39}$$

Recalling the temperature law of Equation (31) we can observe that $T_{A''} = T_A$ and that $T_{A'} = T_A + L\Delta H_{A'A''}$. Therefore, we can define the following quantities:

$$\Delta H_{A'A''} = \frac{T_A}{L}\left[\left(\frac{P_A}{P_{A''}}\right)^{-\frac{LR_S}{\bar{g}}} - 1\right] \tag{40}$$

$$\Delta H_{QA'} = \frac{T_A + L\,\Delta H_{A'A''}}{L}\left[\left(\frac{P_Q}{P_A}\right)^{-\frac{LR_S}{\bar{g}}} - 1\right] = \frac{T_A}{L}\left[\left(\frac{P_Q}{P_A}\right)^{-\frac{LR_S}{\bar{g}}} - 1\right]\left(\frac{P_A}{P_{A''}}\right)^{-\frac{LR_S}{\bar{g}}} \tag{41}$$

$$\widetilde{\Delta H}_{QA'} = \frac{T_A}{L}\left[\left(\frac{P_Q}{P_A}\right)^{-\frac{LR_S}{\bar{g}}} - 1\right] \tag{42}$$

$$\mu_{AA''} = \left(\frac{P_A}{P_{A''}}\right)^{-\frac{LR_S}{\bar{g}}} - 1 \qquad (43)$$

Introducing Equations (40), (41), (42) and (43) into Equation (39), we finally obtain

$$\Delta H_{QA''} = (1 + \mu_{AA''})\widetilde{\Delta H}_{QA'} + \Delta H_{A'A''} \qquad (44)$$

Since a barometric altimeter set at the P_A value measures the $\widetilde{\Delta H}_{QA'}$ term, this observation has to be correct by two terms to be able to retrieve the orthometric height difference of the point Q with respect to A: the first is a bias $\Delta H_{A'A''}$ related to the pressure difference at the reference orthometric height (see Figure 5-12) and the second is a scale factor $\mu_{A'A''}$ related to the temperature variation as a consequence of the height variation of the P_A isobar line (see Figure 5-13).

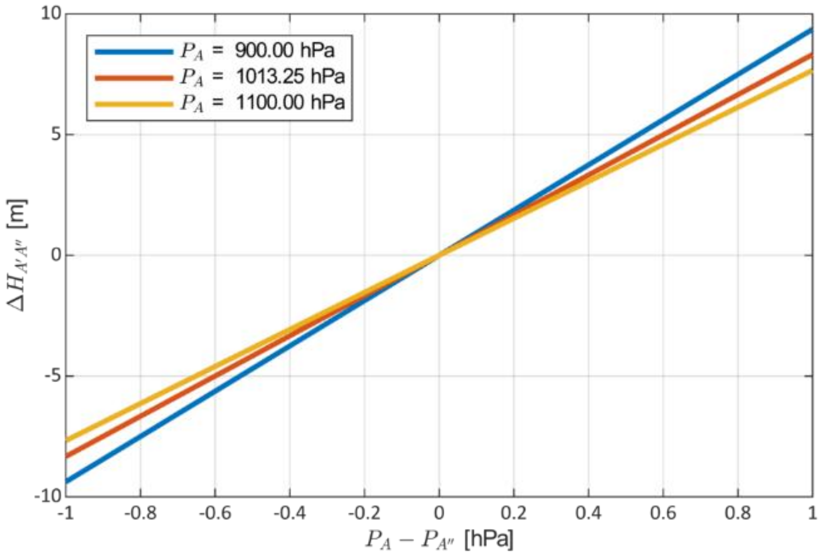

Figure 5-12: Effect of the $\Delta H_{A'A'}$ term by testing different values of P_A

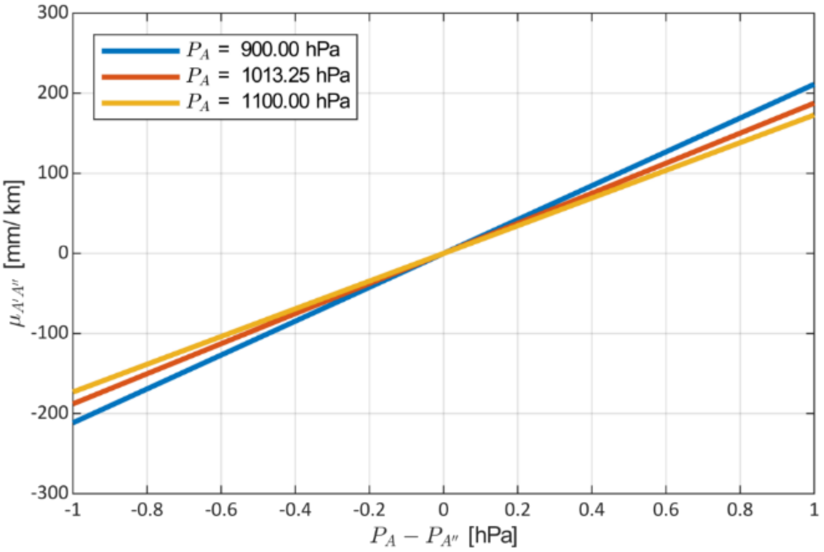

Figure 5-13: Effect of the $\mu_{A'A''}$ term by testing different values of P_A

Figure 5-12 and Figure 5-13 assume a maximum pressure variation of 1 hPa at the reference height.

These corrections have to be applied in both the QFE and QNH cases and depend on the value of $P_{A''}$, that, given a reference orthometric height, can be estimated from the pressure observations of a network of ground barometric stations, for example.

5.5 References

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6 ICARUS use cases

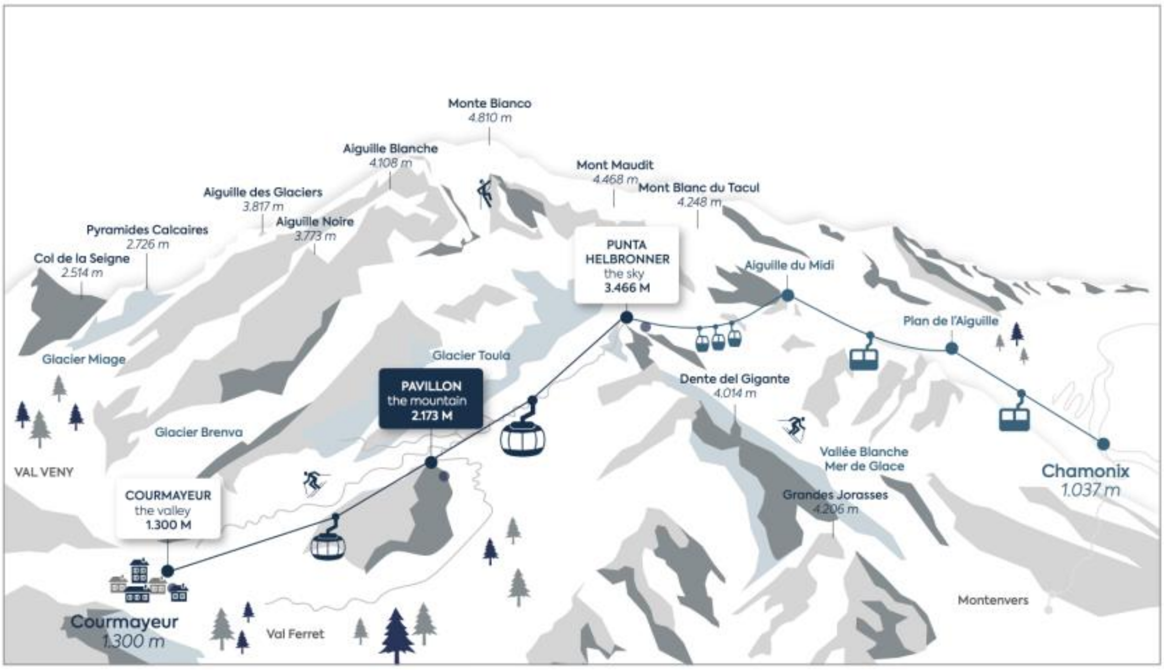
6.1 Introduction

This chapter presents five use cases. Its purpose is to present nominal situations where drones are likely to be involved in flight operations, and interactions with other drones, ground obstacles or manned aircraft are possible. Use case 0 gives the current "State of the Art" of operations undertaken with small drones, while the last use case (use case 4) envisages a future drone taxi scenario (UAM). Each use-case covers both uncontrolled and controlled airspaces, urban and non-urban scenarios, and considers different typologies of drones with different capabilities. Finally, additional details have been provided in the specification of the GNSS receivers envisaged for on-board altitude measurements.

The use cases presented here will contribute, together with the other themes described in the document, to the definition of the high-level requirements.

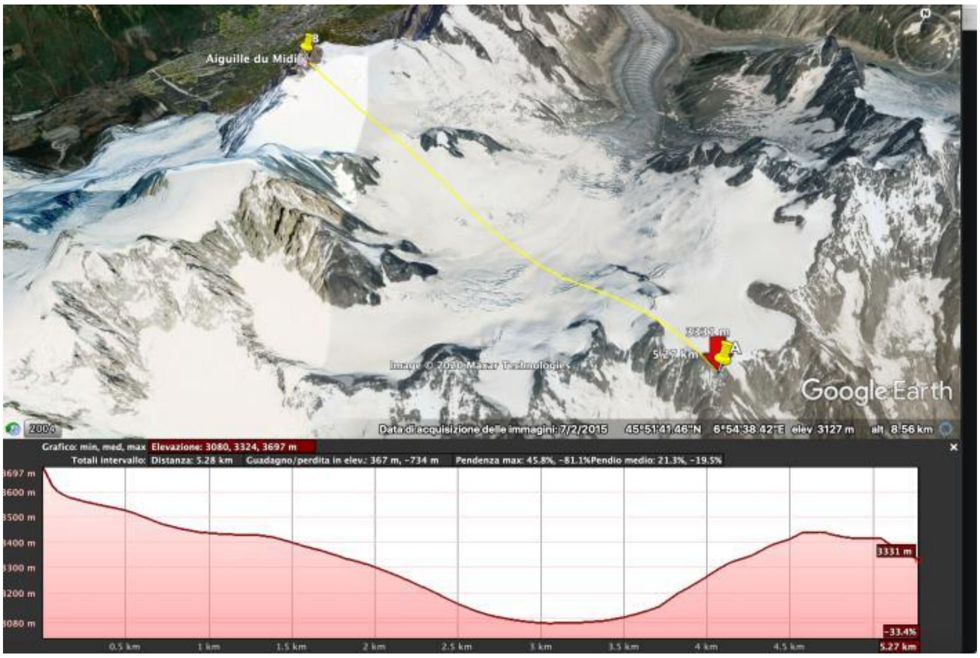
6.1.1 Use Case 0 – state of the art

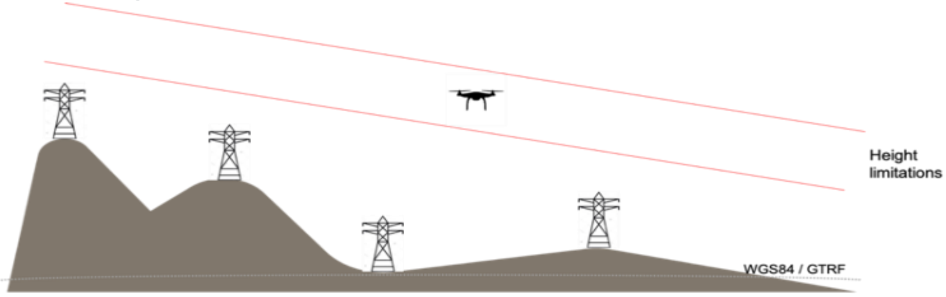
Scenario: Inspection of a ski lift / cableway between Italy and France



Storyboard	A UAS operator has been contracted to perform an industrial inspection of cableways and ski lifts using state-of-the-art UAS technology for visual and thermographic inspections of the most critical parts of the infrastructure, with a significant enhancement in terms of safety of the personnel involved in the actual procedures and with a strong cost reduction with respect to normal maintenance procedures.

	The UAS operations are requested for the inspection of one route of the infrastructure at a time; most of the cases having a strong vertical slope. All the operations fall under BVLOS conditions for the UAS operator with an average distance of 2 km to be covered in Radio Line of Sight conditions. The planning of the operations is a critical part for this mission as updated information is required about: • Position of artificial ground obstacles (including those to be inspected) • Vertical distance of the UA from the ground (drone height, AGL) • GA traffic is not expected; mitigation is achieved at the strategic phase (i.e. NOTAM issued for flying in a protected area)
UAS 	Multicopter UAS < 25 kg for Industrial inspection E.g.: DJI M300 RTK https://www.dji.com/it/matrice-300/specs • Quadcopter 9 kg MTOM • Dimensions: 810×670×430 mm (without propellers - 21’’) • Autonomy: up to 55 minutes • Wind resistance: 15 m/s • IP45 certified
GNSS Receiver	• DF (L1/L5, E1/E5a) • MC (GPS + GLONASS + Beidou + Galileo) • RTK (with private local base station or through the EUREF network or similar private networks) NO EGNOS
Altimeter settings	DATUM: Geodetic height (ref. WG84 ellipsoid): UAS home-point height over the DATUM is displayed. For example, when the UA is on the home point, the remote pilot may have the following information on their ground station display: ▪ Home point elevation: 3,439.5 m ▪ UA height (geodetic): 3,439.5 m ▪ UA height (AGL): 0.0 m ▪ Waypoint B elevation: 3,545.0 m ▪ Waypoint elevation difference = 105.5 m ▪ all the other relevant derived height/elevation information.
GIS	Cartographic information displayed to the pilot in static form (paper sheet or digital, but not interactive) ▪ example: updated AIP on a tablet (Electronic Flight Bag) in pdf digital format or printed maps in the form of paper sheets.
Manned traffic	Not foreseen for this scenario. GA traffic (helicopter) is not expected; it is assumed that the UAS operator has obtained a valid authorisation from the Civil Aviation

	Authority to fly in a protected area through the publication of a NOTAM. Interference with GA flights is mitigated in the strategic phase.
Airspace volume	X volume (according to CORUS classification)
RNP	Not applicable for this scenario. Video link return for the pilot is a mitigation and a required element of the UAS architecture to accomplish the inspection mission (video link range up to 7 km in RLOS conditions)
Challenge	- **Cross border operations:** GNSS-based altimetry (WGS-84 as datum) guarantees a common altitude reference to UAS using the same datum (with requirements to be identified in ICARUS WP3). However, an additional U-space service might be needed to provide the DTM/DSM (terrain profile), ground obstacle positions and heights (if any); this service is especially needed during the strategic phase. Cross-border inspection operations may involve two different UTM service providers (USSP), using different cartographic systems for the generation of the terrain model (DTM). The coherence of the information provided by both USSPs and possible service handover procedures are a potential challenge to be addressed  - **Terrain-following during inspection:** The critical elements of the cableway to be inspected are the cables and the trellis that support the cableway /ski lift cables. It is expected that such infrastructures have a vertical height much lower than 120 metres AGL. However, the interconnection of two of these elements may also be expected over a

	deeper crevasse of more than 120 metres. Therefore, during navigation, the UAS may experience some situations where the navigation is performed technically above 120 metres AGL in some parts. The definition of smoothed geo-caging corridors compliant with the elevation profile is expected. The corridor's height limits are expressed using a geodetic height datum. 
Note	This use case represents state-of-the-art UAS operations with the actual UAS equipped with a DFMC GNSS receiver used in RTK mode that can be summarised by: • Excellent positioning accuracy on the horizontal plane • Very promising positioning accuracy on the vertical axis • Bad GNSS signal integrity Moreover, the following should be considered: ▪ The GNSS RTK receivers mounted on-board UAS nowadays can hardly resolve phase ambiguity (float solution easily achievable, fixed solution hardly achievable especially in non-open sky conditions and with high UAS velocity). ▪ Decimetre (20-30 cm) accuracy precision on the horizontal plane and sub-metric (90 cm- 100 cm) accuracy on the vertical axis is achievable when industrial grade dual frequency GNSS receivers are used in multi-constellation mode. ▪ It is not always easy to obtain GNSS receiver information (and configuration) from UAS manufactures. This element is very important as input for the SORA analysis.

6.1.2 Use Case I – Drone Delivery in a Y airspace volume

Scenario: Spare part delivery to an offshore oil & gas platform in the Adriatic Sea

Storyboard

Drone delivery operations are implemented on a weekly basis (or on demand) from the local Port Authority premises to a nearby offshore oil & gas platform. The UAS operator in charge of operations is an express courier that has a logistic hub inside the port and makes use of UAS technology for delivering small packages to the platform or to large vessels (oil tankers) near it.

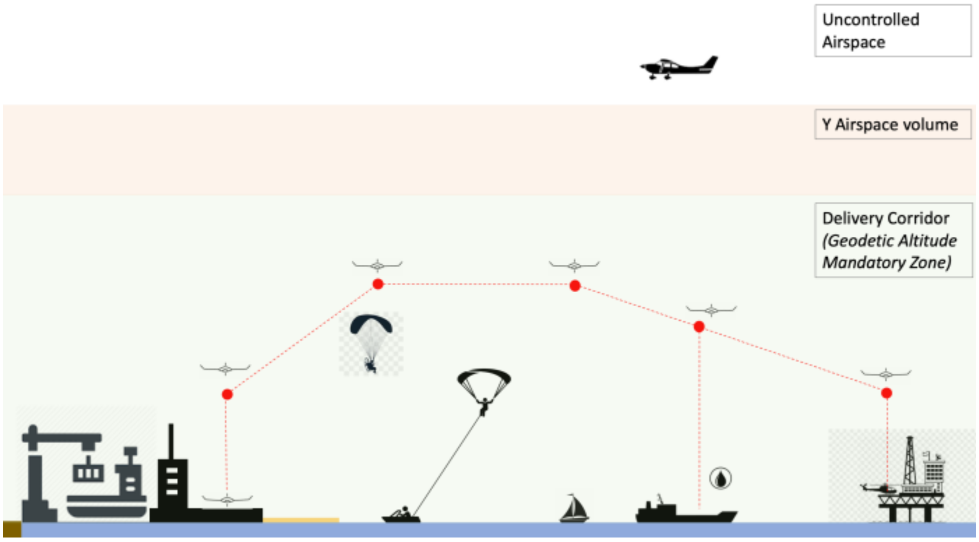
The delivery operations are authorised by the local CAA with the activation of UAS corridor for delivery missions. Considering the possibility of strong gusts of wind, the operations are generally accomplished in the morning (8:00-9:00 local time) or one hour before the sunset.

The corridor is a sub-volume of Y airspace. In this corridor it is mandatory for airspace users to measure their altitudes over the ellipsoid reference datum (WGS-84). This information is directly obtained by the GNSS receivers without requesting any other additional service and it is acceptable for common UAS-UAS height reference.

Because Y airspace is used, conflicts are resolved by U-space during the strategic phase and a traffic information service is typically provided during the flight. According to the requirements of such an airspace volume, the UAS must be capable of reporting its position to the Tracking service during the flight. The UAS position is reported to U-space with respect to the WGS-84 datum.

Key elements

- Medical kit / spare parts delivery from Port Authority premises to offshore oil & gas platform or oil tanker using a corridor;
- Route: 7 km from port to offshore oil & gas platform + 7 km back

	▪ Cruise Height: 110 m AMSL ▪ Waypoint automatic mission for UAS Assumptions: ▪ C2 link from the GCS to the UAS is redundant on two frequency bands; ▪ A contingency plan, including RTH procedures, is present; ▪ Return-to-home (RTH) procedures will not cause the UAS to fly outside the corridor; ▪ Coordination and communication with possible local traffic (i.e. helicopter landing on the same offshore platform) is handled; ▪ Information on local wind conditions and traffic over the platform is handled through VHF radio communications; ▪ Position reporting service is implemented through the 4G LTE network / LEO communications. 
UAS 	Multicopter UAS < 25 kg for package delivery • VTOL quad-plane configuration of 24.9 kg MTOM • 70 km autonomy RLOS • 6 kg payload • Dimensions: 2200×3600×830 mm • Autonomy: up to 3 hours • Engine: 4 electric motors (quad configuration) + 1 4-stroke gasoline motor (fixed-wing configuration) • Wind resistance: 18 m/s • Vision system for Accurate Landing (7 metres) • Sense & Avoid technology (or V2I for landing)
GNSS Receiver	• SF (L1) • MC (GPS + Galileo) • EGNOS Enabled

Altimeter settings	**Geodetic:** UAS home-point height over the WGS-84 DATUM is displayed to the pilot and is used for common UAS-UAS altitude reference. For example, the remote pilot's ground station might display: ▪ Hub home-point height reference: 12.0 m (geodetic height of the hub home point) ▪ Landing-pad height reference: 36.0 m (geodetic height of the landing platform) The difference in height of the two points is 24 metres.
GIS	Cartographic information displayed to pilots in static form (paper sheet or digital, but not interactive) ▪ example: updated AIP on a tablet in pdf format or printed maps on a paper sheet
Other traffic	Other UAS traffic might be present around the area of operations (close to the coast). However, conflicts should have already been resolved during the strategic phase. No U-space service involvement is needed for a common UAS-UAS altitude reference, with the assumption of a common WGS-84 datum and GNSS-based height measurement or a Performance Based Navigation approach. Leisure ultralight flights near the area of operations are a possibility, especially during the summer time. This traffic includes paragliders, hang-gliders as well as kite-surfs, kite-boats and other "tethered" flying things not typically linked to the aeronautics domain. This traffic is identified as a major air risk for this scenario that must be mitigated. In fact, in most of the cases, such manned ultralights only fly in VFR conditions and it is not uncommon for no instruments to be present on this type of aircraft (not even an altimeter!) **Assumptions** ▪ It is assumed that in the worst cases the identified ultralight flights do not have VHF radio for communications or instruments (altimeter, artificial horizon, or other analogic capsule instruments). For this category of user, a U-Space transponder (UTM box) is proposed to feed the Tracking Service. In fact, such a device could also be worn as pocket device by paragliders and leisure users (potentially, even in the form of a mobile phone app). Position reporting would be provided natively in the WGS-84 datum, considering the presence of an internal GNSS receiver. Warnings and alerts may be delivered through vibration, lights or acoustic signals. ▪ It is assumed that in many cases the remote UAS pilot is not able to see this traffic with video link feedback ▪ It is assumed that UAS cannot be seen by the other traffic
Airspace volume	Y volume (according to the CORUS classification); a corridor is defined within Y airspace.
RNP	Required Navigation Performance capabilities are envisaged in this use case and in particular:

	▪ **RNP 0.01 (18-metres buffer**) on the horizontal and vertical axes is feasible for this typology of drone in a quadcopter configuration (during take-off/landing phase) ▪ **RNP (somewhere from 0.01 to 0.1 – 18 to 180-metres buffer)** is expected for this typology of drone flying in a fixed-wing configuration. Video Link return is available for the pilot and used as mitigation for mobile obstacle detection (e.g. tall vessels) and for remote landing procedures. Drone telemetry for the UAS operator and position reporting to U-space is mandatory in this flight corridor.
Challenge	• **Altitude reference with other ultra-light traffic:** The common altitude reference system also for GA shall be considered (i.e. Reporting service, ADS-B or a dedicated U-space service to be used also by GA). • **U-space / ATC Interface at procedural level:** Air information service is not always provided in class G airspace. A possible mitigation strategy can be put in place with the introduction of the VLL “Geometric Altitude Mandatory Zone”. The agreed corridor (over the sea) can be accessed by drones or GA flights that set their altimeters on the WGS-84 datum or GA flights that report their position, according to a given procedure, to the U-space position reporting service (i.e. tracking service) or a dedicated U-space service potentially used also by GA. • **Landing on a remote site:** The oil & gas landing platform can potentially be a resource shared with helicopters or other drone operators. Coordination and communication with the platform control tower are also needed for other information such as local weather (e.g. weather conditions, wind gusts).
Note	This use case represents the next step for drone delivery operations. Many pilot projects have started in the last two years, however the common altitude reference problem for UAS and GA has not yet been solved. This use case focuses on: • first ATC/U-space procedural mitigation (strategic / tactical phase) • WGS-84/barometric datum translation service requirements • Certification of GNSS receivers for UAS (EGNOS-enabled) with better integrity features

6.1.3 Use case II – Power line inspection in Y airspace

Scenario: inspection of a power line in Poland 	
Storyboard	A UAS operator has been contracted for the industrial inspection of a power line, since access to the area of operation renders inspection with helicopters difficult. A thermographic analysis is requested to detect potential hot spots and to collect data for later maintenance scheduling. The resulting inspection will be cheaper, quicker, safer and more effective than normal helicopter maintenance procedures, reducing costs and enhancing the safety of people involved in the operations. The operation requires scanning volumes (corridors) each about 2-3 km long, with electric pylons heights up to 100 m. All the operations fall under BVLOS condition in an uncontrolled airspace. Planning of the power line inspection requires: ▪ 3D terrain mapping to determine the flight path ▪ updated obstacle mapping, with at least the position and height (AGL) of towers and cables; ▪ a trained operator for reading the inspection results; ▪ drones suited for power line inspection work (protection against electrical field and magnetic interference) ▪ low GA traffic is expected; low drone traffic might be present. Deconfliction is achieved in the strategic phase by uploading the flight plan in advance to the USSP.
UAS 	Hexacopter RPAS < 25 kg for industrial inspection equipped with RGB cameras, thermal camera and LIDAR for powerline maintenance (impact of vegetation nearby the infrastructure, 3D model reconstruction, etc.) • Hexacopter drone (24 Kg MTOM) • 20 km autonomy RLOS (C&C encrypted, ADS-B in)

	- Up to 8 kg payload - Dimensions: 1680 x 1680 x 840 mm - Diameter with rotors: 2330 mm - Autonomy: up to 60 minutes
GNSS Receiver	- DF (L1/L5, E1/E5a) - MC (GPS + GLONASS + Beidou + Galileo) - RTK (with private local base station network or through the EUREF network) - EGNOS enabled
Altimeter settings	Geodetic (set on WGS-84 Datum): UAS home-point height over the DATUM displayed.
GIS	Cartographic information displayed to pilots digitally using a U-space service.
Manned traffic	Other UAS traffic might be present around the area of operation. No U-space service is needed for common UAS-UAS altitude reference, with the assumption of a GNSS-based height measurement (or PBN approach) and a WGS-84 datum. Position reporting in the tactical phase is mandatory. Leisure GA traffic may be present in the area and will continue using barometric reference (e.g. QNH). Also, other technical aerial intervention (helicopters for other kinds of inspection in the same area). It is assumed that the UAS operator has obtained a valid permanent authorisation from the Civil Aviation Authority (e.g. valid for 1 year) to fly on a regular basis in an agreed limited volume. A NOTAM has been issued **Assumptions** ▪ Drone position is reported to U-space (tactical, air volume Y); ▪ Deconfliction with other drones is managed at the strategic phase (air volume Y) ▪ Drone altitude is reported using the WGS-84 datum. GNSS-based altimetry (good for quick assessments of other UAS traffic height) ▪ Drone height is translated from one datum to another (WGS-84->local QNH) by a dedicated U-space service, fed by the U-space Tracking service. The information is updated every 30 minutes and kept available for ATM as a Traffic Information Service if requested, for other airspace users (in nearby class G airspaces) broadcast over a VHF channel. ▪ GA traffic flying in VFR conditions report their position and height to Air Traffic Information (VHF, vocal communication, e.g. 1000 ft QNH) when reaching a reporting point. A simple ATM /UTM interface invoking the barometric – geodetic conversion service can be defined for reporting manned traffic position and height information to remote UAS pilots. ▪ Separation is not provided; "Stay well clear of other traffic" is accomplished in the strategic phase and procedurally during the tactical phase.
Airspace volume	Y volume (according to CORUS classification)

RNP	Required Navigation Performance Capabilities are envisioned in this use case and in particular: ▪ RNP 0.01 (18 meters buffer) on the horizontal and vertical axis is feasible for this typology of drones (hexacopters)
Challenge	• **Electromagnetic interference from power lines:** High-voltage lines generate their own magnetic field. The resulting interference increases with proximity to the power lines. This may result in temporary loss of the control link with the drone. Additional risks are potential electric arc discharge in a highly ionized environment, that can damage the flight controller and propeller. Precautions can be taken by using appropriate ferromagnetic shielding (e.g. Faraday cage for protection or spectrometer to detect and manage interference points) or more importantly by flying at a certain distance from the lines (e.g. at least 100ft) • **Field of vision limits:** Power lines can be several miles long. This requires an appropriate control range to be taken into account when planning the inspection both for the choice of the drone (autonomy) and authorisation from the CAA. Limitation of corridors for inspections (2-3 km long) may be a solution. • **Terrain and obstacle mapping:** A digital model of the terrain and obstacles must be provided to the operator to allow a safe path to be determined to prevent collisions. The obstacle map may need to be updated after any maintenance intervention. The drone itself can be equipped to scan the area and record terrain data to update the model. • **Altitude reference with other manned traffic:** The common altitude reference system must provide means of communication for solving conflictual problems in cases of multiple operations in the interested area. Translation of altitude reference may be possibly offered to both drones and GA flights.
Note	This use case is an example of a drone application to support dangerous inspection operations and increase the safety of technicians. The advantages in further using drones may be seen in multiple maintenance operations, allowing cheaper, safer, quicker and more effective intervention. An analysis of risks is required according to SORA methodology. <u>**Key elements:**</u> • GAMZ operations inside Y airspaces • Datum translation service for GA • PBN approach (implemented by GNSS-based altimetry for drones) • Reliable digital terrain information for mission planning

6.1.4 Use Case III – Autonomous drone for biological sample delivery

<table>
<tr><td colspan="2">**Scenario: delivery of biological samples to a laboratory**
</td></tr>
<tr><td>**Storyboard**</td><td>A private clinic has a great number of patients for surgeries, but preparation procedures are time-consuming since there is no laboratory on site. In fact, samples need to be transported to the nearest analysis centre 7 km away, inside the city, requiring fast transport delivery as well as rapid analysis. A drone operator has been contracted by the local city hospital (hub) to offer a biological sample delivery service using drones to small clinics (spokes) with a typical hub-and-spoke architecture.
Drone delivery may offer a significant benefit in terms of transportation time, comparing to the actual transportation procedures, especially during rush hours.


Medical professionals load the drone’s secure container, set the destination (from a pre-defined list) by using a map loaded into system, and the drone follows the path through the urban environment, on pre-arranged low-level routes designed to mitigate ground and air risk.</td></tr>
</table>

	The operation is conducted in BVLOS in a Zu volume of airspace, uncontrolled by ATM but managed by U-space. The flight is envisaged to be autonomous[4] from one docking/recharging station at the hospital (hub) to the collection point at the clinic (spoke). The mission planning must take in account: ▪ **Training medical professionals** to load/unload the payload and start drone operation (providing a digital interface at the starting base) ▪ **Updated and accurate digital 3D models of the urban environment** for path planning and with an update link for weather-condition information to ensure that the autonomy management of the mission effectively reaches the level of safety required ▪ **Missions pre-authorised** on specific low-level routes that minimise the ground and air risks. ▪ **Well-defined contingency plans** in case of non-nominal situations. ▪ **GNSS receiver accuracy** may be degraded in an urban environment during the take-off/landing procedures because of urban canyon effect (fewer satellites in view, multipath, etc.). Detect & Avoid technologies may help to fill the gap as well as using other technologies for position determination (5G, vision systems, etc.)
UAS 	Multicopter < 25 kg As an example: Matternet M2 https://mttr.net/product • VTOL Quadcopter configuration of 11.5 kg MTOM • 20 km autonomy BVLOS • Payload: 2 kg with 4 litre volume • Dimensions: 800x800x260 mm (without propellers) 1280x1280x260 mm (with propellers) • Autonomy: up to 30 min (depending on cargo and conditions) • Cruise speed: 10 m/s • Cruise altitude: 120 m AGL
GNSS Receiver	• DF (L1/L5, E1/E5a) • MC (GPS + GLONASS + Beidou + Galileo) • RTK (with private local base station network or through the EUREF network) • EGNOS-enabled
Altimeter settings	**WGS-84 datum:** UAS home-point height over the DATUM is displayed and is used for common UAS-UAS altitude reference.

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[4] Level of autonomy 4/5 according to the DroneII.com Industry Insights https://dronelife.com/2019/03/11/droneii-tech-talk-unraveling-5-levels-of-drone-autonomy/

GIS	Cartographic information is provided as a web service in the form of M2M communication. The drone itself can interact with the U-space service. ▪ Obstacle database available ▪ DTM /DSM service ▪ Video link and telemetries available to UAS operator control room Ground obstacles and maps, including 3D model of the buildings are provided to the UAS operator relative to the datum used for Common Altitude Reference (U-space Geospatial Information service)
Manned traffic and other drone traffic	Other UAS traffic might be present in the urban area, considering the Zu volume. All UAS must provide position reporting. Moreover, tactical deconfliction is offered to the drone pilot or to the drone itself by U-space UAS-UAS altitude reference is possible with vertical accuracy to be evaluated. However, considering the environment, additional information might be needed on: ▪ Navigation Coverage information ▪ GNSS signal Monitoring (Integrity information / "trust" in the GNSS measured signal, presence of jamming or cybersecurity threats) ▪ Electromagnetic interference information Manned traffic, specifically helicopters, could be encountered at take-off and landing sites, since a hospital platform may host air ambulances. Usually VFR navigation is adopted. Both manned and unmanned operations require strict communication with hospital service personnel to ensure timely medical intervention. Radio communication will therefore be adopted to coordinate operations and avoid interference. ▪ GAMZ may be temporarily removed by institutional players (i.e. during HEMS operations), forcing drones to return to home immediately or implement other defined contingency plans. ▪ Low-level drone routes inside GAMZ must be pre-defined and well known by other GA traffic before flight Regulations stipulate that aircraft are not allowed to fly below 500 ft above urban areas, so leisure GA traffic should not be encountered during the low-level UAS routes inside Zu airspace.
Airspace volume	Zu
RNP	Required Navigation Performance capabilities are envisaged in this use case and in particular:

	▪ RNP0.005 (9-metres buffer) or RNP0.003[5] (5 metres) on the horizontal and vertical axis is feasible for this type of drone. ▪ A number of narrow vertical "corridors" can be defined over the cities in order to enhance the airspace capacity. Drones traffic cannot be separated vertically without precise height measurements, therefore new methodologies to (2-3 or 4 levels are expected at VLL, ICARUS study is studying under which conditions this is possibility) Video link return is available in the UAS operator fleet control room and used when needed.
Challenge	Challenges for these kinds of operation are related to the level of autonomy expected, since the presence of people in the urban area requires pre-arranged routes that minimise the ground risk to people not aware of these operations. In particular: ▪ **Geospatial Information service** (U-space service) for accurate 3D model of buildings (ground risk); ▪ **Population Density Map** (U-space service): Heatmaps of population in pre-flight and tactical phase for safety assessment; ▪ **Electromagnetic Interference Information** (U-space service) ▪ **Autonomy:** This operation is envisaged to have a high degree of autonomy. However, a UAS operator control room is required for monitoring the operations of the fleet • **Other technologies** are needed such as Detect & Avoid systems for ground obstacles (multi-stereo cameras, LIDAR, etc.) and ADS-B (in / out) for direct local communication with manned aircraft that have this technology. • **Micro weather** information is needed (at least over landing and take-off hubs). • **Cyber security threats:** Both for C&C / telemetry link and for GNSS SIS. New EGNSS services (OS-NMA[6]), providing authentication of GNSS user terminals may represent a mitigation for meaconing, spoofing and other intentional threats for GNSS signal)

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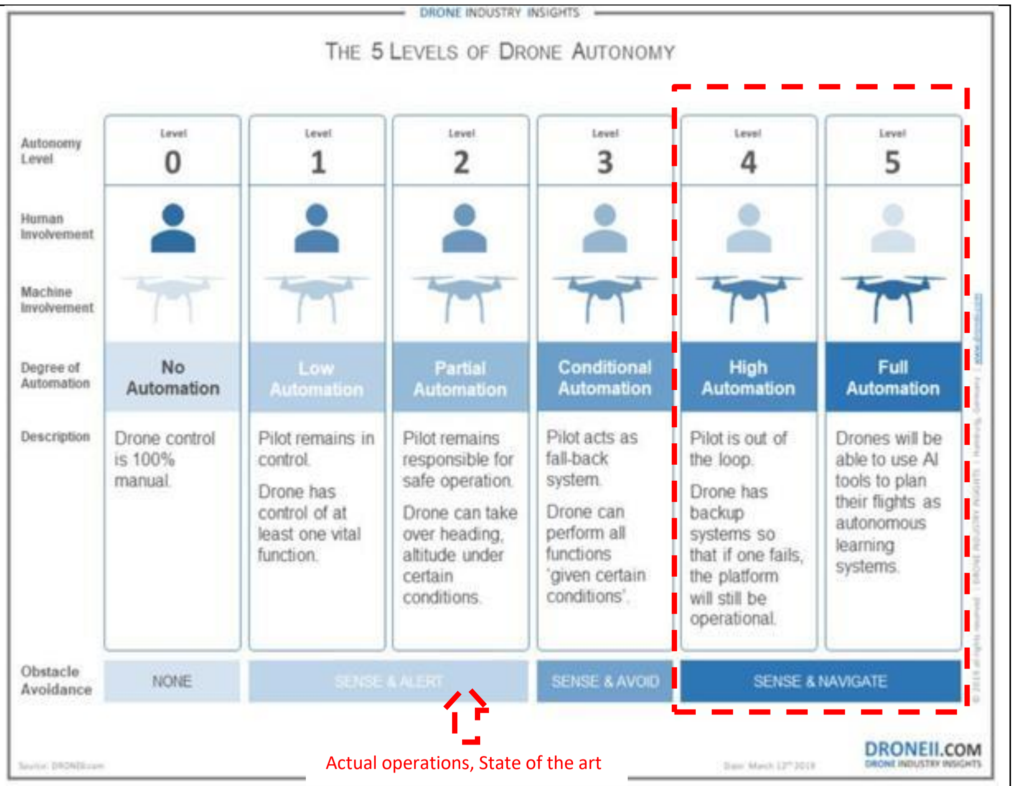
[5] RNP0.003 (about 5 metres of buffer) capability is equivalent to RUNP5 capability defined in CORUS ConOps examples.

[6] https://www.gsa.europa.eu/newsroom/news/new-generation-os-nma-user-terminals



Autonomy Level	Level 0	Level 1	Level 2	Level 3	Level 4	Level 5
Degree of Automation	No Automation	Low Automation	Partial Automation	Conditional Automation	High Automation	Full Automation
Description	Drone control is 100% manual.	Pilot remains in control. Drone has control of at least one vital function.	Pilot remains responsible for safe operation. Drone can take over heading, altitude under certain conditions.	Pilot acts as fall-back system. Drone can perform all functions 'given certain conditions'.	Pilot is out of the loop. Drone has backup systems so that if one fails, the platform will still be operational.	Drones will be able to use AI tools to plan their flights as autonomous learning systems.
Obstacle Avoidance	NONE	SENSE & ALERT	SENSE & ALERT	SENSE & AVOID	SENSE & NAVIGATE	SENSE & NAVIGATE

Actual operations, State of the art

- **Landing on a remote site in an urban environment:** Autonomous take-off and landing need to be reliable enough to complete the mission without involvement of people or facilities. Traditional GNSS-based operation may degrade in an urban environment, so a solution may be to integrate vision-based systems (and or other proximity technologies) to ensure a safe distance from surrounding obstacles.
- **Failures in an urban environment:** Failure is a possibility in mid-flight, posing a danger for people. Systems must be installed to avoid any kind of harm (e.g. flight termination systems with parachutes to reduce the descent velocity).
- **Urban mapping:** A digital model of the terrain and obstacles must be provided to the operator and updated regularly to guarantee the safe execution of the mission. In an urban environment, accuracy of the models should be enhanced and updates should be more frequent, since buildings and infrastructure may change very dynamically. The period of update must be chosen carefully to record significant/dangerous changes.

Note	Drone delivery plays an important role in time-demanding operations. To maintain the time advantage, an increasingly high level of autonomy will be required, until independence from planning can be reached. This requires further self-diagnostics and fail-safe capabilities that can be achieved today with the integration of multiple sensors.

6.1.5 Use Case IV – Air-taxi Operations

Scenario: Air-taxi service from an airport to the city centre

Storyboard	Business travel often requires a strict time schedule and time wasting because of traffic congestion can be very annoying. An air-taxi is requested to transport one person from the airport to a vertiport located inside the city, thus using the air to avoid other vehicles and reach the destination faster. A dedicated air-taxi operator area is situated far away from the airport apron but still in the ATZ, within easy access of airport passengers. The operator asks the air taxi passenger for their destination and sets the route for the flight, following procedures and routes pre-approved by the local CAA, to avoid any kind of conflict with manned traffic. Since the air-taxi service will provide a comfortable cruise for its passengers late in the evening, a lighting system similar to that used on manned aircraft will allow it to be visible to other traffic. Departing from the airport and reaching the vertiport in the city will require a flight of approximately 16 km. The flight will be performed in BVLOS conditions, starting from a controlled airspace (ATZ) and then flying and landing in an airspace uncontrolled by ATM, but served by U-space services (Zu). Once the destination has been reached, the air-taxi will return to the airport station or wait on the veritport's landing pad to recharge its power supply.
UAS	For example: Volocopter air taxi For reference: https://www.volocopter.com/en/urban-mobility/

	https://press.volocopter.com/images/pdf/Volocopter-WhitePaper-1-0.pdf • Capacity: one passenger • Length: 3.20 m excluding propeller ring • Width: 9.15 m including propellers • Height: 2.15 m • Empty weight: 290 kg • Gross weight: 450 kg • Maximum speed: 100 km/h • Range: 27 km at 70 km/h • Endurance: 27 minutes
GNSS Receiver	• DF (L1/L5, E1/E5a) • MC (GPS + GLONASS + Beidou + Galileo) • Supposed EGNOS (V3) enabled (integrity for GPS and Galileo) • Supposed Galileo Next generation enabled
Altimeter settings	**WGS-84 datum:** before entering the GAMZ in the Zu volume **QNH / QFE Barometric:** when entering or departing from ATZ airspace only Both measurement (supposed certified) systems are available to the autopilot computer. A strong connectivity with U-space services guarantees the use of the required reference system in the corresponding airspace (e.g. barometric for ATZ, geodetic for Y, Zu outside the ATZ)
GIS	Cartographic information is provided as a web service in the form of digital M2M communication. The air-taxi itself can interact with U-space services. ▪ Updated obstacle database available ▪ DTM /DSM service
Manned traffic	While operating in the ATZ, the presence of both manned VFR and IFR traffic is certain. ATM services are required to coordinate with the air-taxi operator to avoid conflict. The taxi drone must handle the requirement applicable in ATZ airspace when entering /departing from ATZ. Other air-taxis operating to different destinations are possible especially at large airports. **Assumptions** ▪ The air-taxi is visible to terminal radars so that ATC can track it and record its position and altitude information. Transponder equipment will allow more precise tracking and easier recording of data by ATC. ▪ Since it is allowed to enter the ATZ, manned traffic is equipped with at least VHF radio for communication with ATC. This will be the minimum link for manned pilots to be informed of drone traffic. In the best cases, IFR aircraft equipped with a transponder will have digital information on

	their cockpit display. It is assumed that there will be a specific symbol or colour to indicate unmanned traffic. ▪ The air-taxi operator has a link with the ATC terminal service to be informed of manned traffic (e.g. M2M link reporting radar display) for surveillance purposes. .
Airspace volume	(ATZ) Za, Y, Zu volumes
RNP	A Required Navigation Performance approach with very strict requirements when accessing the GAMZ (Zu) is envisaged in this use case ▪ RNP 0.005 (9-metres buffer) on the horizontal plane and vertical axes still need to be proved for this type of drone Video-link return is available in the air taxi operator control room for the remote pilot responsible for monitoring the flight.
Challenge	• **Altitude reference with other traffic:** IFR aircraft equipped with GNSS receivers or ADS-B will use the same altimetry reference. VFR traffic is the main critical issue due to the lack of reliable altimetry sources for terminal procedures. Since air-taxis should be large enough to transport people and carry positioning lights, visual detection by VFR pilots may be enough to enable avoidance. If a conflict could occur, a visual separation instruction would be required from ATC. • **U-space / ATM interface at procedural level:** Standard traffic procedures might be defined for the air-taxi. These procedures should take into account: • The planned path from the aerodrome to the vertiport compatible with assessed manned terminal procedure paths; • The scheduled time of departure/arrival of the air-taxi as an independent service from a specific airline operation; • alternative paths in case there is a high level of congestion in the terminal area; • safety requirements in terms of weather conditions in accordance with the limitations of the air-taxi. Scheduled time and planned path may allow the air-taxi to be treated as a constant in general operations. • **Involvement of AT Controller:** to allow the integration of air-taxi traffic, the ATC display must include specific markers to distinguish unmanned aircraft and establish a direct communication link with the air-taxi operator in case of detected conflict. This kind of procedure may generate additional stress on the controller. This can be mitigated by integrating systems of autonomous data collection (e.g. transponders) for both reception and transmission. • **Landing on a remote site in the urban environment:** High accuracy, anti-spoofing and jamming technology is required to ensure safe localisation

	of the platform and the air-taxi itself. Vision-based landing systems may be integrated for precision landing on ground markers. • **Urban mapping:** A digital model of the terrain and obstacles must be provided to the operator to allow safe routes to be scheduled and to strategically prevent conflict. For an urban environment, updates can be more challenging, since buildings and infrastructure (e,g, cranes) may change quite often. The update period must be chosen carefully to allow significant/dangerous changes to be included. • **Sky tunnel:** A flying corridor with dimensions proportional to the RNP capabilities defined may support the remote pilot in charge of the operation, for monitoring any discrepancy against the planned trajectories.  • **Public acceptance:** In general, it is not easy to assess the impact of the new service since many factors may contribute its success. • **Vertiport:** New operations and methods, most likely similar to those for helicopters at airports and helipads, might be defined for these structures.
Note	This use case highlights the direct involvement of external people in drone operations by considering a typical air taxi operating in different type of airspaces and with different procedures. Transporting people will likely require a higher level of safety to be certified. Avoidance systems must be equipped to resolve unforeseen conflicts. Also, contingency and emergency procedures and equipment must be provided to mitigate possible problems. The area of operation may require the use of instruments capable of “speaking the same language” as manned aviation to be considered. This could include Mode-S transponders able to make the air-taxi visible to the TCAS system, so that manned-aviation pilots can perform avoidance manoeuvres if procedures fail. Further integration of ADS-B may be discussed.

6.2 Use Case Summary

	Use Case 0	Use Case I	Use Case II	Use Case III	Use Case IV
Application	Industrial ski-lift inspection	Spare parts delivery to off-shore platform	Industrial powerline inspection	Biological sample delivery between city hospital and clinics	Airport-Vertiport passenger transfer
Scenario	Mountains / rural	Above the sea	Rural / suburban	Urban / suburban	Airport / rural / suburban / urban
Actors	Remote pilot	Remote pilot, ultralight flight pilots, GA Pilot	Remote pilots, GA pilot, helicopter pilot	Drones, HEMS pilot	Tower controller, CA pilot,
Population density / anthropic activities	None / low	None / low	Low	Medium / high	Medium/high variable during the flight trajectory
UAS	Industrial grade quadcopter RPAS 9 Kg MTOM	Industrial grade VTOL RPAS 24.9 Kg MTOM	Industrial grade hexacopter RPAS 25 kg MTOM	Industrial grade quadcopter Autonomous UAS 11 kg MTOM	Ultralight taxi drone for 1 or 2 passengers autonomous/remote piloted UAS 450 kg MTOM
Interfering manned flights	None	Ultralight flights GA flight (Cessna 172) in neighbouring airspace	Other drones Helicopters aware of drones operations Leisure GA flights	Other drones HEMS	CA flights Other taxi drones Other drones
GNSS receiver	DFMC industrial grade GNSS receiver RTK NO EGNOS	SFMC industrial grade GNSS receiver EGNOS (GPS)	DFMC industrial grade GNSS receiver RTK EGNOS (GPS)	DFMC industrial grade GNSS receiver RTK EGNOS (GPS)	DFMC certified GNSS receiver RTK EGNOS V3 (GPS + Galileo) Galileo next generation
Altimeter and other navigation sensors	MEMS barometric altimeter (low accuracy) Vision system for detect & avoid and landing	MEMS barometric altimeter (low accuracy) Vision system for landing	MEMS barometric altimeter (low accuracy) ADS-B (in), LIDAR, Vision system for detect & avoid	MEMS barometric altimeter (low accuracy) ADS-B (in/out), Vision system for detect & avoid and landing	Certified barometric altimeter ADS-B (in/out), Vision system for detect & avoid and landing
Airspace	X only: Neighbouring airspace: G	Y only: Neighbouring airspace: G	Y only: Neighbouring airspace: G	Zu only Neighbouring airspace: CTR	ATZ (Za), CTR, Zu Neighbouring airspaces: G
Datum for common altitude	Ellipsoid WGS-84 for BVLOS Home point for VLOS	UAS: WGS-84 for BVLOS Ultralight flights: WGS-84 (proposed UTM box) GA flight: QNH	UAS: WGS-84 for BVLOS Ultralight flights: WGS-84 (proposed UTM box) GA flight: QNH	UAS: WGS-84 for BVLOS HEMS: QNH / ADS-B	Taxi drone: QFE (or QNH) in ATZ, WGS-84 inside GAMZ (Zu)
Key U-space services	Geospatial information service (DSM)	Tracking Altitude translation service Navigation infrastructure & Coverage information	Tracking Altitude translation service Navigation infrastructure & Coverage information	Tracking Navigation infrastructure & Coverage information Population density map (DSM – buildings 3D detailed model)	Tracking Collaborative interface with ATC Population density map Geospatial information service (DSM – Buildings 3D detailed model)
GIS	Paper sheet or digital AIP (not interactive)	Paper sheet or digital AIP (not interactive)	Digital, real time and interactive	Digital, real time and interactive	Digital, real time and interactive
RNP Capabilities	N.A.	RNP0.01 (quadcopter cfg) RNP0.05 (fixed wing cfg)	RNP0.005	RUNP 5m (RNP0.003)	RNP0.005

Table 6-1: Summary of use cases presented

6.3 References

[1] ICAO, (2008). Performance-Based Navigation (PBN) Manual, Doc 9613, 5th edition, (2017)

[2] SESAR, (2019). U-space Concept of Operations. Corus exploratory research. Edition 03.00.02, 25/10/2019

[3] DJI M300 RTK drone technical specification https://www.dji.com/it/matrice-300/specs (2019)

[4] Drone Industry Insights https://dronelife.com/2019/03/11/droneii-tech-talk-unraveling-5-levels-of-drone-autonomy/ (2019)

[5] Matternet M2 drone technical specification https://mttr.net/product

[6] OS-NMA User Terminals https://www.gsa.europa.eu/newsroom/news/new-generation-os-nma-user-terminals (2018)

[7] Volocopter VoloCity technical specification https://www.volocopter.com/en/product/ (2020)

[8] John Bradley, FAA - Advanced Air Mobility (AAM) Ecosystem Use Case (Air Taxi simulator) – TIM Technical interchange meeting (TIM) on unmanned aerial systems and urban air mobility. (2020) https://www.eurocontrol.int/event/tim-meeting-uas-uam

7 Preliminary safety assessment & compliance with EU regulation

The scope of this section is to assess the identified use cases from a safety perspective and to determine their compliance with applicable EU regulations. In particular, the following specific objectives can be defined:

- to perform a preliminary risk assessment of the five uses cases selected for the ICARUS project demonstration scenarios;
- to verify the regulatory compliance of the envisaged operations, taking into account current and expected future EU regulations on UAS.

Additional analyses will be required to confirm the applicability of this risk assessment to a specific use case during ICARUS project activities. In fact, the aim of this preliminary risk assessment is to define general safety requirements for each scenario, without providing evidence that such requirements have been implemented.

The risk posed by ICARUS use cases will be assessed using two different methodologies:

a) SORA (Specific Operations Risk Assessment) methodology developed by the Joint Authorities for Rulemaking on Unmanned Systems (JARUS) as recommended by EASA through AMC 1 to Art. 11 of Commission Regulation 2019/947; and

b) the classic ICAO risk matrix approach as defined in the ICAO Safety Management Manual (Doc 9859).

The starting point of the assessment will be the CONOPS related to each use case.

7.1 The applicable regulatory framework

The most relevant EU legal acts on the matter are:

a) The “New EASA Basic Regulation” (NBR) 2018/1139 [1] which has extended the mandate of EASA to civil drones of any mass and established a solid legal basis for a common regulatory framework in Europe for the use of such drones;

b) The Commission Implementing Regulation (IR) 2019/947 [2], for operations of UAS in the “Specific” and “Open” Categories, as lastly amended by Regulation 2020/746; and

c) The Commission Delegated Act (DA) 2019/945 [3] for putting on the market drones of less than 25 kg, as lastly amended by Regulation 2020/1058.

The NBR is already in force and has been applicable since 2018. The two Commission Acts are in force and under transition towards full applicability, which will be achieved at the end of 2023. However, the common rules on the Specific category (see below) and related risk assessment will become applicable on 31st December 2020.

According to the regulations listed above, UAS operations fall into one of three possible categories:

- “Open”, in which operations that pose a low risk to society are allowed without needing any regulatory approval. These typically include small UAS, often multicopters, flying in VLOS at less than 400 ft above ground level (AGL). These UAS often weigh less than a few kgs and may in no case have an MTOM > 25 kg (4kg over populated areas);
- “Specific” operations that pose a medium-level risk to society. This may be either because it is a relatively small UAS flying above urban areas, or because it is large - even if it is not flying over populated areas, or because the flight performances or intended operation bring it into airspaces where conflicting traffic may be present (e.g. controlled airspace; BVLOS, or flying above 400 ft AGL);
- “Certified”, in which, due to the high societal risk, the entire range of aviation regulatory processes (i.e. airworthiness, licensing of remote pilots and requirements for the organisation of the operator) applies.

All proposed ICARUS use cases (see Chapter 6) imply BVLOS operation; thus, the envisaged operations are beyond the limitations of the Open category. This category will therefore no longer be considered in this safety assessment.

On the other hand, according to Art. 40 of DA 2019/945, if people are to be carried, the UAS must be certified, i.e. a valid Certificate of Airworthiness issued by the State of Manufacture, based on a Type Certificate issued by EASA, must be available. While the last use case should be considered in the Certified category, including the need for the remote pilots to be licenced and for the operator’s organisation to be certified, the other use cases envisaged by ICARUS can be included in the Specific category.

A risk assessment must be conducted in either the Specific or the Certified category to determine the applicable requirements and confirm this initial category assignment.

In fact, according to Art. 11 of IR 2019/947, airworthiness and operational requirements for “Specific” category operations are determined as the result of a risk assessment of the operation envisaged. The SORA methodology [4], developed by JARUS, has been identified by EASA as the recommended Acceptable Mean of Compliance (AMC) to the above-mentioned Art. 11. This methodology applies an assessment process to provide a list of safety barriers (i.e. mitigations) in the form of requirements to be imposed on the operator, on the UAS, on the competency of the remote pilots or on the operation itself.

SORA also suggests two different levels of robustness:

a) Integrity robustness, which leads to the potential use of certain consensus-based documents issued by Standard Development Organisations (SDOs), such as ISO, EUROCAE or similar; and

b) Assurance robustness, which dictates the necessary Means of Evidence (MoE) for demonstrating that mitigations have been properly implemented.

There are also cases where a risk assessment is carried out by the competent authority. This can lead to the publication of standard scenarios or pre-defined risk assessments (PDRA). So far, two standard scenarios have been published through EU Reg. 2020/639 and one PDRA is part of the AMC and GM to IR 2019/947. If the operator can fulfil the limitations and the requirements of a standard scenario, then they only need to submit a declaration to the CAA of the state where the UAS is registered and where the operation is intended to take place. On the other hand, if the operation is compliant with a PDRA an authorisation must be obtained before flying. The five use cases presented in Chapter 6 are not compliant with any of the standard scenarios or PDRA currently available. This option is discarded, therefore.

For the fifth use case, we need to apply the processes of the Certified category as a whole. In fact, SORA is not currently applicable to operations involving the carriage of people, thus the non-design related requirements from this process cannot be determined. There is therefore no need to perform a dedicated safety assessment of the whole scenario, since we can assume that a type certificate will be issued for an air taxi, along with a certificate for the operator and a license for the pilot. Safety will thus be ensured by properly developing the system in accordance with a recognised airworthiness code. However, no applicable airworthiness code has yet been published by EASA for any class of UAS, but the recently published special condition for VTOL aircraft may be used as a starting point [5]. The operational requirements of air taxis and those related to the competences of the pilot are currently being adapted from manned aviation and are not yet available. The other option would be to carry out a risk assessment with SORA to determine the requirements that are not related to the UAS design. This is the option chosen in the present document.

The applicable regulatory framework will thus depend on which category of operation is applicable. For the Specific category, a risk assessment carried out using SORA is mandatory, while in the Certified category a more structured approach will be required starting at the development of the system.

However, in both cases the risk related to a possible failure of the common altitude reference system might not be explicitly addressed. This leads to the need to use a different risk assessment approach to evaluate the risks related to possible failure conditions related to the altitude reference systems used. A risk-matrix approach is chosen for this purpose since it is a more flexible way to cover a wider range of risk areas. Several methods based on risk matrices exist:

- ICAO risk matrix [6]
- EASA risk matrix, reported in the EASA Pre-Regulatory Impact Assessment
- ESARR4 risk matrix [7]
- EUROCAE risk matrix [8]

Among these, the model proposed by EASA is preferred since it provides a numeric risk index, a more immediate parameter for hazard evaluation, as output.

It is important to underline that in this approach:

- Failure conditions are considered an operational hazard.
- Safety objectives are the minimum allowable quantitative probability in relation to a failure condition (determined with a risk matrix).
- Safety requirements are the mitigation strategies that must be implemented.

7.2 SORA Methodology

This section provides an overview of the SORA methodology by outlining its main steps. The EASA version is considered the reference for the current assessment. For further details on the methodology, the reader may refer to the AMC published by EASA [9].

7.2.1 Objectives

The Specific Operation Risk Assessment (SORA) is a methodology for the risk assessment primarily required to support the application for an authorisation to operate a UAS in the “Specific” category.

This methodology may be applied where the traditional approach to aircraft certification (approving the design, issuing an airworthiness approval and type certificate) may not be appropriate due to an operator/applicant’s desire to operate a UAS in a limited or restricted manner.

The methodology is based on the principle of a holistic/total system risk-based safety assessment model used to evaluate the risks related to a given operation. The model considers threats of all natures for a specified hazard, the relevant design and operational mitigations, and evaluates them systematically to determine the boundaries for a safe operation. This method is applicable to the operator/applicant as a way to determine acceptable risk levels and to validate that those levels are complied with by the proposed operations.

7.2.2 Key concepts and definitions

To properly understand the SORA process, it is important to introduce the key concept of robustness. Any given risk mitigation or operational safety objective can be demonstrated at different level of robustness. SORA proposes the use of three different levels of robustness: Low, Medium and High.

The robustness designation is achieved with consideration to both the level of integrity defined as the safety gain provided by each mitigation and the level of assurance defined as the proof that the claimed safety gain has been achieved (see Table 7-1).

General guidance for the level of assurance is provided below.

- A low level of assurance can be one for which the operator declares that the required level of integrity has been achieved.
- A medium level of assurance can be one for which the operator provides supporting evidence that the required level of integrity has been achieved. This is typically achieved by means of testing (e.g. for technical mitigations) or by proof of experience (e.g. for human-related mitigations).
- A high level of assurance is typically one for which validation of the achieved integrity has been accepted by a competent third party.

	Low Assurance	**Medium Assurance**	**High Assurance**
Low Integrity	Low robustness	Low robustness	Low robustness
Medium Integrity	Low robustness	Medium robustness	Medium robustness
High Integrity	Low robustness	Medium robustness	High robustness

Table 7-1: Determination of Robustness level

7.2.3 The SORA Process

The SORA methodology provides a logical process to analyse the proposed concept of operations and establish an adequate level of confidence that the operation can be conducted with an acceptable level of risk. There are essentially nine steps supporting the proposed SORA methodology. The current SORA focuses on the assessment of ground and air risk. In addition to the SORA, a risk assessment of critical infrastructure should be performed in cooperation with the organisation responsible for the infrastructure, as they are most knowledgeable about the threats.

The SORA methodology (EASA version) consists of the following steps:

- **Step 0 – Pre-application evaluation**
    - Before commencing the SORA process, the operator should verify that the proposed operation is feasible, not subject to specific exclusions from the competent authority or subject to a standard scenario. Things to verify include:
        - If the operation can be covered under a "standard scenario" recognised by the competent authority.
        - If the operation falls under the "Open" category.
        - If the operation is subject to a specific NO-GO from competent authority.
- **Step 1 – ConOps description**
    - The first step of the SORA requires the operator to collect and provide sufficient technical, operational and human information related to the intended use of the UAS needed for the risk assessment.
- **Step 2 – Determination of the intrinsic UAS Ground Risk Class (GRC)**
    - The intrinsic UAS ground risk relates to the unmitigated risk of a person being struck by the UAS (in case of loss of UAS control[7]) and can be represented by ten Ground Risk Classes (GRC), derived only from the intended operation and the UAS's lethal area. A table provides a qualitative method for establishing the GRC.
- **Step 3 – Final GRC determination**
    - The unmitigated risk of a person being struck by the UAS (in case of loss of UAS control) can be controlled and reduced by means of mitigation. This step of the process allows the final GRC to be determined from the availability of these mitigations to the operation. Depending on the level of robustness at which these mitigations are available, the intrinsic GRC can be modified by a correction factor. A positive number denotes an increase in the GRC while a negative number results in a decrease.
- **Step 4 – Determination of the initial Air Risk Class (ARC)**
    - The ARC is a qualitative classification of the rate at which a UAS would encounter a manned aircraft in typical generalised civil airspace. The ARC is an initial assignment

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[7] In SORA Loss of Control corresponds to situations: a) where the outcome highly relies on providence; b) which could not be handled by a contingency procedure; c) when there is grave and imminent danger of fatalities.

  of the aggregated collision risk for the airspace before mitigations are applied. The actual collision risk for a specific local operational volume could be very different and can be addressed by the application of strategic mitigations to reduce the ARC. There are four air-risk classes. ARC-a is generally defined as airspace where the risk of collision between a UAS and manned aircraft is acceptable without the addition of any tactical mitigation. ARC-b, ARC-c, ARC-d generally define airspace with increasing risks of collision between a UAS and manned aircraft. During the UAS operation, the UAS operational volume may span many different airspace environments. The operator needs to perform an air risk assessment for the entire range of the operational volume.

- **Step 5 – Application of Strategic Mitigations to determine Residual ARC (optional)**
  - The initial ARC evaluated in the previous step can be reduced if the applicant believes that the encounter rate is actually lower than the one predicted by SORA. This must be demonstrated by applying adequate strategic mitigations. Strategic mitigations include operational restrictions (e.g. time-based restriction, i.e. flying at night when traffic density is lower) or compliance with structure and rules (e.g. common flight rules).
- **Step 6 – Tactical Mitigation Performance Requirement (TMPR) and Robustness Levels**
  - Tactical mitigations are applied to mitigate any residual risk of mid-air collision to achieve the applicable airspace safety objective. Tactical mitigations will take the form of either “See and Avoid” (i.e. operations under VLOS) or may require a system which provides an alternate means of achieving the applicable airspace safety objective (operation using a DAA, or multiple DAA systems).
- **Step 7 – Specific Assurance and Integrity Level (SAIL) determination**
  - The parameter chosen to consolidate the ground and air risk analyses and to drive the required activities is the SAIL. The SAIL represents the level of confidence that the UAS operation will stay under control. Having established the final GRC and ARC, it is possible to derive the SAIL associated with the proposed ConOps.
- **Step 8 – Identification of Operational Safety Objectives (OSOs)**
  - The last step of the SORA process is to evaluate the defences within the operation in the form of operational safety objectives (OSOs) and their associated levels of robustness depending on the SAIL. The SORA provides a qualitative methodology for making this determination. The various OSOs are grouped together based on the threat they help to mitigate. Depending on the SAIL, the operator must fulfil each OSO at a different level of robustness.
- **Step 9 – Adjacent Area/Airspace Considerations**
  - The objective of this step is to address the risk posed if a loss of control of the operation results in an infringement of the adjacent areas/airspace. Adjacent airspace may vary with different flight phases and include high-density airspace (i.e. airport environment classified as ARC-d) or crowded areas (i.e. assemblies of people). Depending on the characteristics of the adjacent airspace/area, the operator will need to demonstrate their ability to ensure a specific level of containment.

7.3 EASA Risk Assessment Methodology

The EASA risk assessment methodology is defined in the EASA Pre-Regulatory Impact Assessment. It is divided into two processes: Failure Condition Analysis (FCA) and Allocation of Safety Objectives and Requirements (ASOR). All the potential failure related to Common Altitude Reference Systems can be inspected through FCA. The SORA methodology does not take these failures into account. Moreover, collision between UASs is not considered by the SORA methodology. Therefore, an FCA should be performed using the EASA risk matrix to detect these issues that imply a reduction in safety.

7.3.1 Safety risk probability

The process of controlling safety risks starts with assessing the probability that the consequences of hazards will appear during aviation activities performed by the organisation. Safety risk probability is defined as the likelihood or frequency that a safety consequence or outcome might occur. The determination of likelihood can be aided by questions such as:

- Is there a history of occurrences similar to the one under consideration or is this an isolated occurrence?
- What other equipment or components of the same type might have similar defects?
- How many staff follow, or are subject to, the procedures in question?
- What percentage of the time is the suspect equipment or the questionable procedure in use?
- To what extent are there organisational, managerial or regulatory implications that might reflect larger threats to public safety?

Any factors underlying these questions will help in assessing the likelihood that a hazard may exist, taking all potentially valid scenarios into consideration. The determination of likelihood can then be used to assist in determining safety risk probability.

Table 7-2 gives the levels of probability identified by the EASA risk assessment methodology.

LIKELIHOOD	MEANING	VALUE
FREQUENT	Likely to occur many times (has occurred frequently)	5
OCCASIONAL	Likely to occur sometimes (has occurred infrequently)	4
REMOTE	Unlikely to occur, but possible (has occurred rarely)	3
IMPROBABLE	Very unlikely to occur (not known to have occurred)	2
EXTREMELY IMPROBABLE	Almost inconceivable that the event will occur	1

Table 7-2: EASA Safety risk probability table

7.3.2 Safety risk severity

Once the probability assessment has been completed, the next step is to assess risk severity, taking into account all the potential consequences related to the hazard. Safety risk severity is defined as the extent of harm that might reasonably occur as a consequence or outcome of the identified hazard. The severity assessment can be based upon:

- Fatalities/Injury: How many lives may be lost (employees, passengers, bystanders and the general public)?
- Damage: What is the likely extent of aircraft, property or equipment damage?

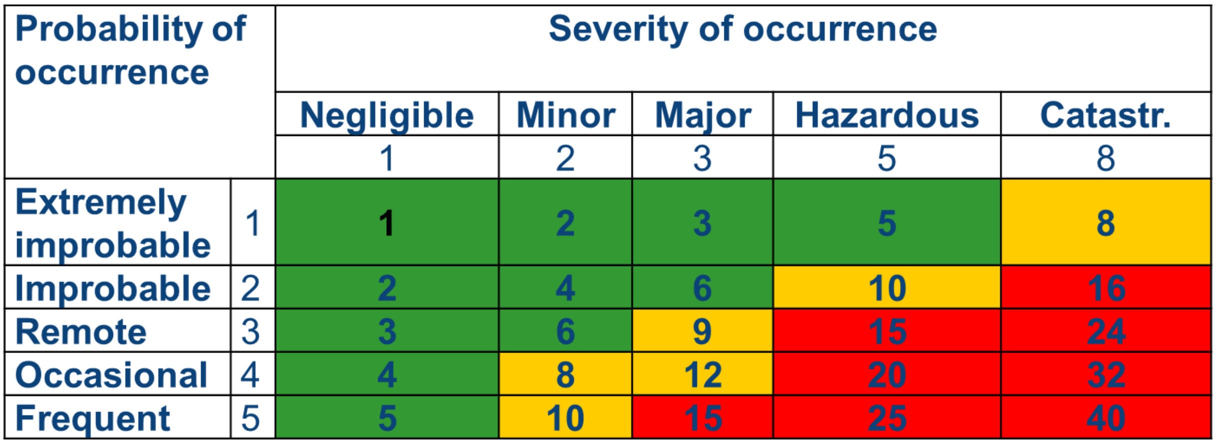
Table 7-3 presents the severity classification proposed by EASA in the Special Condition SC-RPAS.1309 [10].

SEVERITY	MEANING	VALUE
CATASTROPHIC	- One or more fatalities	8
HAZARDOUS	- Loss of the RPA where it can be reasonably expected that one or more fatalities will not occur - Large reduction in safety margins or functional capabilities or separation assurance - Excessive workload such that the remote crew cannot be relied upon to perform their tasks accurately or completely	5
MAJOR	- Reduced capability of the RPAS or of the crew to cope with adverse operating conditions to the extent that there would be a significant reduction in safety margins, functional capabilities or separation assurance - Significant increase in remote crew workload and decrease in crew efficiency	3
MINOR	- Not a significant reduction in RPAS safety - Slight reduction of safety margins or functional capabilities or separation assurance - Slight increase in crew workload	2
NEGLIGIBLE	- No effects on safety	1

Table 7-3: Safety risk severity classifications (SC-RPAS.1309)

7.3.3 Safety risk matrix

The safety risk probability and severity assessment process can be used to derive a safety risk index. The index created through the methodology described above consists of a numeric designator, indicating the combined results of the probability and severity assessments. The respective severity/probability combinations are presented in the safety risk assessment matrix in Table 7-4



Probability of occurrence		Severity of occurrence				
		Negligible	Minor	Major	Hazardous	Catastr.
		1	2	3	5	8
Extremely improbable	1	1	2	3	5	8
Improbable	2	2	4	6	10	16
Remote	3	3	6	9	15	24
Occasional	4	4	8	12	20	32
Frequent	5	5	10	15	25	40

Table 7-4: Safety risk matrix (EASA Pre-regulatory impact assessment)

The risk index is fully numeric, and the severity scale is non-linear so that high-risk areas are better differentiated. In other words, the risk index provides a more immediate comprehension of the identified hazardous situations.

7.4 Preliminary Risk Assessment using SORA methodology

Each step described in section 7.2.3 is applied here to perform a SORA-based assessment of the four proposed use cases.

7.4.1 Pre-Application Evaluation

As discussed in section 7.1, four of the five use cases can be handled with processes of the Specific category. None of the envisaged operations are covered by a standard scenario; hence an operational risk assessment is required. The operational characteristics that determine this classification are expressed in the use case descriptions in chapter 6.

7.4.2 Step 1 – ConOps Description

The ConOps definition requires an extensive amount of information about the operator, the operations and the technical characteristics of the UAS to be gathered. For this preliminary risk assessment, we will only rely on the information provided in the use case descriptions, and which will need to be further updated before the final risk assessment is completed.

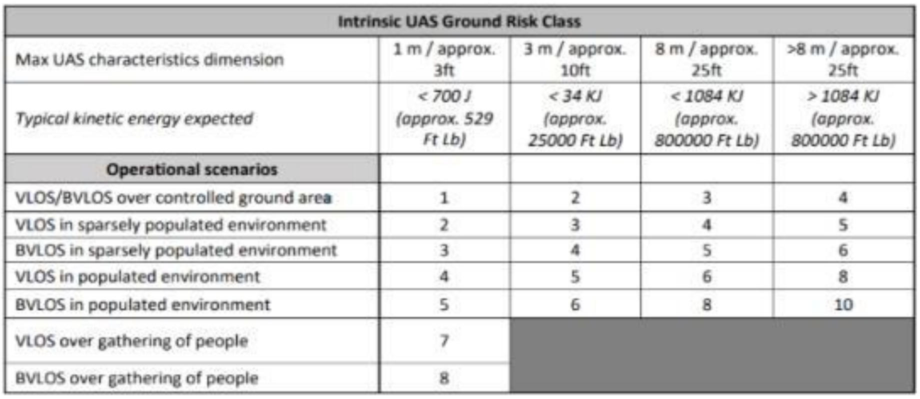
7.4.3 Step 2 – Determination of the intrinsic UAS Ground Risk Class (GRC)

The intrinsic UAS ground risk relates to the risk of a person being struck by the UAS (in the case of loss of control of the UAS). To establish the intrinsic GRC, the maximum UA characteristic dimension is required (e.g. wingspan for fixed wing, blade diameter for rotorcraft, max. dimension for multicopters, etc.) as well as the knowledge of the intended operational scenario, in terms of:

- Flight conditions (VLOS/EVLOS/BVLOS); and
- The environment to be overflown (populated, sparsely populated, controlled area, assembly of people).

The controlled area only includes active participants; those persons directly involved with the operation of the UAS or fully aware that the UAS operation is being conducted near them. There are no quantitative definitions for “sparsely populated”, “populated” or “assembly of people”. According to Art. 2 of EU Reg. 2019/947, “assemblies of people” means gatherings where persons are unable to move away due to the density of the people present.

The initial GRC can be determined using Table 7-5 below.



Intrinsic UAS Ground Risk Class				
Max UAS characteristics dimension	1 m / approx. 3ft	3 m / approx. 10ft	8 m / approx. 25ft	>8 m / approx. 25ft
Typical kinetic energy expected	*< 700 J (approx. 529 Ft Lb)*	*< 34 KJ (approx. 25000 Ft Lb)*	*< 1084 KJ (approx. 800000 Ft Lb)*	*> 1084 KJ (approx. 800000 Ft Lb)*
Operational scenarios				
VLOS/BVLOS over controlled ground area	1	2	3	4
VLOS in sparsely populated environment	2	3	4	5
BVLOS in sparsely populated environment	3	4	5	6
VLOS in populated environment	4	5	6	8
BVLOS in populated environment	5	6	8	10
VLOS over gathering of people	7			
BVLOS over gathering of people	8			

Table 7-5: Initial GRC determination

The initial GRC associated to the four use cases can be determined as follows:

Use Case	MTOM [kg]	Max Characteristic Dimension [m]	Typical Kinetic Energy [KJ]	Operational Scenario	Intrinsic GRC
0	9	0.81	9.39	BVLOS in sparsely populated environment	4
I	24.9	3.6	n.a.	BVLOS in sparsely populated environment	5
II	24	2.33	4.08	BVLOS in sparsely populated environment	4
III	11.5	1.28	4.15	BVLOS in populated environment	6

Table 7-6: Intrinsic GRC of the proposed use cases

All proposed ICARUS use cases feature BVLOS operations in a sparsely populated environment, except in use case III, where the UAS follows a flight-path through an urban area. The maximum intrinsic GRC is provided by the last case due to its operational scenario. In use case I, the kinetic energy does not affect the value of the intrinsic GRC that is given by the wingspan of the proposed VTOL quad-plane (see chapter 6). For Use Case III, the assumption is that gatherings of people due to events (e.g. concerts, sporting events) within the mission area force a change in the UAS flight path for the biomedical delivery. Table 7-6 shows the intrinsic GRC of each use case.

7.4.4 Step 3 – Final GRC Determination

The intrinsic risk of a person being struck by the UAS (in the case of loss of control of the operation) can be controlled and reduced by means of mitigation.

The mitigations used to modify the intrinsic GRC have a direct impact on the safety objectives associated with a particular operation, and it is therefore important to ensure their robustness. This is relevant for technical mitigations associated with ground risk.

The final GRC determination is based on the availability of these mitigations to the operation.

Table 7-7 provides a list of potential mitigations and the associated relative correction factor. A positive number denotes an increase in the GRC, while a negative number results in a decrease in the GRC. All mitigations must be applied in numerical order to perform the assessment.

MITIGATION	GRC ADAPTATION	ROBUSTNESS		
		Low/None	Medium	High
M1	Strategic mitigations for ground risk	0: None -1: Low	-2	-4
M2	Effects of ground impact are reduced	0	-1	-2
M3	An Emergency Response Plan (ERP) is in place, the UAS operator is validated and effective	1	0	-1

Table 7-7: Mitigations for final GRC determination

For this preliminary risk assessment, we assume that a Low level of robustness for the strategic mitigations for ground risk M1 is available for each of the proposed use cases (except in use case III): low levels of integrity and assurance are achieved for all generic criteria. Mitigation M1 is not available for use case III.

Mitigation M2 is only available for use case III. A Medium level of robustness is assured by flight termination systems and/or parachutes that reduce the descent velocity and avoid any kind of harm in case of malfunction. Test, analysis, simulation must prove that the required level of integrity is achieved. Training medical professionals to load/unload the payload and start drone operation (providing a digital interface at the starting base) is expected. Finally, we assume that the training syllabus will be available.

We assume that mitigation M3 is available at a Medium level of robustness. An emergency plan is defined by the applicant in the event of loss of control of the operation for all proposed use cases.

Therefore, the final GRC of each use case differs from the intrinsic GRC determined above. It decreases by one unit (see Table 7-8).

Use Case	Final GRC
0	3
I	4
II	3
III	5

Table 7-8: Final GRC of the proposed use cases

7.4.5 Step 4 – Determination of the Initial Air Risk Class

The air risk in SORA is a qualitative classification of the rate at which a UAS would encounter a manned aircraft in typical generalised civil airspace. The ARC is an initial assignment of the aggregated collision risk for the airspace before mitigations are applied.

The air risk is classified according to 12 Airspace Encounter Categories (AEC). Categories are defined as a function of altitude, controlled versus uncontrolled airspace, airport versus non-airport environments, and airspace over urban versus rural environments.

Each AEC class is then mapped to the corresponding ARC, as shown in Table 7-9.

Operational environment, AEC and ARC		
Operations in	**Corresponding AEC**	**Initial ARC**
Airport/Heliport Environment		
OPS in Airport/Heliport environment in Class B, C or D airspace	AEC 1	ARC-d
OPS in Airport/Heliport environment in Class E airspace or in Class F or G	AEC 6	ARC-c
Operations above 400 feet AGL but below Flight level 600		
OPS >400ft AGL but <FL600 in a Mode-S Veil or Transponder Mandatory Zone (TMZ)	AEC 2	ARC-d
OPS >400ft AGL but <FL600 in controlled airspace	AEC 3	ARC-d
OPS >400ft AGL but <FL600 in uncontrolled airspace over urban area	AEC 4	ARC-c
OPS >400ft AGL but <FL600 in uncontrolled airspace over rural area	AEC 5	ARC-c

Operations below 400 ft AGL		
OPS <400ft AGL in a Mode S Veil or Transponder Mandatory Zone (TMZ)	AEC 7	ARC-c
OPS <400ft AGL in controlled airspace	AEC 8	ARC-c
OPS <400ft AGL in uncontrolled airspace over urban area	AEC 9	ARC-c
OPS <400ft AGL in uncontrolled airspace over rural area	AEC 10	ARC-b
Operations above Flight Level 600		
OPS >FL600	AEC 11	ARC-b
Operations in Atypical or Segregated Airspace		
OPS in Atypical/Segregated airspace	AEC 12	ARC-a

Table 7-9: AEC/ARC Determination

Table 7-10 gives the initial AECs and corresponding ARCs determined from Table 7-9, for four use cases.

Use Case	Applicable AEC	Corresponding ARC	Rationale
0	AEC 12	ARC-a	OPS in Atypical Airspace. The UAS operator has obtained a valid authorisation from the Civil Aviation Authority to fly in a protected area through the publication of a NOTAM.
I	AEC 10	ARC-b	OPS <400ft AGL in uncontrolled airspace over Rural Area.
II	AEC 12	ARC-a	OPS in Atypical Airspace. Manned aircraft normally cannot go (airspace within 5/10 ft of a power line).
III	AEC 9	ARC-c	OPS <400ft AGL in uncontrolled airspace over Urban Area.

Table 7-10: AEC/ARC of the proposed use cases

For use case II, it is assumed that the UAS operator has obtained a valid permanent authorisation from the Civil Aviation Authority (e.g. valid for 1 year) to fly on a regular basis in an agreed limited volume.

7.4.6 Step 5 – Application of Strategic Mitigations (optional)

By applying strategic mitigations, SORA offers the applicant the possibility of demonstrating that the collision risk with manned aircraft in the operational volume is actually lower than the one predicted, to potentially reduce the initial ARC.

However, no mitigation may be employed to reduce a residual ARC to ARC-a, as it is assumed that the lowest encounter rate may only be achieved in a segregated/atypical airspace.

Two types of strategic mitigation are available:

1. Strategic mitigations by operational restriction; and/or
2. Strategic mitigation by structure and rules.

7.4.6.1 Strategic Mitigations by Operational Restriction

Operational restrictions are controlled by the operator and intended to mitigate collision risk prior to take-off. Three different categories of mitigation exist:

1. Mitigation by boundary: mitigations that bind the geographical volume in which the UAS operates (e.g. certain boundaries or airspace volumes); and/or
2. Mitigation by chronology: mitigations that bind the operational time frame (e.g. restricted to certain times of day, such as fly only at night); and/or
3. Mitigation by time of exposure: mitigation that limits the time of exposure to the operational risk.

7.4.6.2 Strategic Mitigations by Structures and Rules

Strategic mitigations by structures and rules require all aircraft within a certain class of airspace to follow the same structures and rules to lower collision risk within the airspace. Two types of such mitigation exist:

1. Common flight rules: this is accomplished by setting a common set of rules that all airspace users must comply with. Examples of common flight rules that reduce risk of collision include right of way rules, implicit and explicit coordination schemes, conspicuity requirements, cooperative identification system, etc.
2. Common airspace structure: this is accomplished by controlling the airspace infrastructure through physical characteristics, procedures and techniques that reduce conflicts or make conflict resolution easier. Examples of common flight airspace structures that reduce risk of collision are airways, departure and approach procedures, airflow management, etc.

These mitigations cannot provide more than a one-point ARC reduction. They can only be implemented at VLL.

Table 7-11 provides a list of all the applicable strategic mitigations for computing the residual ARC for use case III.

Use Case III		
Strategic Mitigations	**Available (Y/N)**	**Rationale**
Strategic Mitigations by Operational Restrictions		
Mitigation by Boundary	N	Not available
Mitigation by Chronology	N	Availability at any time of a day
Mitigation by Time of Exposure	Y	Each mission lasts 6/7 minutes
Strategic Mitigations by Structures and Rules		
Common flight rules	Y	Coordination between autonomous drone and emergency helicopters could be provided to avoid conflicts in the strategic phase
Common airspace structure	N	Not available

Table 7-11: Strategic Mitigations – Use Case III

Strategic mitigations are useless in use cases 0 and II that present an initial air-risk class of ARC-a, and in use case I that presents an initial air-risk class of ARC-b. In use cases 0 and II the initial ARC is the lowest possible as the flight is in an atypical area. In use case III, strategic mitigations allow a Residual air-risk class of ARC-b to be reached.

Regulations (FAR 91.119, GM1 CAT.OP.MPA.145) state that aircraft are not allowed to fly below 500ft over urban areas, so leisure GA traffic should not be encountered during the UAS travel in Zu airspace and no UTM service involvement is needed. Manned traffic, specifically helicopters, could be encountered at take-off and landing sites since a hospital platform may host air ambulances. VFR navigation is usually adopted. Both manned and unmanned operations require strict communication with hospital service personnel to ensure timely medical intervention.

Given the above mitigations, the residual ARCs can be computed as follows:

- **Use Case 0:** ARC-a
- **Use Case I:** ARC-b
- **Use Case II:** ARC-a
- **Use Case III:** ARC-b

7.4.7 Step 6 – Tactical Mitigation Performance Requirement (TMPR)

Tactical mitigations are applied to mitigate any residual risk of mid-air collision needed to achieve the applicable airspace safety objective. Tactical mitigations will take the form of either “See and Avoid” (i.e. operations under VLOS) or may require a system which provides an alternate means of achieving the applicable airspace safety objective (operation using a DAA, or multiple DAA systems).

Annex D provides the method for applying tactical mitigations.

For BVLOS operations, the applicant must use the residual ARC determined in Step 5, and Table 7-12 below to determine the Tactical Mitigation Performance Requirement (TMPR).

Residual ARC	Tactical Mitigation Performance Requirement (TMPR)
ARC-d	High
ARC-c	Medium
ARC-b	Low
ARC-a	No requirement

Table 7-12: TMPR Requirement

The TMPR requirements applicable for the residual ARCs determined above are given in Table 7-13 and Table 7-14.

TMPR function	TMPR requirement		
	Low (ARC-b)	Use Case I	
		Compliant	Evidence
Detect	The expectation is for the applicant's DAA plan to enable the operator to detect approximately 50% of all aircraft in the detection volume. This is the performance requirement in absence of failures and defaults. The applicant must be aware of most of the traffic operating in the area in which the operator intends to fly, by relying on one or more of the following: • Use of (web-based) real-time aircraft tracking services • Use of low-cost ADS-B in /UAT/FLARM/Pilot-aware aircraft trackers • Use of UTM dynamic geofencing • Monitoring aeronautical radio communication (i.e. use of a scanner)	Y	Coordination and communication with possible local traffic (i.e. helicopter landing on the same offshore platform) is handled. Information on traffic over the platform is handled through VHF radio communication. The common altitude reference system for GA shall be considered (for instance the Reporting service, ADS-B or a dedicated U-space service to also be used by GA).
Decide	The operator must have a documented deconfliction scheme, in which they explain which tools or methods will be used for	To be verified	

	detection, and which criteria will be applied when deciding to avoid incoming traffic. If the remote pilot relies on detection by someone else, the use of phraseology must also be described. Examples: • The operator will initiate a rapid descent if traffic is crossing an alert boundary and operating at less than 1000ft. • The observer monitoring traffic uses the phrase: 'DESCEND! DESCEND! DESCEND!'.		
Command	The latency of the whole command (C2) link, i.e. the time between the moment that the remote pilot gives the command and the airplane executes the command must not exceed 5 seconds.	To be verified	C2 link from the GCS to the UAS is redundant on two frequency bands.
Execute	UAS descending to an altitude not higher than the nearest trees, buildings, or infrastructure or ≤ 60 feet AGL is considered sufficient. The aircraft should be able to descend from its operating altitude to the 'safe altitude' in less than a minute.	To be verified	
Feedback Loop	Where electronic means assist the remote pilot in detecting traffic, the information is provided with a latency and update rate for intruder data (e.g. position, speed, altitude, track) that support the decision criteria. For an assumed 3 NM threshold, a 5-second update rate and a latency of 10 seconds is considered adequate.	To be verified	
Integrity	Allowable loss of function and performance of the Tactical Mitigation System: < 1 per 100 Flight Hours.	To be verified	
Assurance	The operator declares that the Tactical Mitigation System and procedures will mitigate the risk of collision with manned aircraft to an acceptable level.	Y	

Table 7-13: Detailed TMPR Requirement – Use Case I

TMPR function	**TMPR requirement**		
	Low (ARC-b)	**Use Case III**	
		Compliant	**Evidence**
Detect	It is expected that the applicant's DAA plan will enable the operator to detect	Y	ADS-B for a direct communication link

	approximately 50% of all aircraft in the detection volume. This is the performance requirement in absence of failure and faults. The applicant must be aware of most of the traffic operating in the area in which they intend to fly, by relying on one or more of the following: • Use of (web-based) real-time aircraft tracking services • Use of low-cost ADS-B in /UAT/FLARM3/Pilot-aware aircraft trackers • Use of UTM dynamic geofencing • Monitoring aeronautical radio communication (i.e. use of a scanner)		with manned aircraft is expected.
Decide	The operator must have a documented deconfliction scheme, in which they explain which tools or methods will be used for detection, and which criteria will be applied for deciding to avoid incoming traffic. If the remote pilot relies on detection by someone else, the use of phraseology must also be described. Examples: • The operator will initiate a rapid descend if traffic is crossing an alert boundary and operating at less than 1000ft. • The observer monitoring traffic uses the phrase: 'DESCEND! DESCEND! DESCEND!'.	To be verified	
Command	The latency of the whole command (C2) link, i.e. the time between the moment that the remote pilot gives the command and the airplane executes the command must not exceed 5 seconds.	Not required	This operation is thought to be highly autonomous, allowing the drone to be independent from a pilot.
Execute	UAS descending to an altitude not higher than the nearest trees, buildings, or infrastructure or ≤ 60 feet AGL is considered sufficient. The aircraft should be able to descend from its operating altitude to the 'safe altitude' in less than a minute.	To be verified	
Feedback Loop	Where electronic means assist the remote pilot in detecting traffic, the information is provided with a latency and update rate for	To be verified	

	intruder data (e.g. position, speed, altitude, track) that support the decision criteria. For an assumed 3 NM threshold, a 5-second update rate and a latency of 10 seconds is considered adequate.		
Integrity	Allowable loss of function and performance of the Tactical Mitigation System: < 1 per 100 Flight Hours.	To be verified	
Assurance	The operator declares that the Tactical Mitigation System and procedures will mitigate the risk of collision with manned aircraft to an acceptable level.	Y	

Table 7-14: Detailed TMPR Requirement – Use Case III

All proposed ICARUS use cases feature BVLOS operations.

Use case 0 and use case II present a residual air-risk class of ARC-a, therefore no TMPR is required. A residual air-risk of ARC-a defines a low-risk operation that will take place in an airspace where the manned aircraft encounter rate is expected to be very low. It is generally defined as an airspace in which the risk of collision between a UAS and manned aircraft is acceptable, without the need for additional tactical mitigations.

A system risk ratio lower than 0.67 must be ensured in use case I and use case III.

7.4.8 Step 7 – SAIL Determination

The SAIL parameter consolidates the ground and air risk analyses and drives the required activities. The SAIL represents the level of confidence that the UAS operation will stay under control.

After determining the final GRC and residual ARC, it is possible to derive the SAIL associated with the proposed ConOps.

SAIL is not quantitative but instead corresponds to:

- Operational Safety Objectives (OSO) to be complied with; and
- Description of activities that might support compliance with these objectives; and
- The evidence that indicates that the objectives have been satisfied.

The SAIL for the proposed ConOps is computed using the data in Table 7-15.

SAIL Determination				
	Residual ARC			
Final GRC	**a**	**b**	**c**	**d**
≤2	I	II	IV	VI
3	II	II	IV	VI
4	III	III	IV	VI

5	IV	IV	IV	VI
6	V	V	V	VI
7	VI	VI	VI	VI
>7	Certified Category			

Table 7-15: SAIL computation

Taking into account the final GRC computed in section 7.4.4 and the residual ARC derived from section 7.4.6, the SAILs associated with the four use cases are:

- **Use Case 0:** II
- **Use Case I:** III
- **Use Case II:** II
- **Use Case III:** IV

7.4.9 Step 8 – Identification of Operational Safety Objectives (OSOs)

The last step of the SORA process is to employ the SAIL to evaluate the necessary defences within the operation in the form of operational safety objectives (OSOs) and to determine the associated level of robustness. Table 7-16 provides a qualitative methodology for determining this. The following robustness scheme applies:

- "O" stands for Optional (meaning that the specific requirement does not have to be fulfilled).
- "L" stands for low robustness (meaning that a declaration of compliance by the operator is generally sufficient).
- "M" stands for medium robustness (meaning that evidence shall be provided to demonstrate compliance).
- "H" stands for high robustness (meaning that a competent third party shall check for compliance with the requirement).

The various OSOs are grouped based on the threat they help to mitigate.

OSO	**Description**	**SAIL**					
		I	**II**	**III**	**IV**	**V**	**VI**
1	Ensure the operator is competent and/or proven	O	L	M	H	H	H
2	UAS manufactured by competent and/or proven entity	O	O	L	M	H	H
3	UAS maintained by competent and/or proven entity	L	L	M	M	H	H
4	UAS developed to authority-recognised design standards	O	O	O	L	M	H
5	UAS is designed considering system safety and reliability	O	O	L	M	H	H

6	C3 link performance is appropriate for the operation	O	L	L	M	H	H
7	Inspection of the UAS (product inspection) to ensure consistency to the ConOps	L	L	M	M	H	H
8	Operational procedures are defined, validated and adhered to, to address technical issues with the UAS	L	M	H	H	H	H
9	Remote crew are trained, current and able to control an abnormal situation (technical issues with the UAS)	L	L	M	M	H	H
10	Safe recovery from technical issue	L	L	M	M	H	H
11	Procedures are in place to handle any deterioration of external systems supporting UAS operation	L	M	H	H	H	H
12	The UAS is designed to manage a deterioration of external systems supporting UAS operation	L	L	M	M	H	H
13	External services supporting UAS operations are adequate for the operation	L	L	M	H	H	H
14	Operational procedures are defined, validated and adhered to, to address human errors	L	M	H	H	H	H
15	Remote crew trained, current and able to control an abnormal situation (human error)	L	L	M	M	H	H
16	Multi-crew coordination	L	L	M	M	H	H
17	Remote crew is fit to operate	L	L	M	M	H	H
18	Automatic protection of the flight envelope from human error	O	O	L	M	H	H
19	Safe recovery from human error	O	O	L	M	H	H
20	A human factors evaluation has been performed and the HMI found appropriate for the mission	O	L	L	M	M	H
21	Operational procedures are defined, validated and adhered to, to address adverse operating conditions	L	M	H	H	H	H
22	The remote crew is trained to identify critical environmental conditions and to avoid them	L	L	M	M	M	H
23	Environmental conditions for safe operations defined, measurable and adhered to	L	L	M	M	H	H
24	UAS designed and qualified for adverse environmental conditions	O	O	M	H	H	H

Table 7-16: Robustness associated to each OSO

The required robustness is determined from the matrix in Table 7-17 that combines integrity and assurance. If, according to Table 7-16, the required robustness for OSO 3 is Low, it will be necessary for both integrity and assurance to meet the Low robustness criteria. If the required robustness is Optional for a certain OSO, the corresponding requirement will not be assessed.

	Low Assurance	Medium Assurance	High Assurance
Low Integrity	Low robustness	Low robustness	Low robustness
Medium Integrity	Low robustness	Medium robustness	Medium robustness
High Integrity	Low robustness	Medium robustness	High robustness

Table 7-17: Robustness computation

In use case 0 and use case II, the required robustness level for most of OSOs is Optional or Low according to the SAIL. Medium robustness is required for OSOs that are related to operational procedures (OSO 8, OSO 11, OSO 14 and OSO 21). Operational procedures must be validated against standards considered adequate by the competent authority and/or in accordance with a means of compliance acceptable to that authority. The adequacy of the contingency and emergency procedures is proven through dedicated flight tests or simulations that are valid for the intended purpose with positive results. On the other hand, use case I needs a Medium robustness level for almost all OSOs. In use cases I and III, the operational procedures (e.g. procedures for addressing human error and adverse operating conditions) must provide a High robustness level; therefore, they must be validated by a competent third party. Finally, in the last case, the requirements in terms of robustness level are stricter than in the other use cases. In this case, a High robustness level is required for OSO 1, OSO 13 and OSO 24. OSO 1 requires that the applicant hold an Organisational Operating Certificate or have an organisation recognised for flight tests. Moreover, the operator's competences must be verified by a competent third party. OSO 13 requires evidence of externally provided service performance through demonstrations. The UAS must be designed using environmental standards considered adequate by the competent authority and/or in accordance with a means of compliance acceptable to that authority for achieving a high level of integrity for OSO 24. A competent third party must validate the claimed level of integrity for OSO 13 and OSO 24.

7.4.10 Step 9 – Adjacent Area/Airspace Considerations

The objective of this section is to address the risk posed if loss of control of the operation were to result in an infringement of the adjacent areas on the ground and/or adjacent airspace.

In SORA, two different requirements regarding adjacent area/airspace considerations exist (see Table 7-20 below). The first requirement must be fulfilled in any operation, whereas the second must be complied with only if at least one of the following "critical" conditions apply:

1. Airspace adjacent to the operational volume is classified as ARC-d (unless the residual ARC of the operational airspace volume intended to be flown in is already ARC-d).
2. Areas adjacent to the operational volume contain assemblies of people (unless already taken into account in the initial GRC evaluation).
3. Operations within a populated environment carried out in a controlled ground area, or where an M1 mitigation has been applied to lower the GRC.

Each of the previous points are analysed in the following section.

7.4.10.1 Safety requirements

The analyses of the aforementioned critical scenarios are given in Table 7-18 and Table 7-19; the operator must comply with the additional requirement if at least one of the following conditions are met.

Operational conditions	Y/N	Rationale
Adjacent area contains gatherings of people	**N**	No gatherings of people in adjacent area.
Adjacent airspace classified as ARC-d	**N**	No airport/heliport environment. No flight in controlled airspace or TMZ above 400 feet AGL but below Flight level 600.
Flight in populated area where: **1.** M1 has been applied, or **2.** Flight in controlled area	**N**	BVLOS conditions in sparsely populated environment.

Table 7-18: Adjacent Airspace critical conditions compliance (Use cases 0, I, II)

Operational conditions	Y/N	Rationale
Adjacent area contains gatherings of people	**Y**	Adjacent area may contain gatherings of people (urban area).
Adjacent airspace classified as ARC-d	**N**	No airport/heliport environment. No flight in controlled airspace or TMZ above 400 feet AGL but below Flight level 600.
Flight in populated area where: **1.** M1 has been applied, or **2.** Flight in controlled area	**N**	M1 has not been applied and operations are carried out in an uncontrolled ground area.

Table 7-19: Adjacent Airspace critical conditions compliance (Use Case III)

Following the conclusions of Table 7-18 and Table 7-19, the safety requirements reported in Table 7-20 must be fulfilled:

Applicable Requirement	ADJACENT AREA/AIRSPACE REQUIREMENTS
1[8]	No probable failure of the UAS or any external system supporting the operation shall lead the operation outside of the operational volume. *Compliance with the requirement above shall be substantiated by a design and installation appraisal and shall include:* ● *Design and installation features (independence, separation and redundancy).* ● *Any relevant particular risk (e.g. hail, ice snow, interferences) associated to the ConOps.*
2	The probability of leaving the operational volume shall be less than 10^{-4}/FH. No single failure of the UAS or any external system supporting the operation shall lead to its operation outside of the ground risk buffer. Software (SW) and Airborne Electronic Hardware (AEH) whose development error(s) could directly lead to operations outside of the ground risk buffer shall be developed to an industry standard or methodology recognised as adequate by the competent authority.

Table 7-20: Adjacent Area/Airspace requirements

Requirement 2 in Table 7-20 must be guaranteed for use case III, whereas the lower safety requirement (requirement 1) may be considered in the other use cases. In use case III, the safety requirement is ensured through a “geo-caging” system, redundancy of critical functions (such as GPS, antenna, flight controller), and controller systems, as well as return-to-home (RTH) and flight termination system (FTS). The “geo-fencing” system ensures that the autonomous drone for biological sample delivery is kept within the operational volume.

7.4.11 SORA Assessment conclusions

A preliminary SORA-based assessment, recommended by EASA as Acceptable Means of Compliance (AMC) to Art. 11 of EU 2019/947, of the four proposed use cases has been performed in Section 7.4.

The assessment has identified the robustness level for each safety requirement prescribed by SORA. Both the risk for third parties on the ground (Ground Risk) and in the air (Air Risk) have been assessed.

The level of risk associated with a specific operation is defined in SORA by means of a specific parameter, the Specific Assurance and Integrity Level (SAIL). This parameter represents the level of

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[8] Always applicable

confidence that the operation will stay under control. The higher the SAIL, the more demanding the safety requirements to be fulfilled.

The operations are performed in sparsely populated environments, except in use case III; therefore, the intrinsic GRC ranges from 4 to 6 for the four proposed use cases. The analyses carried out show that the mitigations reduce the Intrinsic GRC by 1 unit in all use cases.

The final ARC is evaluated as ARC-a for use case 0 and use case II and ARC-b for use case I and use case III.

In summary, the SAIL associated with the proposed ConOps was determined to be SAIL II for use case 0 and use case II, SAIL III for use case I and SAIL IV for use case III. The requirements for achieving the necessary integrity and assurance levels of OSOs in accordance with the SAIL have been provided in chapter 7.4.9.

Finally, in use case III the compliance with the adjacent airspace requirement should be demonstrated with a flight termination system, redundancies in the system, and geo-fencing.

7.5 Failure condition analysis with EASA risk matrix approach

The safety assessment performed using the risk matrix approach has the aim of evaluating the potential failure conditions associated with common altitude reference systems, which are in turn necessary to support the scenarios described in section 2.1.

This analysis is divided into two inter-related processes:

- Failure Condition Analysis (FCA).
- Allocation of Safety Objectives and Requirements (ASOR).

This approach is described in EUROCAE ED 78A and applied, for data link with manned aircraft in continental and oceanic environments, in EUROCAE ED 120 [11] and EUROCAE ED 122 [12] respectively.

It is to be noted, however, that:

- In EUROCAE documents, the process is named “Operational Hazard Analysis” (OHA), which is equivalent to the term FCA used in this document.
- In this document, the term FCA is preferred since failure condition affecting digital services is considered.
- The model adopted in this document is based on the EASA risk matrix, while the safety assessment process in EUROCAE documents is carried out based on a different risk matrix.

Typical failure conditions considered will be identified during the course of the project in relation to the technical and procedural solution chosen and assessed following the approach explained hereafter.

7.5.1 Failure Condition Analysis

Once all the operational details of ICARUS scenarios have been defined, as well as the related CARS, all the potential failure conditions are identified through the FCA.

As the purpose of ICARUS is to determine the optimal CARS solution, the risk assessment is carried out addressing all the risks associated with failure conditions[9] or procedural errors in the context of a CARS. Hence this process of failure identification considers:

- **Total loss or unavailability of information.**
- **Misleading information.**
- **Detected/undetected errors.**

Total loss or unavailability of information: the information is lost, or the service is unavailable.

Misleading information:

- **Partial loss** - Part of the information is lost, or the function is only partially completed.
- **Corruption** - The information is altered from what was intended to be transmitted.
- **Misdirection** - The data has come from the wrong source or received by the wrong destination.
- **Delay** - The data received is out of date or the function is carried out late in relation to succeeding processes.
- **Inconsistency** - Here diverse information paths convey different information.

Any of the above might be either detected or undetected. This consideration may result in two failures different from the list above for a given descriptor, where one is more severe than the other.

In addition, the following possible procedural errors, are considered:

- Human failure to respond appropriately to functional failure.
- Human error or omission during normal use.
- Human underestimation of a potential hazardous situation.
- Transitional failures (those that may result from changing from an existing operation to a new operation).
- External factors (e.g. outages, weather).

Once all the potential failure conditions have been identified, the severity of the consequences is determined for each of them. Operational effects may include:

- Collision or loss of margin of safety with respect to collision between airborne aircraft.
- Collision or loss of margin of safety with respect to collision with terrain or loss of separation with terrain.
- Loss of separation or loss of margin of safety with respect to loss of separation with significant weather or atmospheric contamination effects (e.g. volcanic ash, birds).
- Collision or loss of margin of safety with respect to collision between drones and other aircraft or vehicles on the ground.

When assessing the effects of system failures or operational errors on the margin of safety it is important to consider contributory factors such as:

- Is the effect dependent on outage time?
- Is more than one aircraft affected?

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[9] A failure condition may be the failure of hardware, but also malfunction of software or corruption of the information or performances of a network outside the specified limits.

- Is more than one sector affected?
- Is the effect dependent on the time the hazard occurs or on its duration?
- Is the effect dependent on the phase of flight?
- Is the effect related to a specific workload or skill issue?
- Is the pilot adequately aware of the operational environment?

The purpose of this phase of the analysis is to establish the extent to which the identified failures and procedural errors could lead to a reduction in safety margins in the operational environment.

This reduction in safety margins can be described by the severity of the effect on operations as defined in the risk classification matrix. The risk classification matrix is a tool that assists in assigning the proper likelihood requirement (safety objective) as a function of the severity of each of the identified failure conditions (see Table 7-4).

The severity class for a given failure condition is determined by evaluating the worst credible effects on operations, remote crew/controller workload and keeping in mind the contingent environmental conditions using the template in Table 7-21.

# LIST	FAILURE CONDITION[10]	OPERATIONAL EFFECTS	SEVERITY[11]	SAFETY OBJECTIVE
Failure condition reference number.	Description of the failure condition.	Description of the effects on operations and workload.	Failure condition severity classification (based on EASA SC-RPAS 1309).	Establishes the required threshold of probability of occurrence of the associated failure condition (based on EASA risk matrix).

Table 7-21: Failure condition classification

7.5.2 Allocation of Safety Objectives and Requirements

Once the severity class for each failure condition is known, it is possible to identify minimum safety objectives that bring the associated risk into a tolerable region (Figure 7-1). The safety objective is the maximum allowable quantitative probability tolerable for the occurrence of each failure condition (i.e. the 'green' or, if necessary, the 'yellow' cells in the risk matrix in Table 7-4).

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[10] Labelled "Operational Hazard" in EUROCAE ED-78A

[11] Labelled "Hazard Class" in EUROCAE ED-78A.

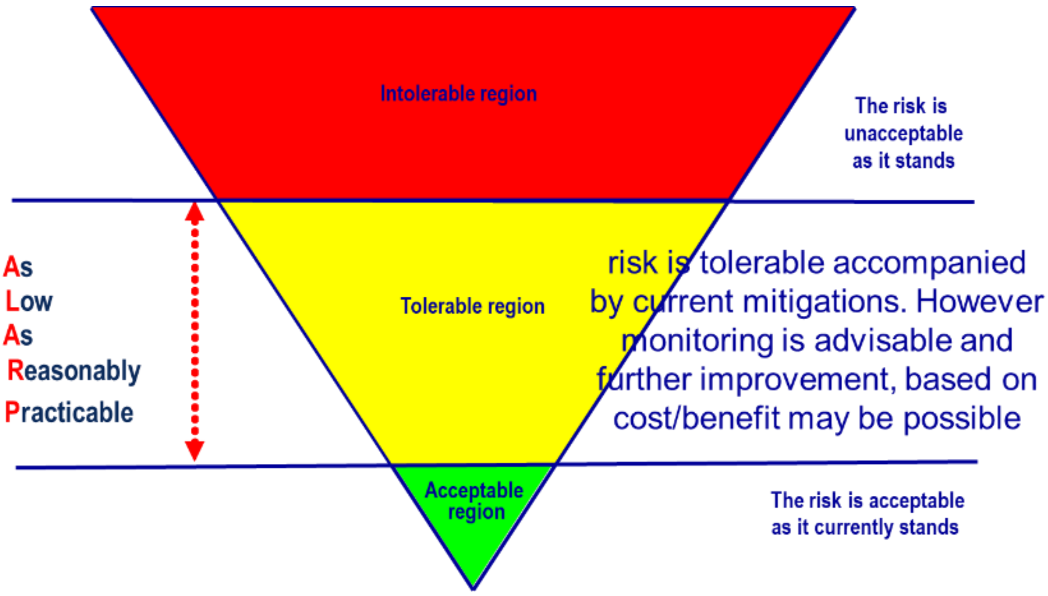


Figure 7-1: Risk management

This maximum tolerable probability (or frequency or likelihood) is the safety objective.

The term safety requirement refers to the risk mitigation strategies (e.g. redundancy of equipment) that are adopted to reach the corresponding safety objective for a given failure condition. A template for these is given in Table 7-22.

SAFETY REQUIREMENT	FAILURE CONDITION REFERENCE #
Description of mitigation strategy required to enable the safety objective associated to each failure condition to be fulfilled.	Provides backward reference to the failure condition to be mitigated.

Table 7-22: Safety requirements definition

The logic described above is based on the ASOR concept, which is intended to start from the safety objective derived from the failure condition analysis and developed as an agreed strategy for achieving these objectives, considering possible procedural or architectural mitigations.

The mitigations constitute the set of safety requirements. These safety requirements are generally composed of a function to be executed, together with a safety objective.

Several candidate risk-mitigation strategies can be used at the ASOR level:

- Remove the risk by removing the function.
- Remove the risk by changing the operational mode in which the function is most critical.
- Design diversity.
- Isolation.
- Proven reliability.
- Failure warning or indication.
- Check procedures, flight crew/controller.
- Removal of common cause.
- Designed failure effect limits.
- Designed failure path.

- Margins or factors of safety.
- Error tolerance.
- Error avoidance, reduction, or transfer.

Whatever risk mitigation strategy is adopted, the resultant allocation/apportioning should be applied and documented, through Means of Evidence (MoE).

7.5.3 EASA Assessment conclusions

The potential failure conditions associated with common altitude reference systems must be analysed using the risk matrix approach. During the course of the project, some typical malfunctions will be identified so that a reduction in the safety margins may be considered in the operational scenarios.

After defining all the operational details of the different scenarios and the related CARS, the FCA can be adopted to determine all the potential failure conditions. The risk assessment takes into account all the risks related to failure conditions or procedural errors in the context of a CARS.

The safety risk matrix will give a numeric designator of the hazardous situations identified. It will be provided by the combined results of the probability and severity of an occurrence.

Starting from the safety objectives provided by the FCA, the ASOR procedure will develop a strategy for achieving these objectives, considering possible mitigations. Some risk mitigations strategies are listed above.

7.6 Conclusions

A preliminary risk assessment based on SORA methodology has been performed in this chapter.

The required integrity and assurance level of OSOs in accordance with the SAIL and compliance with the adjacent airspace requirement will be demonstrated in the final risk assessment after defining the operational details of the various use cases.

The SORA methodology does not take into account possible malfunctions of operations support systems (e.g. a common altitude reference system and U-space services). These malfunctions may lead to collisions between UASs or leakage from the operational volume. For this reason, they will be analysed with the EASA risk matrix.

7.7 References

[1] Regulation (EU) 2018/1139 of the European Parliament and of the Council, Official Journal of the European Union, 4 July 2018.

[2] Commission Implementing Regulation (EU) 2019/947, Official Journal of the European Union, 24 May 2019.

[3] Commission Delegated Regulation (EU) 2019/945, Official Journal of the European Union, 12 March 2019.

[4] JARUS guidelines on Specific Operations Risk Assessment (SORA), Joint Authorities for Rulemaking of Unmanned Systems, 30 January 2019, v2.0.

[5] Proposed Means of Compliance with the Special Condition VTOL, European Union Aviation Safety Agency, 25 May 2020.

[6] Development of the seventh MID annual Safety Report, International Civil Aviation Organization, 4-5 February 2018.

[7] Risk assessment and mitigation in ATM, European Organization for the Safety of Air Navigation, 5 April 2001.

[8] Guidelines for UAS safety analysis for the Specific category (low and medium levels of robustness), European Organization for Civil Aviation Equipment, 14 May 2020.

[9] Acceptable Means of Compliance (AMC) and Guidance Material (GM) to Commission Implementing Regulation (EU) 2019/947, European Union Aviation Safety Agency, 9 October 2019.

[10] Special Condition SC-RPAS.1309 Equipment, systems, and installations, European Union Aviation Safety Agency, 24 July 2015.

[11] ED-120 – Safety and Performance Requirements Standard for Air Traffic Data Link Services in Continental Airspace (Continental SPR Standard), European Organization for Civil Aviation Equipment, 1 May 2004.

[12] ED-122 – Safety and Performance Standard for Air Traffic Data Link Services in Oceanic and Remote Airspace (Oceanic SPR Standard), European Organization for Civil Aviation Equipment, 1 December 2007.

8 Gap Analysis & Gap Filling: service missing bricks

The ICARUS CARS concept introduces many technological, conceptual and legislative challenges. The proposed CARS solution requires a number of identified issues to be overcome. This chapter tries to list and describe them and proposes a way of mitigating them to achieve the desired state i.e. a deployed CARS solution.

The approach described in this document will also allow the progress of deployment to be monitored by the introduction of measures describing the current state and a proposed action plan. The project's outcomes in the form of performed studies, tests and experiments should be used as a proof of concept and an input for European and global regulations in their respective areas.

This analysis integrates the perspective of many interdisciplinary areas (law, technology, regulations, etc.) covering different businesses (general aviation, commercial aviation, unmanned systems, etc.). As the necessary technologies, e.g. 5G, are in many cases still under development, it will be necessary to perform many experiments, validations and tests, including field tests. The proposed action plans should therefore be treated tentatively and can evolve during the project.

The project introduces many innovative, green-field areas of development. While making use of the consortium members' experience when solving the problems identified, we will try to efficiently connect many reference systems, along with using technologies that have not yet been explicitly used in the aviation world, such as telecommunications networks, edge server concepts, and broadly understood aspects related to cybersecurity. During this process we should ensure that core safety and security aspects, as well as aviation business related best practices are preserved, e.g. we cannot assume and propose that a change of altimetry tools is necessary or required for implementing a CARS solution for manned aviation, because this would be not feasible.

All topics identified in this gap analysis are gathered and described in detail in the following sections.

Currently there are five principal (but arbitrarily defined) areas of analysis:

- Part 1: General: GAMZ Geometric Altitude Mandatory Zone
- Part 2: Topography aspects: DEM / DTM / DSM models
- Part 3: GNSS systems
- Part 4: Conversions and implementation: Altitude / Height reference systems - technical aspects and security
- Part 5: Others

Within each area, a number of topics (usually related to the specific concept) have been identified. Each such topic is presented with a thorough analysis:

- Definition of the focus area – provides a brief summary of highlighted problem
- Short description of the concept – provides the short description of solution idea
- Short description of the expected result – provides descriptive information about expected improvement areas and its estimated level of importance (arbitrarily assigned, based on expert estimations within the scale 1-10 – 1=low, 10=high)

- Description of the current situation – explains the current situation and provides an arbitrary measure (Current State level) of the maturity level of the current solution (1-5, where 1 is the least mature and 5 is the expected target level)
- Definition of deficiencies to be addressed to achieve the target state/solution – defines the missing components that need to be deployed
- Description of actions/tasks to be performed, components to be introduced to achieve the target state/situation – defines steps to be performed to achieve the desired, highest maturity level
- Each topic is assigned an owner from the project consortium, with implementation deadlines, to track the progress of development of the topic.

As a rule, we suggest performing a gap analysis review on a regular basis, e.g. at quarterly intervals, until the end of the project, to monitor the progress and effectiveness of planned/performed actions.

For now, the following types of actions have been identified:

1. Recommend amendment of EC legally binding implementing rules on aviation safety (e.g. SERA; 923/2011);
2. Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar;
3. Gap possibly filled by planned activities in ICARUS Project;
4. Future additional research.

As a part of the analysis, consortium members have evaluated all the gaps and indicated which proposed actions are most relevant to each gap. The result of this is shown in the sections dedicated to each gap. Among the types given above, type 3 relates directly to the project scope. Gaps falling into this category should be considered to be addressed by this project. For gaps of type 1 and 2, depending on the importance level set, the project can potentially prepare input to relevant organisations or standardisation/regulatory bodies. Gaps of type 4 will most probably require being addressed by separate projects.

If, during the project implementation, it turns out that any assumptions are incorrect, the related concept should be adjusted with the consortium's consent.

The following section gives a brief review and summary of the conclusions of the gap analysis. Each section covers a different area. It provides a holistic view from the perspective of experts on the subject matter on the advantages and disadvantages of the current situation, and the proposed approach with reference to current legislation and best practices where applicable.

8.1 Detailed analysis of identified gaps

Each gap has been thoroughly analysed. This section provides an extensive analysis, mainly prepared by dedicated subject matter experts, containing their views on the topic and the advantages and disadvantages of the current state and the proposed approach.

As mentioned above, part of the analysis was focused also on the evaluation of importance of particular gaps and their relevance to the scope of ICARUS. This analysis was performed together by experts and consortium members.

Results are presented in the Figure 8-1.

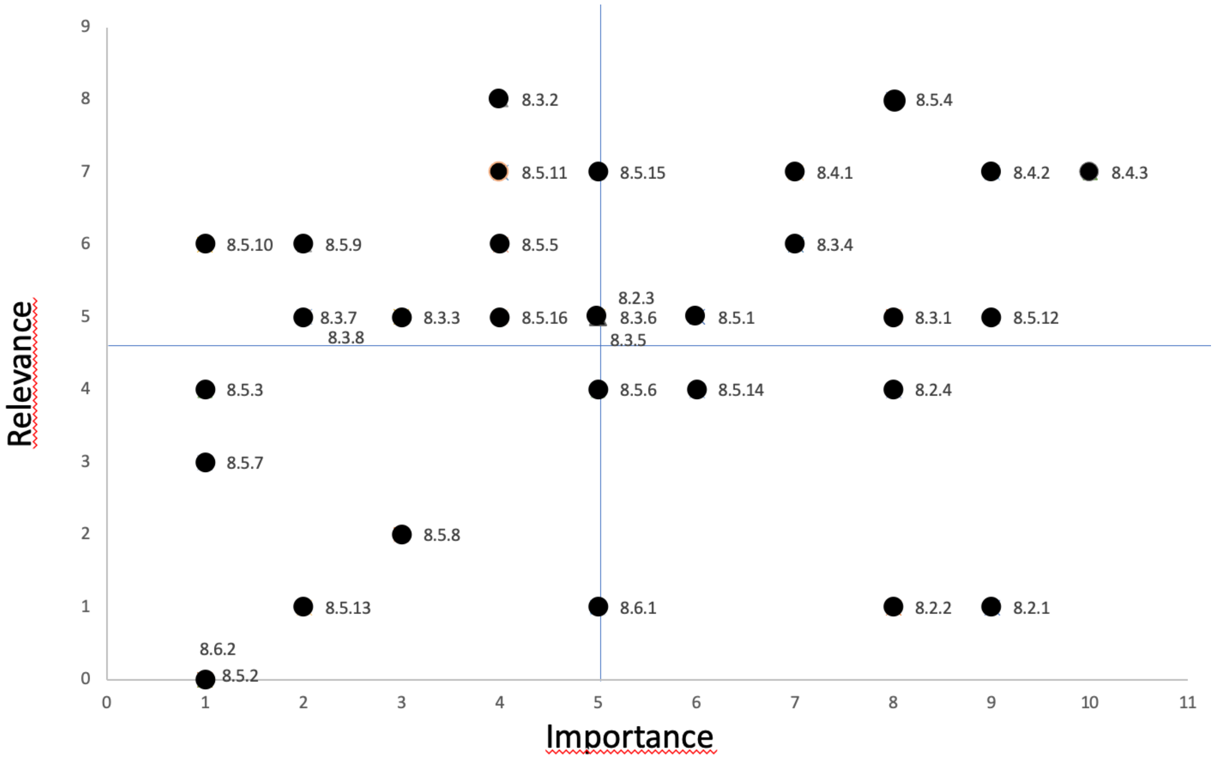


Figure 8-1 Importance and relevance to ICARUS project of identified gaps

Importance is scaled from 1 (least important) to 10 (most important), based on the average scores given by all partners in the evaluation. In turn, relevance of the topic to the scope of the ICARUS project is based on the number of votes given to each item and measured on a scale from 0 (not relevant) to 9 (most relevant).

From this analysis of relevance and importance, it can be concluded that the following gaps from the upper-right quarter of the diagram, representing the most important and most relevant topics, should be considered and thoroughly addressed by the ICARUS project:

- A reliable positioning service with integrity calculation (i.e. protection levels) essential for drone operation, especially BVLOS. There are no reference values defined for UAS (section 8.4.3)
- Communication of GNSS augmentation data. There is the need for a wide telecommunication data link to provide required data (section 8.4.2)
- Standardisation of handling of known measurement and calculation errors. Lack of standards and recommendations (section 8.5.12)
- Standardising the display of information about the height / altitude reference system. Lack of standards for display information about the H/A reference system to the UAS operator (section 8.5.4)
- Definition of rules to be used for DEM / DTM / DSM models. Correlation with current and future legislation (section 8.3.1)
- Navigation System Error Estimation/Evaluation. There is no a unified manner for determining NSE (section 8.4.1)

- Obstacle standardisation. Dimensions plus surrounding zone. Lack of definition for minimum surroundings (section 8.3.4)
- The concept involves connecting U-space systems to official QNH pressure data sources. There are no standards for exchanging QNH data across EU/World. Support for emergency situations in which the QNH pressure was not specified. (section 8.5.1)

On the other hand, during the analysis some of the gaps were classified as being of very little relevance to ICARUS (but it could be important for them to be addressed by standardisation/regulatory bodies or in another project than ICARUS), and have been assigned low importance. These gaps, located in lower-left quarter of the diagram, are:

- Intellectual properties vs normative law. No guidance for meteorological data in terms of access and payment (section 8.6.2)
- The issue of cost and legal distribution of official QNH data among U-space users (CIS / FIMS / USSP / SUSSP). Cost of data acquisition (section 8.5.2)

All the identified gaps are described in following section. Recommended actions are also provided.

8.2 General: GAMZ Geometric Altitude Mandatory Zone

8.2.1 Achieve safe segregation between manned and unmanned aviation at low level

Concept	**Introduction of GAMZ (Geometric Altitude Mandatory Zones)**
Purpose	Using a common altitude readout for traffic separation
Current state Level 1	Except for take-off and landing or within segregated flight areas, minimum flight altitude is specified for aircraft operated under VFR in visibility conditions of 1,500m horizontally and 300m (1,000 ft) vertically is: • 150m AGL (500ft) or • 150m (500ft) above the highest obstacle within a radius of 150m (500ft) from the aircraft or • 300m (1,000ft) above the highest obstacle within a radius of 600m from the aircraft over congested areas of cities, towns or open-air assembly of persons. (SERA.5005) This does not exclude light aircraft using airspace below 150m AGL.
Identified gap Weight 9 Owner All	Determining maximum vertical level of UAS flight altitude.
Solution/Action Available Q3 2021	The concept of a U-space Transition Altitude (UTA). UAS flights must use same reference as aircraft when in close proximity to the lower limit of the aircraft flight altitude band and above. Regional QNH will be considered and when check in for flight is performed it shall be translated to a value readable by UAS with subsequent updates if necessary. This allows a common pressure reference be used near the upper boundary of low-level airspace. Use of QNH by all users.
Analysis	Except for certain activities (HEMS, crop-dusting, air-lifting, etc.), and take-off and landing, manned flights are not possible below 150m AGL. However, ultralight-aircraft can use airspace below 150 mAGL. In all cases, pilots maintain visual contact with the surroundings/ground/ obstacles/terrain and take decisions for avoidance. During low-level flights, a pilot’s attention is focused on avoiding obstacles and traffic. It is highly difficult to see a UAS in flight unless there is some kind of technological aid. A system for determining pressure altitude will not deliver an adequate solution for this issue (barometric gradient, errors).
Recommended actions	Recommend amendment of EC legally binding Implementing Rules on aviation safety (e.g. SERA; 923/2011) Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar

8.2.2 Achieve safe vertical segregation between manned / unmanned aviation at low level

Concept	**Introduction of GAMZ (Geometric Altitude Mandatory Zones)**
Purpose	Use of a common altitude readout for traffic separation
Current state Level 1	Most UAS flights are based on altitude defined as vertical distance from the place of departure. Other airspace users use barometric altitude with an appropriate QNH or QFE setting depending of the type of operation.
Identified gap Weight 8 Owner All	Different reference systems for altitude reporting.
Solution/Action Available Q3 2021	Use of a translation service for UAS users to enable commonality with existing air traffic. Use of QNH for separation from manned aircraft does not exclude use of GNSS-derived altitude for UAS-UAS conflict resolution.
Analysis	Manned aircraft operators – pilots – do not expect to have to divert attention at low altitudes from piloting to cope with a new altitude reference or an altitude indicator other than that normally used. At low altitudes, a pilot's main concern is to avoid structures, terrain and traffic. The main focus is airspeed, vertical speed indicators and the "world outside". Even a brief deviation from that routine can lead to compromising of safety. If a segregated GAMZ is of 2 NM diameter and light aircraft is crossing it with speed of 90 KIAS, the pilot stays within it for 80 sec. During such a short period, it would be necessary to set/change the altimeter reference after obtaining an adequate value. VHF communications at such low altitudes is questionable. In addition, most low-level flyers sacrifice radio-comms for safety since in most cases they are out of VHF range. Even if it were assumed that the altimeters could automatically rescale when entering or leaving the GAMZ, horizontal buffer zones would be necessary to allow the change to the correct height/altitude to take place (similar to altitude transition layer used by manned aviation). Such an assumption calls into question the existence of relatively small GAMZ zones.
Recommended actions	Recommend amendment of EC legally binding Implementing Rules on aviation safety (e.g. SERA; 923/2011) Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar

8.2.3 Achieve safe vertical / horizontal segregation between manned / unmanned aviation at low level

Concept	**Introduction of GAMZ (Geometric Altitude Mandatory Zones)**
Purpose	Defining a common altitude reference system.
Current state Level 1	Rules of air and airspace segregation for different users.
Identified gap Weight 5 Owner All	Lack of technical solutions common to manned and unmanned aviation.
Solution/Action Available	A common and economically viable solution is needed. For time being, airspace segregation seems to be only option. This segregation may be of different forms such as zones areas, tracks or corridors for UAS.
Analysis	Detecting UAS traffic using human senses is difficult. In addition, determining the direction and speed of movement might be impossible for a human operator in a given set of circumstances. From this point of view, it is imperative to channel UAS traffic around areas of manned air activity. For this, altitude reference must be set to local practice e.g. QNH for determining air structures and reporting within CNS system requirements
Recommended actions	Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar **Gap possibly filled by planned activities in ICARUS Project**

8.2.4 Achieve safe vertical / horizontal segregation between unmanned airspace users at low level

Concept	**Introduction of GAMZ (Geometric Altitude Mandatory Zones)**
Purpose	Defining a common altitude reference system.
Current state Level 1	GNSS-derived altitude and when required pressure sensor or/and translation for CNS purposes.
Identified gap Weight 8 Owner All	Lack of translation information and common standard to derive pressure-based altitude information from GNSS data as appropriate to the flight area. Lack of local QNH broadcast for autonomous systems, lack of thorough analysis of QNH values at very low level.
Solution/Action Available	GNSS altitude can be used for this purpose – in most cases vertical displacement of the flight track will stay within the barometric step. Designing an appropriate airspace buffer in the vertical plane will compensate for GNSS system inaccuracies. This buffer can share the PBN/RNP navigation concept in respect to area of operation and altitude.
Analysis	For some more advanced UAS applications, it is necessary to design a certain amount of freedom in the command module to achieve autonomous avoidance within designated limits. Segregated airspace can have a discreet parameter describing the level of freedom for manoeuvrings during avoidance (e.g., overtaking, overpassing).
Recommended actions	Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar

8.3 Topography - DTM/DSM models

8.3.1 U-space area definition

Concept	**Definition of rules, to be used of DEM / DTM / DSM models.**
Purpose	Clear and easy to understand standardisation of field models is needed.
Current state Level 1	There are many field models, scattered across multiple sources and databases.
Identified gap Weight 8 Owner EGEOS DICEA	Correlation with current and future legislation
Solution/Action Available	Definition of areas where single DTM/DSM or hybrid DTM/DSM models can be used
Analysis	947 docs: ANNEX UAS OPERATIONS IN THE 'OPEN' AND 'SPECIFIC' CATEGORIES, PART A, UAS OPERATIONS IN THE 'OPEN' CATEGORY: (3) When flying an unmanned aircraft within a horizontal distance of 50 metres from an artificial obstacle taller than 105 metres, the maximum height of the UAS operation may be increased up to 15 metres above the height of the obstacle at the request of the entity responsible for the obstacle.
Recommended actions	Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar **Gap possibly filled by planned activities in ICARUS Project**

8.3.2 Data model standardisation

Concept	**Definition of metadata specific to operations in U-space.**
Purpose	Clear and easy to understand standardisation of field models is needed.
Current state Level 1	No standardised metadata to describe the terrain profile and obstacles.
Identified gap Weight 4 Owner EGEOS DICEA	Lack of U-space specific metadata for DEM/DTM/DSM models.
Solution/Action Available	Knowing the needs related to flight planning as well as the methods of risk estimation, a metadata description model should be created for U-space needs.
Analysis	The use of standard metadata will facilitate flight planning and risk assessment processes for operations in the area of GRC risks.
Recommended actions	**Gap possibly filled by planned activities in ICARUS Project**

8.3.3 Timeliness of data and distribution methods

Concept	**DTM/DSM distribution model**
Purpose	Worldwide process standardisation
Current state Level 1	Lack of coherent systems, standards, formats that clearly define the validity of the data model each time the model is requested. The lack of a single, common communication model for unmanned operations.
Identified gap Weight 3 Owner EUSCIT	Lack of distribution standards. Lack of distribution timeline (e.g. 947 docs, etc.)
Solution/Action Available	Standardisation of acceptable formats for storing data models along with their metadata. Use of AIRAC-based distribution concept.
Analysis	Data timeliness is one of the key aspects of the use of field models. Our observations show that the up-to-date aspect of the data has been neglected so far. It is well known that the terrain is changing, and a map created on the basis of collected data illustrates, at least in a static way, dynamically changing reality. Another important aspect is the way of distributing data in such a way that they are accessible in an understandable format, are unambiguous in terms of the time of use and have updating mechanisms. Additionally, the aspect of transferring relatively large data files should be taken into account. It should be remembered that the higher the accuracy, the more data there are. As a rule, survey data are large, often fragmented files, the analysis of which requires connection, which takes time and resources. During the ICARUS project, we would like to test a data distribution model conceptually similar to Aeronautical Information Publication (AIP) used by manned aviation. An AIP is a publication issued by or with the authority of a state and contains aeronautical information of a lasting character essential to air navigation. (ICAO Annex 15 - Aeronautical Information Services) The AIP contains details of regulations, procedures and other information pertinent to the operation of aircraft in the particular country to which it relates. It is usually issued by or on behalf of the respective civil aviation administration and constitutes the basic information source for permanent information and long duration temporary changes. We believe that this data distribution model, taking into account data retention, accuracy specification, information about temporary or repeated changes, should have similar mechanisms as official aeronautical publications. During the ICARUS project, we would like to develop a standardised structure and contents, taking the features of topographic information into account. The implementation of the idea of data rotation about field models would be similar to AIP. AIPs are kept up-to-date by regular revision on a fixed cycle. For operationally significant changes in information, the cycle known as the AIRAC (Aeronautical Information And Control) cycle is used: revisions (normally 1 every 28 days) are produced every 56 days (double AIRAC cycle) or every 28 days (single AIRAC cycle). These changes are received well in advance so that users of the aeronautical data can make necessary amendments, for example, updating standard routes and flight management systems (FMS), drone mission planners, Edge servers, and so on. AIPs are cumbersome documents, not usually intended to be used in the air. Commercial organisations make relevant extracts to form flight information publications (Flight Information Publication) of convenient size to be used on aircraft.
Recommended actions	Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar **Gap possibly filled by planned activities in ICARUS Project**

8.3.4 Obstacle standardisation

Concept	**Review and standardise definitions for U-space.**
Purpose	Clear and easy-to-understand definitions.
Current state Level 2	
Identified gap Weight 7 Owner EGEOS DICEA	Dimensions plus surrounding area. Lack of definition for minimum surroundings.
Solution/Action Available	Definition of a point (slender) and a line obstacle. Minimum dimensions (width and height) of an obstacle, which determines whether it will be treated (counted) as a DSM model or an obstacle within the meaning of eTOD. The presence of higher obstacles in the area determining the need to report a new obstacle in the system.
Analysis	The definition of an obstacle is not as trivial as it might seem at first glance. The presence of an obstacle should always be taken in the context of other natural and unnatural structures surrounding it. Imagine a mast 12 metres high. Such masts might not obstruct air traffic in a forest or relatively close to a taller building. But if the same mast is put on the roof of a building or in a field, its presence can have a significant impact on the safety of operations and, in this sense, the aspect of flight planning. Another extremely important aspect is the pixel size (data resolution). If the pixel has an accuracy of 3 metres and the mast has a radius of 30 cm, it most likely will not appear on the DSM model. Hence the need to create another layer containing information about slender obstacles and their visualisation on appropriate models.
Recommended actions	Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar **Gap possibly filled by planned activities in ICARUS Project**

8.3.5 Obstacle standardisation for U-space services

Concept	**U-space requirements added to official regulations.**
Purpose	Distinct area definition
Current state Level 1	The current area definitions only apply to manned aviation.
Identified gap Weight 5 Owner EGEOS DICEA	Understanding the needs specific to U-space and defining minimum requirements categorised in a similar way to those used in aviation. A review of current standards is needed.
Solution/Action Available	Stringent numerical requirements established for four distinct areas of the state territory Area 1-4. Dissemination to standardisation bodies.
Analysis	The definition of an obstacle (source: SKYBRARY) An obstacle database is a digital representation of the obstacles that includes the horizontal and vertical extent of man-made and natural significant features. In the context of eTOD, obstacles are defined as: “All fixed (whether temporary or permanent) and mobile objects, or parts thereof, that a) are located on an area intended for the surface movement of aircraft; or b) extend above a defined surface intended to protect aircraft in flight; or c) stand outside those defined surfaces and that have been assessed as being a hazard to air navigation.” There is a need, by analogy, to define, revise and update the definition of areas for U-space. States are required to ensure the availability of electronic TOD, in accordance with stringent numerical requirements established for four distinct areas of state territory. These areas are: • Area 1: the entire territory of a state; • Area 2: terminal control area (or limited to a 45-km radius – whichever is smaller), sub-divided in 4 smaller sections; • Area 3: aerodrome/heliport area: area that extends from the edges of the runway to 90 m from the runway centre line and for all other parts of aerodrome/heliport movement areas, 50 m from the edges of the defined areas; • Area 4: Category II or III operations area (restricted to those runways intended for Category II or III precision approaches): the width of the area shall be 60 m on either side of the extended runway centre line while the length shall be 900 m from the runway threshold measured along the extended runway centre line.
Recommended actions	Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar **Gap possibly filled by planned activities in ICARUS Project**

8.3.6 Terrain change monitoring

Concept	**Method to remotely detect anthropological kind changes in a given area.**
Purpose	Worldwide process standardisation
Current state Level 1	There are purely legislative methods for monitoring areas for new obstacles
Identified gap Weight 5 Owner EGEOS DICEA	Lack of methods for identifying obstacles automatically.
Solution/Action Available	Checking the possibility of tracking and notifying about changes thanks to satellite observations
Analysis	There are many factors that affect the capacity of the airspace, and thus the determination of the minimum safe distances between aircraft (separations). Conceptually, the most desirable concept from a business point of view is the concept in which drones will fly along any shortest route. This concept has been known for years in manned aviation and is called the Free Route concept. But, due to the necessity to reconcile the interests of many airspace users, including the safety of people and property on the ground, in certain areas, especially highly urbanised ones, there will be a need to channel traffic. Traffic shaping will need to consider, assess and minimise the risk of GRC and ARC, as well as the safe establishment of UAS through paths with obstacles. At present, there is no law that, as is the case with public, controlled airports, could protect such areas from unexpected construction. The point is that the Local Administration Unit, when issuing any consent for the construction of a facility, assuming a facility higher than the nearest facility in the vicinity, would have to consult with the organiser of unmanned traffic, e.g. U-space provider about its construction. This might require adjusting local construction law. Therefore, a temporary solution, but nevertheless burdened with a large error, could be to monitor terrain changes by means of satellite observations. Another solution could be monitoring changes with dedicated flights.
Recommended actions	**Gap possibly filled by planned activities in ICARUS Project** Future additional research

8.3.7 Identification of slender obstacles

Concept	**Discovery the height of the slender obstacles using satellite observations**
Purpose	Worldwide process standardisation
Current state Level 1	There are no effective methods of observing slender obstacles using satellite data.
Identified gap Weight 2 Owner EGEOS DICEA	There is no unambiguous method of detecting slender obstacles by means of satellite observation.
Solution/Action Available	Possibility of installing inexpensive deflectors, and of enforcing their use through law.
Analysis	In areas where there is no legislative protection against the creation of new obstacles, it is necessary to use wide-area monitoring systems, capable especially of determining slender (tall) obstacles. The only global method is to use satellite observations. However, due to the point-like nature of obstacles, they may not be visible to satellites. Hence the idea of using small deflectors installed on obstacles that could be seen through satellite radar images.
Recommended actions	**Gap possibly filled by planned activities in ICARUS Project** Future additional research

8.3.8 Support for Flight Planning

Concept	**Discovery of critical obstacle and profile heights within contingency volumes**
Purpose	Increasing the safety of planned operations
Current state Level 4	Currently, there are no standards for presenting data for planned routes and the surrounding contingency areas. An example solution was presented in the BFPaaS (ESA project) project.
Identified gap Weight 2 Owner DRAR	We are lacking the ability to check profiles on various terrain models. An algorithm is available, and developed by the BFPaaS (ESA) project.
Solution/Action Available Q2 2021	The ability to check the highest terrain point for the route profile and the given contingency area, based on the known terrain model
Analysis	Mapping a route for an BVLOS flight, without information about the altitude of the terrain and obstacles in the immediate vicinity of the designated route, may give erroneous confidence in the safety of flight planning. Unfortunately, our analyses showed that the calculation of the flight route without taking into account the contingency buffer might result in a collision with an obstacle in the event of position errors. This rule applies to the planned flight paths, to arrivals and departures, and to holding or controlled zones. Attempts have been made to apply algorithms that, for the designated routes, will provide information about obstacles in the vicinity for set parameters derived from the aircraft characteristics. To establish the intrinsic UAS Ground Risk Class (GRC), the applicant needs the maximum characteristic UA dimension (e.g. wingspan for fixed wing, blade diameter for rotorcraft, maximum dimension for multicopters, etc.) and the knowledge of the intended operational scenario. The applicant needs to have defined the area at risk when conducting the operation including the operational volume, which is composed of the flight geography and the contingency volume. To determine the operational volume the applicant should consider the position-keeping capabilities of the UAS in 4D space (latitude, longitude, height and time). In particular the accuracy of the navigation solution, the flight technical error of the UAS and the path definition error (e.g. map error) and latencies should be considered and addressed in this determination. The associated ground risk buffer with at least a 1 to 1 rule (i.e. if the UA is planned to operate at 150m altitude, the ground risk buffer should at least be 150m.) (Source Edition 2.0, JAR-DEL-WG6-D.04)
Recommended actions	**Gap possibly filled by planned activities in ICARUS Project**

8.4 GNSS

8.4.1 GNSS Positioning, Integrity, and Signal Monitoring

Concept	**Navigation System Error Estimation/Evaluation**
Purpose	Worldwide process standardisation
Current state Level 2	Currently, there are no standards for NSE applied to UAS
Identified gap Weight 7 Owner TPZ TOPV	There is no a unified manner for determining NSE
Solution/Action Available	NSE is estimated a-priori from: [1] Global Positioning System Standard Positioning Service Performance Standard, USA DoD, April 2020. [2] Global Positioning System Precise Positioning Service Performance Standard, USA DoD, February 2007. [3] Global Positioning System Wide Area Augmentation System (WAAS) Performance Standard, USA DoD / FAA, October 2008. [4] Galileo Open Service Service Definition Document, May 2019. [5] GSA, EGNOS Safety of Life (SoL) Service Definition Document, Issue 3.3. [6] GSA, EGNOS Open Service (OS) Service Definition Document. [7] O. Montenbruck, P. Steigenberger, A. Hauschild, “Multi-GNSS signal-in-space range error assessment – Methodology and results”, 2018. [8] Space and Geophysics Laboratory Applied Research Laboratories of The University of Texas at Austin, “An Analysis of Global Positioning System (GPS) Standard Positioning Service Performance for 2019”, May 2020. [9] U.S. Federal Aviation Administration, “Global Positioning System Standard Positioning Service Performance Analysis Report”, July 2020. [10] European GNSS (Galileo) Services Open Service Quarterly Performance Report, April-June 2020.
Analysis	The accuracy of the computed position solution is tightly related to several aspects that are difficult to specify a-priori. Usually, in the navigation domain, the accuracy is defined as the 95th percentile of the navigation positioning solution error, both in the vertical and horizontal dimensions (2-sigma error). Extensive test campaigns are suggested for the specification of NSE before validation of a GNSS receiver for UAS. Nevertheless, since accuracy is usually not the main driver (although accuracy requirements are given in Minimum Operational Performance Standards) in the application domains related to human safety, the most important aspect is usually the real-time reliability of the solution, i.e. its integrity.
Recommended actions	Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar **Gap possibly filled by planned activities in ICARUS Project**

8.4.2 Communication of GNSS augmentation data

Concept	**Communication of GNSS augmentation data**
Purpose	Backup satellite channel for data communication
Current state Level 3	Augmentation data need a data link to be sent to UTM, drone pilots or the drone itself to improve accuracy and enable integrity calculation
Identified gap Weight 9 Owner TPZ TOPV	There is a need to have a wide telecommunication datalink to provide required data
Solution/Action Available	To solve the possible lack of a terrestrial communication link a satellite channel could be used to provide data or the calculation should be done on board taking data directly from satellite broadcast
Analysis	In the current project, the effective throughput of navigation-related data generated can be detected. It has to be emphasised that a satellite link could introduce too high a latency in the data provision, threatening the possibility of computing the solution and its integrity-related parameters timely enough. This aspect could be investigated in ICARUS activities and in future projects.
Recommended actions	**Gap possibly filled by planned activities in ICARUS Project**

8.4.3 Definition of Minimum Performance Standard for Integrity of BVLOS operations

Concept	**Reliable positioning service, integrity computation (i.e. Protection Levels) essential for drone operation especially BVLOS**
Purpose	Defining a minimum performance standard for integrity to enable safe drone operations in BVLOS
Current state Level 4	Integrity reference values are derived from manned aviation
Identified gap Weight 10 Owner TPZ TOPV	There are no reference values defined for UAS
Solution/Action Available	Make theoretical studies and intense test campaigns starting from one done in ICARUS to determine UAS integrity parameters
Analysis	This is one of the very critical points of the use of GNSS as a positioning and navigation method for the UAS. The analysis and definition of standards and requirements for what concerns these aspects is out of scope of the present project. Nevertheless, ICARUS studies and outcomes could lead to interesting results and to recommendations or notes. Besides, the topic is treated in other different scopes (such as EUROCAE WG-105 SG-62, “GNSS for UAS”, and RTCA SC-228 “Minimum Performance Standards for Unmanned Aircraft Systems”). The outcomes of the deliberations of these working groups have not yet been published, so the suggestion is to adopt the performance standards used for manned aviation for current project, and eventually to try to study the effect of tuning some of the fixed parameters, to better adapt them to the context.
Recommended actions	Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar **Gap possibly filled by planned activities in ICARUS Project**

8.5 Altitude/Height reference systems - technical aspects

8.5.1 Data exchange

Concept	**The concept involves connecting U-space systems to official QNH pressure data sources.**
Purpose	Ensuring a minimum of safety in the transition areas and wherever there will be manned traffic mixed with unmanned
Current state Level 1	Each member state (ANSP) has its own system for collecting QNH pressure data
Identified gap Weight 6 Owner DRAR ECTL	No standards for exchanging QNH data across EU/world. Support for emergency situations in which the QNH pressure was not specified.
Solution/Action Available	Connection to official QNH pressure information distribution systems in the region and local data (at the airport). Information on primary and backup QNH regions. Monitoring of changes in the boundaries of QNH regions.
Analysis	Undoubtedly, the use of barometric sensors will be necessary in the transition layers as well as wherever there will be manned and unmanned aviation. Hence, access to the official QNH pressure data for selected official areas as well as local pressure for airports is absolutely required. The issue of the use of barometric sensors in GAMZ spaces should also be considered, but with increased measurement accuracy, greater than the unit change of 1hPA, 1mmHg, inHg, as is the case for manned aviation.
Recommended actions	Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar **Gap possibly filled by planned activities in ICARUS Project**

8.5.2 Distribution of QNH information

Concept	**The issue of cost and legal distribution official QNH data among U-space users (CIS / FIMS / USSP / SUSSP)**
Purpose	Ensuring a minimum of safety in the transition areas and wherever there is both manned and unmanned traffic.
Current state Level 1	The cost of obtaining QNH data is probably negotiated individually with official meteorological data suppliers. It must be assumed that in some countries the cost of obtaining QNH information is included in the state support for VFR flights.
Identified gap Weight 1 Owner DRAR ECTL* EUSCIT	Cost of data acquisition
Solution/Action Available	As QNH data may belong to the group of normative information, the data should be distributed free of charge. The consortium members decided to send a question to all European ANSPs asking: QNH questionnaire for ATS 1. Are there any legal or financial constraints or issues prohibiting you from sharing real-time QNH values used by your system/ subsystem/ ATS with a U-space/ICARUS service provider? If so, what are they? 2. How can real-time QNH values be legally obtained by an ICARUS service provider in your FIR? 3. Are there any technical issues to be overcome before providing QNH values? If so, what are they? 4. What QNH contingency procedures are used if there are problems with local sensors or their communication channels, etc.? Especially, what QNH value do aircraft use in such cases? 5. Are there any areas where measured, forecast, or calculated QNH cannot be treated as accurate for aviation purposes? The aggregated results of the questionnaire will be used to further analyses.
Analysis	It should be considered whether QNH pressure data is legally normative. If so, this data should be public and free of charge.
Recommended actions	

8.5.3 Usage of telecommunication networks' capabilities

Concept	**An attempt to use telecommunications networks, especially Edge computing, to distribute information about local obstacles**
Purpose	Increasing the safety of unmanned flights, without the need to involve on-board obstacle detection systems, either visual or radar.
Current state Level 1	The idea of publishing information about local obstacles using telecommunications networks is a new feature. There are no current standards.
Identified gap Weight 1 Owner DRAR	There are no systems that broadcast information about local obstacles.
Solution/Action Available	Need to analyse the available telecommunications systems (3G / LTE / 5G / Wi-Fi / BT). Recommendations for effective protocols should be produced.
Analysis	Information about obstacles is required at the flight planning stage and during the flight. While there are methods for storing and updating obstacle databases, due to the possibility of a sudden obstacle, it would be useful to have a system that publishes the current data locally. This would be the equivalent of a lighthouse, also informing users about other local threats. In addition, the function could be used in the event of a drone which was suddenly in a place where it was not planned, e.g. due to a failure.
Recommended actions	Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar

8.5.4 Drone vertical position standardisation

Concept	**Standardising the display of information about the height / altitude reference system.**
Purpose	Standards for the defining the reference system used for height/altitude across drone manufacturers and the ways it is calculated by every drone (manufactured or home-made). Only by knowing the reference systems and methods of calculating altitude in all aircraft will it be possible to clearly determine their respective heights.
Current state Level 1	Lack of recommendations and standards for defining height/altitude across drone manufacturers.
Identified gap Weight 8 Owner TOPV EUSCIT	Lack of standards for displaying information about H/A reference system to the UAS operator
Solution/Action Available	A proposal for a nomenclature to be used when defining the reference system
Analysis	The vocabulary used to specify the reference model used must be unambiguous and easy to remember and understand. Description kits to explain their meaning in the application's help and FAQ should also be prepared.
Recommended actions	Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar **Gap possibly filled by planned activities in ICARUS Project**

8.5.5 Standardisation of the of switching between altitude/height reference systems

Concept	**Standardisation of the method of switching between altitude/height reference systems.**
Purpose	Only by knowing the reference systems and methods of calculating altitude in all aircraft will it be possible to clearly determine their respective heights.
Current state Level 1	Lack of recommendations and standards for defining height/altitude across drone manufacturers
Identified gap Weight 4 Owner TOPV EUSCIT	Lack of possibility to switch between reference systems in cheaper drones. No standard or recommendation.
Solution/Action Available	Recommendations for manufacturers to use switches for reference models.
Analysis	The menu of the application controlling the drone should include a switch between reference models for defining altitude. The switch should be provided with an instruction manual with information where and at what time the model should be used.
Recommended actions	Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar **Gap possibly filled by planned activities in ICARUS Project**

8.5.6 Standardisation of the method of enforcing the use of specific height/ altitude reference system.

Concept	**Standardisation of the method of enforcing the use of specific height/ altitude reference system.**
Purpose	Only by knowing the reference systems and methods of calculating altitude in all aircraft will it be possible to clearly determine their respective heights.
Current state Level 1	Lack of recommendations and standards for defining height/altitude across drone manufacturers
Identified gap Weight 5 Owner TOPV EUSCIT	It is not possible to force the use of a specific reference model. No recommendation for producers.
Solution/Action Available	An interface or API must be created for the U-space interface (in addition to document 945) so that the take-off of a drone in the GAMZ area will only be possible after enforcing that drone to use a GAMZ-specific reference system.
Analysis	The problem of forcing the use of appropriate reference methods in commercial drones is a problem on the border of business and technology. Drone manufacturers are generally reluctant to enforce regulations on their equipment, shifting the responsibility for the flight to the drone operator/pilot. The rule here is that no one will say where my drone can fly as it could potentially limit sales. Unfortunately, such an approach, in which the entire responsibility is shifted to the drone operator, who is often unaware, is not conducive to the general safety of operations. Hence, the necessity to enforce the use of an appropriate reference system should be ensured at the legislative level and legally enforced.
Recommended actions	Recommend amendment of EC legally binding Implementing Rules on aviation safety (e.g. SERA; 923/2011) Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar

8.5.7 Access to device calibration data

Concept	**Possibility to access device calibration data.**
Purpose	By adding calibration calculations, it will be possible to determine vertical position error. It will be possible to clearly determine their respective heights of all aircraft.
Current state Level 1	Lack of recommendations and standards for determination height/altitude across drone manufacturers.
Identified gap Weight 1 Owner POLIMI	There is no information about the calibration of barometric measuring devices.
Solution/Action Available	Definition of a method of exchanging information on calibration data.
Analysis	This element is of particular importance in areas where drones will fly in the presence of manned aviation. Measurement sensors used in IFR / VFR flights are standardised and certified in manned aviation. To maintain the required level of safety, the certification aspect of sensors in drones should be taken into account.
Recommended actions	Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar

8.5.8 High-level recommendation for the use of units and abbreviations specifying the selected reference model.

Concept	**High-level recommendation for the use of units and abbreviations specifying the selected reference model.**
Purpose	Appropriate records in the documentation at each level: manufacturers, standardising bodies, local, European and global regulations.
Current state Level 2	There is no standard for presenting the height format and the reference system with units
Identified gap Weight 3 Owner EUSC?? ECTL	Some ideas already exist from other EU projects
Solution/Action Available	Recommendation to use unified units for selected areas and methods of their conversion (rounding) and presentation.
Analysis	There are many metric systems in the world. Unification and clear recommendations are needed to avoid so-called "obvious errors" in interpretation.
Recommended actions	Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar

8.5.9 Use of an exact take-off position for altitude recalculation

Concept	**Use of an exact take-off position for altitude recalculation**
Purpose	Take-off position could be used for a standardised determination of take-off altitude
Current state Level 1	No reliable analyses
Identified gap Weight 2 Owner TOPV TPZ	It should be checked, among several popular drone manufacturers and controllers, whether there is a method of sending data about the place of take-off in telemetry
Solution/Action Available	Analysis of the possibility of accessing information about the take-off position in popular drones and frequently used open-source flight controllers.
Analysis	For the purposes of the ICARUS project, we assume that it is possible to calculate the altitude based on the take-off site known from the field models used. Additionally, this information can be used to verify whether the currently displayed height is correctly calculated.
Recommended actions	Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar **Gap possibly filled by planned activities in ICARUS Project**

8.5.10 Offline vs online DTM/DSM data sets

Concept	**Definition of when DTM/DSM data can be used offline and when online**
Purpose	Assuming that not all drones, especially the cheaper ones, will be able to upload terrain models before take-off, the possibility of calculating height using external systems, e.g. 5G edge computing, should be taken into account.
Current state Level 1	Lack of standards and recommendations.
Identified gap Weight 1 Owner EGEOS DRAR	There are no reliable analyses of the use of field models in terms of computing power of drones and the necessary bandwidth to send sufficient area to the drone.
Solution/Action Available	For now, there is a need to identify the advantages of using online and offline models.
Analysis	It is well known that field data file sizes are relatively large. It is also known that processing them requires adequate computing power. Due to the current power deficit on the drone, it should be considered whether an online or offline model will be more effective.
Recommended actions	Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar **Gap possibly filled by planned activities in ICARUS Project**

8.5.11 The broadcasting methods for Height / Altitude information.

Concept		**Communication methods for Height / Altitude transformation**
Purpose		Possibility of calculating height using external systems, e.g. 5G edge computing.
Current state		Lack of standards and recommendations.
Level	1	
Identified gap		There is a need to convert and broadcast elevation reference models and converted eIdentification (telemetry) data in the U-apace.
Weight	4	
Owner	DRAR	
Solution/Action		The use of available telecommunications methods for publishing and broadcasting data safely and unambiguously.
Available		
Analysis		The GAMZ concept involves the use of external calculations to determine the vertical position of the aircraft. For this, the existing telecommunications systems should be considered, as well as modern methods currently being developed, e.g. with 5G systems.
Recommended actions		**Gap possibly filled by planned activities in ICARUS Project**

8.5.12 Standardisation of handling of known measurement and calculation errors

Concept		**Standardisation of handling of known measurement and calculation errors.**
Purpose		Errors might change calculations
Current state		Lack of standards and recommendations.
Level	2	
Identified gap		
Weight	9	
Owner	TOPV TPZ	
Solution/Action		
Available		
Analysis		
Recommended actions		Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar **Gap possibly filled by planned activities in ICARUS Project**

8.5.13Vulnerability and responsiveness to cyber attacks

Concept		**Providing resistance to known and potential unknown methods of cyber-attack**
Purpose		Ensuring the safety of air operations.
Current state		Lack of standards and recommendations.
Level	1	
Identified gap		
Weight	2	
Owner	TPZ TOPV	
Solution/Action		The newly created system developed under the ICARUS project will operate in accordance with the CIA paradigm: Confidentiality, Integrity and Availability. In order to produce services and systems on the manned and unmanned aviation market, it is necessary to create a single source of reliable information. Due to the obvious fact that it is not possible to aggregate all the necessary information needed to run the service in one system (database), a coherent, structured communication layer must be created, with the specification of appropriate secure protocols. The implementation of the ICARUS service will be carried out in accordance with the SWIM concept (System Wide Information Management).
Available		
Analysis		
Recommended actions		Future additional research

8.5.14 Achieve safe segregation between manned and unmanned aviation at low level

Concept		**Introduction of GAMZ (Geometric Altitude Mandatory Zones)**
Purpose		Use of common altitude readout for traffic spacing
Current state		Lack of standards and recommendations.
Level	1	
Identified gap		Existence of SORA definitions for manned aviation. Lack of standardisation for unmanned and hybrid flights. No regulation of standardisation for flights near the U-space transition layer.
Weight	6	
Owner	ECTL	
Solution/Action		Definition of rules that precisely characterise the use and area of switching of altitude reference systems
Available		
Analysis		
Recommended actions		Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar

8.5.15 Contingency plans

Concept	**Contingency plans for GNSS degradation.**
Purpose	Ensuring a minimum of safety and contingency plans in the event of failure of a system or one of its components.
Current state Level 1	Barometric sensors are used in drones, but in a non-standardised way. Even with the ADS-B standard, measured values are rounded to the nearest tens of ft according to the protocol.
Identified gap Weight 5 Owner POLIMI	There are no standards for the use of pressure sensors with higher accuracy than 1hpA, 1mmHg, 1inHg. There are no standards for a reference pressure for drones, with the possibility of using an accuracy greater than a standardised unit of measure. There are no standards for determining when and under which circumstances a switch or the use of barometric sensors could be applied.
Solution/Action Available	Based on the analysis of popular barometric sensors, an attempt should be made to determine the minimum safe value of the pressure change providing unambiguous determination of the vertical position. On this basis, an attempt to determine the cruising layers, taking into account the terrain profiles, should be made.
Analysis	In manned aviation, barometric pressure is used, with the unit scale limited to one hectopascal (1hPa), mmHg or inHg. This is dictated by historical reasons as well as the fact that pressure data is transmitted orally via a radio channel, and pressure is dictated by radio. Currently used digital pressure sensors have a much higher accuracy (to the level of centimetres), standards should be considered for the minimum safe value of pressure differences in which popular and cheap pressure sensors used on drones could provide information about the altitude in the event of failure or shortage of the GNSS system, or even in special cases to replace it. Also, it should be noted that where the ATM system converts ADS-B level data to display the barometric equivalent level data, the displayed data should not be used to determine vertical separation until the data are verified by comparison with a pilot-reported barometric level.
Recommended actions	Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar **Gap possibly filled by planned activities in ICARUS Project** Future additional projects

8.5.16Safety promotion, knowledge dissemination

Concept	**Means of promotion and communication of requirements and standards in an understandable manner**
Purpose	Definition of CARS specific documentation and vocabulary.
Current state Level 1	Due to the need to unify experiences between two interest groups, geodetic and aviation services, there is a need to consolidate the methods of naming and communication.
Identified gap Weight 4 Owner EUSCES	The lack of uniform nomenclature can lead to misunderstandings and incorrect use of reference models and field data, which has a direct impact on air traffic safety.
Solution/Action Available	Definition of CARS specific documentation and vocabulary.
Analysis	The aspect of user education cannot be ignored in this project. It should be remembered that the system will only be as good as the people using it understand how it works. Hence, with such a complicated level of progress of procedures and technical requirements, as well as the need to meet the appropriate conditions for the use of systems, proper and easy-to-understand standardised education material is necessary. Promoting education through international organisations such as EuroCAE, JARUS should also be considered.
Recommended actions	Recommend amendment of EC legally binding Implementing Rules on aviation safety (e.g. SERA; 923/2011) Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar **Gap possibly filled by planned activities in ICARUS Project**

8.6 Other

8.6.1 Responsibility vs insurance

Concept	**Establishing clear and transparent rules in the area of responsibility for data processing systems and data delivery platforms**
Purpose	Separation of responsibilities between process participants
Current state Level 1	Existing liability law does not cover the use of data for UAS flights in the context of terrain and obstacle data exploration. There are no defined limits of liability between the participants in the development, analysis, processing and delivery of data.
Identified gap Weight 5 Owner EUSCES	There are no provisions clearly defining the responsibility of data providers and data users.
Solution/Action Available	Creation of norms and principles to define responsibilities in the areas of data production, data analysis, data processing and data delivery. Determining methods for verifying algorithms that have a direct impact on safety.
Analysis	New and emerging digital, and increasingly autonomous, technologies challenge some of the fundamental legal and institutional principles of civil aviation. New entrants have a fundamentally different safety and operational mindset compared with traditional manned-aviation stakeholders. The progressive deployment of U-space solutions will benefit all airspace users (manned and unmanned) by providing a full set of services. However, the smooth adoption and public acceptance of these new technologies and services depend, to a large extent, on clarifying the responsibilities and liabilities of the involved state and non-state actors in this complex environment.
Recommended actions	Recommend amendment of EC legally binding Implementing Rules on aviation safety (e.g. SERA; 923/2011) Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar

8.6.2 Rules and standards for MET service provisions

Concept	**Creating recommendations for regulatory authorities and standard development organisations to ensure safe and uniform data treatment for MET services at VLL**
Purpose	Unifying access to data and relying on suitable MET service providers
Current state Level 1	Lack of clarity and completeness of rules and standards
Identified gap Weight 1 Owner ECTL	No guidance is yet drafted to ensure terms of access and fair payment of weather services in the U-Space.
Solution/Action Available	1. Amend Commission Implementing Regulation (EU) 2019/317 of 11 February 2019 laying down a performance and charging scheme in the single European sky, to allow fair access and pricing of weather services in the EU at VLL, including far from aerodromes. 2. Contribute to the work of SDOs to ensure that their deliverables also cover the needs for exchange of geographical and weather information. 3. Creation of Europe-wide recommendations unifying the access to the QNH data across Europe.
Analysis	Aviation weather information is a service provided to ANSPs and pilots by meteorological air navigation service providers, generally local to the state overflown (e.g. UK Met Office), though there are other sources. It is essential that values used by UASs are the same as those used by manned aviation in the same area. An ANSP, and therefore a USSP, could have to pay for this information, and any price must be within the ability to pay of a USSP. Currently EC Regulation 2017/373 covers MET services, based on Annex 3 to Chicago Convention. However, these provisions are not tailored to the needs of UAS at VLL. The gap at the level of safety regulation is being closed by Art. 12 of draft U-Space regulation, which is being discussed at Commission level, following EASA Opinion 01/2020. Standard Development Organisations (SDOs) are drafting standards for the functional architecture (e.g. ISO 23629-5), data exchange (e.g. ISO 23629-7), UTM Service Provision (e.g. 23629-12) and interfaces with vertiport operators (e.g. 5015-2).
Recommended actions	Recommend to EC/EASA to consider access and charging of U-Space services. Develop or amend, at the level of AMC, consensus-based industry standards, by ISO, EUROCAE, or similar. Investigate the availability, cost, and unicity of standard QNH values for all regions of Europe.

9 Overall error budget

The main technical objectives identified in ICARUS will be investigated in more detail considering different types of error that may affect the direct vertical measurements and/or data provided by USSP or other data providers.

To assess a feasible common vertical reference, possible errors must be estimated with a common datum, especially in the case of a common UAS-UAS reference. This is very important because it is not currently possible to separate drone traffic vertically, therefore a highly accurate vertical measurement is needed to estimate the "thickness" of vertical safety layers to improve VLL airspace capacity and allow other projects to study different traffic separation schemas.

For this reason, this section presents an error budget analysis, following a PBN approach for the UAS-UAS case.

9.1 Introduction on RNP procedures

RNP procedures were introduced in the PANS-OPS (Doc 8168), which became applicable in 1998.

These RNP procedures were the predecessor of the current PBN concept, which defines the performance for en-route operations instead of simply identifying a required radio navigation system performance.

An RNP system uses its navigation sensors, system architecture, and modes of operation to satisfy the RNP navigation specification requirements. RNP requirements may limit the modes of operation of the aircraft, e.g. for low RNP, where flight technical error (FTE) is a significant factor, manual flight by the crew might not be allowed. Dual-system/sensor installations might also be required, depending on the intended operation or need. RNP specifications include requirements for certain navigation functionalities. At the basic level, these functional requirements may include:

- continuous indication of aircraft (drone) position relative to track to be displayed to the pilot flying on a navigation display situated in his primary field of view;
- displaying of distance and bearing to the active waypoint;
- displaying of ground speed or time to the active waypoint;
- navigation data storage function
- appropriate failure indication of the RNP system, including the sensors.

An RNP specification is characterised by a suffix "X", e.g. RNP3. This suffix refers to the lateral navigation accuracy in nautical miles, which is expected to be achieved at least 95 per cent of the flight time by the population of aircraft operating within the airspace, route or procedure.

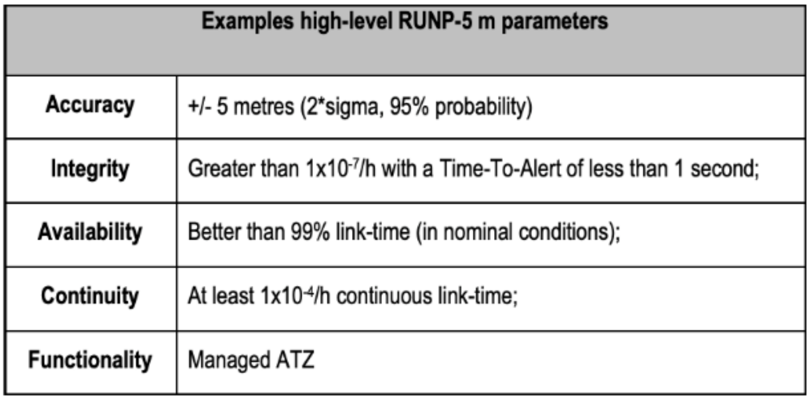
The performance-based descriptions address some characteristics that were causing variations in flight trajectories, leading to more repeatable, reliable and predictable flight tracking, as well as smaller obstacle assessment areas.

Currently, PBN aims to harmonise longitudinal and lateral performance requirements (i.e. 2D) for RNP specifications and in the future, it is expected to include 4D trajectory-based operations. These 4D operations could be very effective for drones, allowing specific “routes” in any portion of airspace where the GNSS signal is “well received”.

The PBN and the RNP specifications were formulated by ICAO for traditional aviation. However, for the last few years such concepts have also been converted for drone use through different R&D projects and initiatives ([14], [15], [16], [17]). GNSS technology in this context can play an important role in the definition of RNP specifications in terms of reduction of the “Navigation System Error” by considering dual frequency GNSS receivers in multi-constellation configurations, as well as a significant enhancement in the accuracy of measurement on the vertical axis above the WGS-84 datum, when used in combination with different GNSS constellations.

9.1.1 Required U-space Navigation Performance

Validated Required U-space Navigation Performance (RUNP) would use the same ICAO principles of validation that are used in RNP and RNAV. The specification would use the same requirements set, although the parameters of what produced a safe operation will have to be validated for a given geospatial implementation. RUNP is written with a distance suffix, as is done for RNP. In the case of RUNP the distance unit is given with an SI abbreviation, and is usually m, for metres ([15]). The following is an example of high-level RUNP parameters.



Examples high-level RUNP-5 m parameters	
Accuracy	+/- 5 metres (2*sigma, 95% probability)
Integrity	Greater than 1x10^{-7}/h with a Time-To-Alert of less than 1 second;
Availability	Better than 99% link-time (in nominal conditions);
Continuity	At least 1x10^{-4}/h continuous link-time;
Functionality	Managed ATZ

Table 9-1: example of high-level RUNP

9.2 Performance-based Navigation approach

ICAO PBN document 9613 explains the PBN concept and defines the aircraft area navigation performance requirements in terms of navigation specifications. These prescribe the accuracy, integrity, availability, continuity and functionality needed to support a particular airspace concept.

The PBN concept represents a shift from sensor-based to performance-based navigation. Performance requirements are identified in navigation specifications, which also identify the choice of navigation sensors and equipment that may be used to meet the performance requirements. These navigation specifications are defined at a sufficient level of detail to facilitate global harmonisation by providing specific implementation guidance for states and operators.

PBN identifies the technologies that allow aircraft to fly flexible, accurate, three-dimensional flight paths using on board equipment and capabilities, freeing them from reliance on fixed, ground-based radio-navigation aids, and creates economic, environmental, safety and access benefits.

The implementation of performance-based flight operations requires not only the functions traditionally provided by the RNAV systems, but may also require specific functions to improve procedures, and airspace and air traffic operations, such as fixed-radius paths and lateral offsets.

This chapter transposes the performance-based navigation concept for manned aviation into the domain of drones, considering GNSS as the primary technology for navigation and the capability of a drone's autopilot to maintain its desired path as explained in the next paragraph.

9.2.1 LATERAL NAVIGATION

The inability to achieve the required lateral navigation accuracy may be due to navigation errors related to aircraft or drone tracking and positioning. The Total System Error (TSE), defined as the deviation of a flight's true position away from the desired path, is the sum of three main errors:

- **Path Definition Error (PDE):** Traditionally this error in manned aviation occurs when the path defined in the RNAV system does not correspond to the desired path. The use of an RNAV system presupposes that a defined path, representing the intended track, is loaded into the navigation database. This error may be transposed in drone domain considering the cartographic systems (digital maps) that pilots use when planning their missions on their ground stations and the actual paths reported to U-space.
- **Navigation System Error (NSE):** refers to the difference between the aircraft's position as estimated by the navigation sensor, i.e. the GNSS receiver in this case, and its true position;
- **Flight Technical Error (FTE):** refers to the aircrew's (pilot's) or autopilot's ability to follow the defined path or track, including any display error. This error can be monitored by the autopilot or by aircrew procedures, and could be provided by a map display. It represents the difference between the aircraft location indicated by the navigation system and the defined flight path.

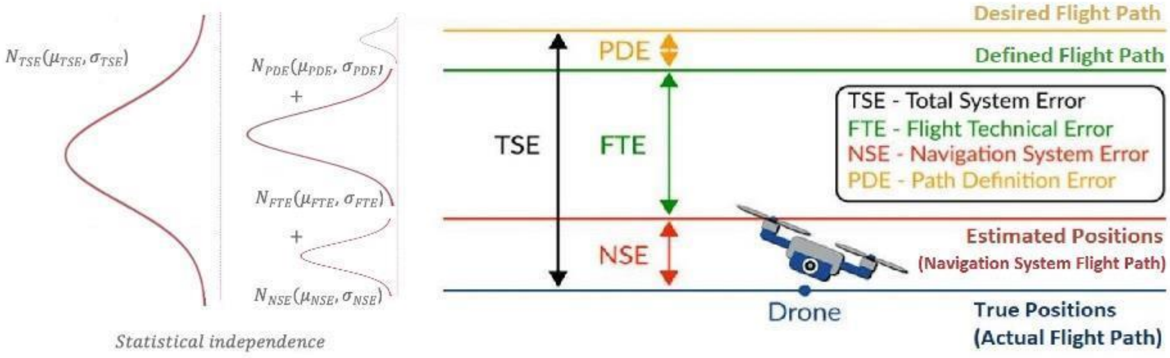


Figure 9-1: Total System Error decomposition

The figure above shows the actual position of the drone, its Actual Flight Path (blue), the Desired Flight Path (yellow), the Navigation System Flight Path (red) – that is the path indicated by the aircraft avionics, and the path that was defined in the flight control system (green). The elements that separate the desired path from the actual one are the components of the Total System Error (TSE). According to the literature for manned aviation, the Path Definition Error (PDE) is sufficiently small compared with the other errors that it can be safely neglected; however, this might be not true for drones due to the accuracy required for certain kinds of operation. In fact, it could be that PDE should not be neglected if the accuracy of cartography required is at a centimetric / decimetric level.

9.2.2 Assumptions on Errors

The distribution of these errors is assumed to be independent, zero-mean and Gaussian. Therefore, the distribution of TSE is also Gaussian with a standard deviation equal to the root sum square (RSS) of the standard deviations of these three errors.

The FTE for drones is expected to be the main contributor to the TSE. FTE is a characteristic function of the specific drone (drone + autopilot guidance or drone + pilot control), sensitive to weather conditions and the drone's velocity. As shown in Figure 9-2, a lateral shift can occur between two consecutive estimations of a drone's position, and this is quantifiable only when a new drone position is updated.

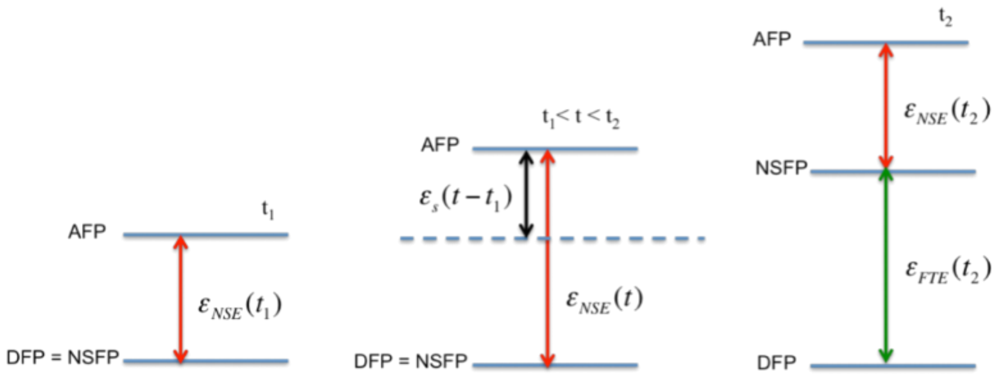


Figure 9-2: Generation of FTE during the update of drone position

At the left of Figure 9-2, if the drone's estimated position at time t_1 coincides exactly with the desired path (DFP=NSFP), this position estimate can have been affected only by the NSE. So the actual position (AFP) differs from the estimated one by $\varepsilon_{NSE}(t_1)$. In a GNSS-based navigation system, the main factors that make up the NSE are the User Equivalent Range Error (UERE) and the Geometric Dilution Of Precision (GDOP), which are described in the following paragraph.

The UERE refers to the pseudorange measurement errors caused by tropospheric and ionospheric errors, the multipath effect, clock error, etc. while GDOP specifies the error propagation as a mathematical effect of satellite geometry on positional measurement precision. So NSE is strongly dependent on the GNSS receiver used and on the techniques and configurations used to mitigate errors on the pseudo-range measurement. Usually, in non-urban environments or in any case where there is a very low multipath error, the NSE value is estimated at around 1-2 m. [14]

If t_2 is the time at which the navigation system next updates the drone's position, during the time interval $t_1 < t < t_2$, the real position of the drone (AFP) could change due to a turbulence effect or a change in the flight direction, while the estimate of the drone's position (NSFP) remains the same, so the navigation error increases by $\varepsilon_s(t - t_1)$. Finally, at t_2 the drone updates its position, detecting a shift compared with the desired path $\varepsilon_s(t_2 - t_1)$. This is the Flight Technical Error and it is denoted in the figure as $\varepsilon_{FTE}(t_2)$.

If the cause of the error persists, it will increase until the drone's pilot or the autopilot do something to fix it. It is interesting to note that at every position update, the navigation error (NSE) depends only on the estimate of the pseudo-ranges and therefore not on the drone's speed or on the wind speed.

Since FTE is the main contributor to the lateral TSE, it is interesting for the purpose of ICARUS project to correlate FTE, NSE and PDE with a sensitivity analysis, varying the speed of the drone, and the wind speed in a direction perpendicular to the direction of the flight (crosswind and updraft).

9.3 UAS-UAS Common altitude reference

The first error-budget investigation, using a WGS-84 datum, is the common altitude reference at VLL where two UAS are flying using the same geometric datum, with no other U-space service request for augmenting their horizontal and vertical accuracy. The model of the datum itself is embedded in the GNSS receiver.

A PBN approach is used for determining vertical and horizontal error for both drones, with the following assumptions:

UAS- UAS Common altitude reference error budget	
UAS 1	Industrial grade Hexcopter (Use Case II) Remotely piloted MTOM: 25 kg
UAS 2	Industrial grade Quadplane, VTOL (Use Case I) Remotely piloted MTOM 24,9 Kg
Planned Trajectory	Point–to-Point, Linear Cruise speed: 10 m/s (ground speed) Automatic (Autopilot engaged)
Environmental Conditions	Cross wind (gust) component 15 m/s Updraft wind (gust) component 15 m/s
GNSS Receiver	DFMC Industrial Grade GNSS Receiver EGNOS enabled for both UAS

Table 9-2: Assumptions for UAS- UAS Common Altitude Reference error budget

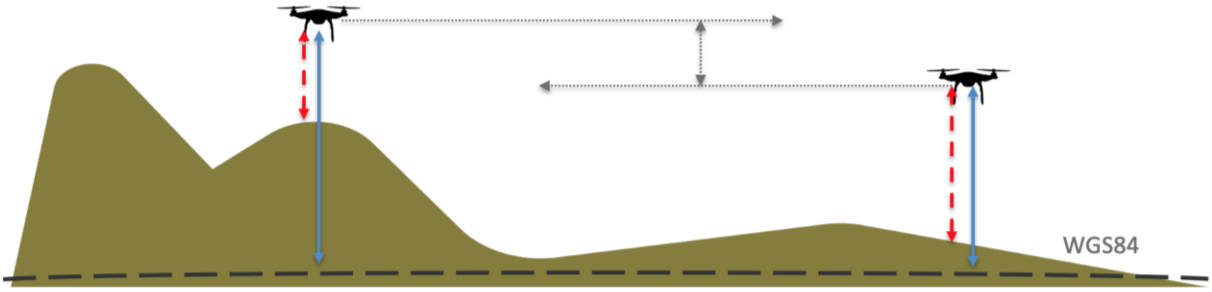


Figure 9-3: UAS-UAS case

The error budget will be determined using a literature review approach for the estimation of the errors, but also by means of numeric simulations and real flight sessions when needed. In particular, once all the sources of error have been identified, a theoretical RNP specification for navigational accuracy can be drafted.

9.3.1 Path definition error

The reference, or desired, trajectory can also be corrupted with errors and anomalies such as administrative errors (e.g. naming and labelling), inaccuracies of data in the database (including as a result of surveying errors), lack of up-to-date information (e.g. unreported new buildings in VLL) and misinterpretations of the geodetic datum.

This Path Definition Error (PDE), typically neglected for traditional aviation, cannot be always neglected for drones, especially when planning missions where a high level of detail is required. In this case, the error can be directly related to the cartographic system used by the ground control station in use (level of zoom, details of the map, accuracy of cartographic representation, etc.) and the DSM used.

This error can spread from the centimetre level up to one metre on the horizontal plane (e.g. Open Street map, etc.). The error on the vertical axis can be much higher as described in the next paragraphs. However, using a GNSS DFMC receiver for the acquisition of the “Home Point fix” for updating the DTM value (especially in case of recurrent missions) could be a good mitigation strategy to limit this error.

9.3.2 Navigation system error

9.3.2.1 Introduction

Generally speaking, it is important to define the Navigation System Error (NSE) so that the Total System Error (TSE – see Figure 9-1) can be defined as accurately as possible. Even if nominally independent from any other error source, it is however difficult to isolate the NSE within the TSE during a normal test campaign. Moreover, if the drone has an autopilot mechanism (even if only for flight stabilization), the NSE and the FTE (Flight Technical Error), if not carefully considered, can be substantially inextricable. For these reason, specific and extensive measurement campaigns to characterize at most the NSE would be necessary. In absence of that, the best that can be done is to do some theoretical considerations, together with the study – when the data are available and applicable – of technical data sheets of the receiver and the antenna, provided by the manufacturer, of the environment, and finally of the historic series and figures of the performances achieved in similar conditions.

9.3.2.2 Theoretical considerations and accuracy according to performance standards

Theoretically speaking, a precise definition, a-priori, of the NSE is quite impossible, due to the large number of factors that must be considered:

1. **Errors originating from the space and control segments**: seasonal and clock errors, satellite hardware biases, non-optimal attitudes, inaccuracies in the definition of centre of phase of antennas, etc.; possible satellite or system failures are not considered here and are treated as outliers – they are allocated in the integrity budget.
2. **Errors introduced by Signal in Space propagation**: uncompensated effects of troposphere, ionosphere, relativistic gradient, etc.

3. **Environment and intrinsic receiver errors**: noise, multipath, signal blocking (obstacles), non-optimal correlators, antenna and circuits, hardware biases, geometry of the visible constellation (DOP), unintentional or malicious interference, type of processing and the observables used in it (e.g.: the ionospheric-free combination eliminates the 99% of the ionospheric delay, but amplifies the noise), etc.

A common way to categorise and provide a rough description of the impact on the positioning accuracy of the abovementioned error components is provided by the GPS/Galileo Performance Standards ([1], [2], [3], [4]):

- URE (User Range Error) / SISE (Signal In Space Error), concern the signal "portion" of the overall error budget
- UEE (User Equipment Error), define the portion of the error due to the receiver
- UERE (User Equivalent Range Error), considers the overall contribution of the above components to the measurement error: $UERE = \sqrt{(URE)^2 + (UEE)^2}$
- DOP (Dilution Of Precision), considers the impact of satellite geometry, as seen by the receiver, on the positioning error (overall – PDOP, or decomposed in the horizontal/vertical components – HDOP/VDOP): $Positioning\_Error \cong UERE \times DOP$

According to performance standards for GPS SPS and Galileo OS, the following signal-in-space accuracy values are guaranteed in nominal conditions:

Constellation	SIS Accuracy	Conditions and Constraints
GPS	• ≤ 7.0 m (95%) Global Statistic URE during Normal Operations over all Age Of Data • ≤ 3.8 m (95%) Global Statistic URE during Normal Operations at Zero Age Of Data • ≤ 9.7 m (95%) Global Statistic URE during Normal Operations at Any Age Of Data	• For any trackable and healthy SPS SIS • Neglecting SF ionospheric delay model errors • Including group delay time correction (TGD) errors at L1 • Including inter-signal bias (P(Y)-code to C/A-code) errors at L1 • Including ISC errors

Galileo	• ≤ 7m (95%) global average, over all Age Of Data	• Calculated over a period of 30 days • For any healthy OS SIS above a minimum elevation angle of 5 degrees • Including Broadcast Group Delay errors • Propagation and user contributions excluded • Neglecting single frequency ionospheric delay model errors

Table 9-3: Signal-in-space accuracy for GPS and Galileo nominally declared in performance standards ([1], [4])

It must be emphasised that the performances listed above do not consider the error induced by atmospheric propagation. Therefore, the residual error after compensation of the affecting delays must be derived statistically from the processing over long time series – this depends, of course, on the compensation model applied in the receiver. At the same time, the error is a function of the Age Of Data, i.e. the time passed since last navigation message update.

In addition to the figures listed above, many other components contribute to building the overall error, and typically depend on the environment and the satellite elevation. Moreover, as previously mentioned, to consider the overall UERE, the errors introduced by the receiver equipment should be considered. Some assumptions are made in [1] related to different receiver qualities: the “traditional” specifications foresee a UEE of 5.5 m (95%; 2.8 m 1-sigma); the “improved” specifications have a UEE of 4.6 m; the “modern” 4.5 m; the “advanced” (dual frequency ionospheric-free), 1.6 m (0.8 m 1-sigma).

As an example, three tables obtained from [1] and [4] with the main error contributions to UERE are given below.

Error source	**1-sigma for E1 Single Frequency [m]**	**1-sigma for DF Iono-Free E1/E5a [m]**
Signal in Space Ranging Error (SISE)	0.67	0.67
Residual ionospheric error	6 (5°) to 3 (90°)	0.08 (5°) to 0.03 (90°)
Residual Tropospheric error	1.35 (5°) to 0.14 (90°)	1.35 (5°) to 0.14 (90°)
Thermal noise, Interference, Multipath	0.69 (5°) to 0.63 (90°)	0.50 (5°) to 0.23 (90°)
Satellite BGD error	0.30	0.0
Code-Carrier ionospheric divergence error	0.30	0.0
Total (1-sigma, i.e. ~68th percentile)	6.24 (5°) to 3.17 (90°)	1.59 (5°) to 0.72 (90°)

Table 9-4: Typical UERE budget in Rural Pedestrian (RP) User Environment (Galileo)

Segment	Error Source	UERE Contribution (95%) [meters]	
		Zero AOD	Max. AOD in Normal Operation
Space	Clock Stability	0.0	7.5
	Group Delay Stability	1.6	1.6
	Differential Group Delay Stability	2.4	2.4
	Satellite Acceleration Uncertainty	0.0	2.0
	Other Space Segment Errors	1.0	1.0
Control	Clock/Ephemeris Estimation	2.0	2.0
	Clock/Ephemeris Prediction	0.0	4.4
	Clock/Ephemeris Curve Fit	0.1	0.1
	Iono Delay Model Terms	N/A	N/A
	Group Delay Time Correction	N/A	N/A
	Other Control Segment Errors	1.0	1.0
User	Ionospheric Delay Compensation	4.5	4.5
	Tropospheric Delay Compensation	3.9	3.9
	Receiver Noise and Resolution	2.9	2.9
	Multipath	2.4	2.4
	Other User Segment Errors	1.0	1.0
95% System UERE (SPS)		8.0	12.0

Table 9-5: Typical Dual Frequency UERE Budget (GPS)

Segment	Error Source	UERE Contribution (95%) [meters]	
		Zero AOD	Max. AOD in Normal Operation
Space	Clock Stability	0.0	7.5
	Group Delay Stability	1.6	1.6
	Differential Group Delay Stability	0.0	0.0
	Satellite Acceleration Uncertainty	0.0	2.0
	Other Space Segment Errors	1.0	1.0
Control	Clock/Ephemeris Estimation	2.0	2.0
	Clock/Ephemeris Prediction	0.0	4.4
	Clock/Ephemeris Curve Fit	0.6	0.6
	Iono Delay Model Terms	9.8 to 19.6	9.8 to 19.6
	Group Delay Time Correction	2.3	2.3
	Other Control Segment Errors	1.0	1.0
User	Ionospheric Delay Compensation	N/A	N/A
	Tropospheric Delay Compensation	3.9	3.9
	Receiver Noise and Resolution	2.9	2.9
	Multipath	2.4	2.4
	Other User Segment Errors	1.0	1.0
95% System UERE (SPS)		11.9 to 20.7	14.8 to 22.6

Table 9-6: Typical Single Frequency UERE Budget (GPS)

Regarding the augmentation system, the different SBAS performance standards ([3], [5], [6]) provide guarantees about accuracy improvements as listed in the tables below.

Error sources (1-sigma)	GPS standalone error size [m]	EGNOS-applied error size [m]
GPS satellite residual error for the worst user location	4.0	2.3
Vertical ionospheric delay residual error	2.0 to 5.0	0.5
Vertical tropospheric delay residual error	0.1	0.1
Receiver noise	0.5	0.5
Multipath (45° elevation)	0.2	0.2
GPS UERE at 5° elevation	7.4 to 15.6	4.2
GPS UERE at 90° elevation	4.5 to 6.4	2.4

Table 9-7: Comparison of typical EGNOS and GPS stand-alone SIS UERE

	Horizontal Accuracy 95% [m]	Vertical Accuracy 95% [m]
APV-I & LPV200 guaranteed performances[12]	3.0	4.0

Table 9-8: EGNOS SoL Service performance values

9.3.2.3 Accuracy according to observed data and performance reports

As previously mentioned, the values declared by the performance standards are quite conservative. In effect, it has been observed that the overall performances of the GNSS systems tend to improve over time, with a gradual refinement of the control segment algorithms and increased experience [11]. The use historical data enables estimates that are more closely aligned to reality to be made. Examples of the accuracy of the four major constellations are given in the following figures ([7]).

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[12] Values committed inside the APV-I & LPV-200 99% availability areas. Accuracy values at given locations are available at: https://egnos-user-support.essp-sas.eu/new_egnos_ops/

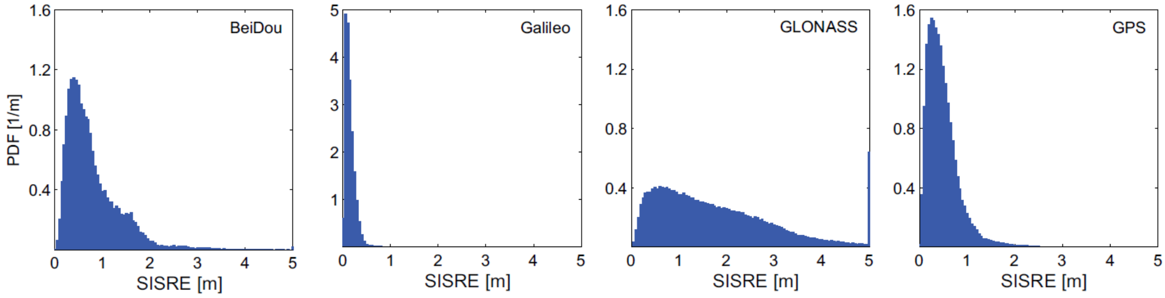


Figure 9-4: Probability density function (PDF) of globally averaged Signal In Space Range Error values for the four major navigation satellite systems in August 2017

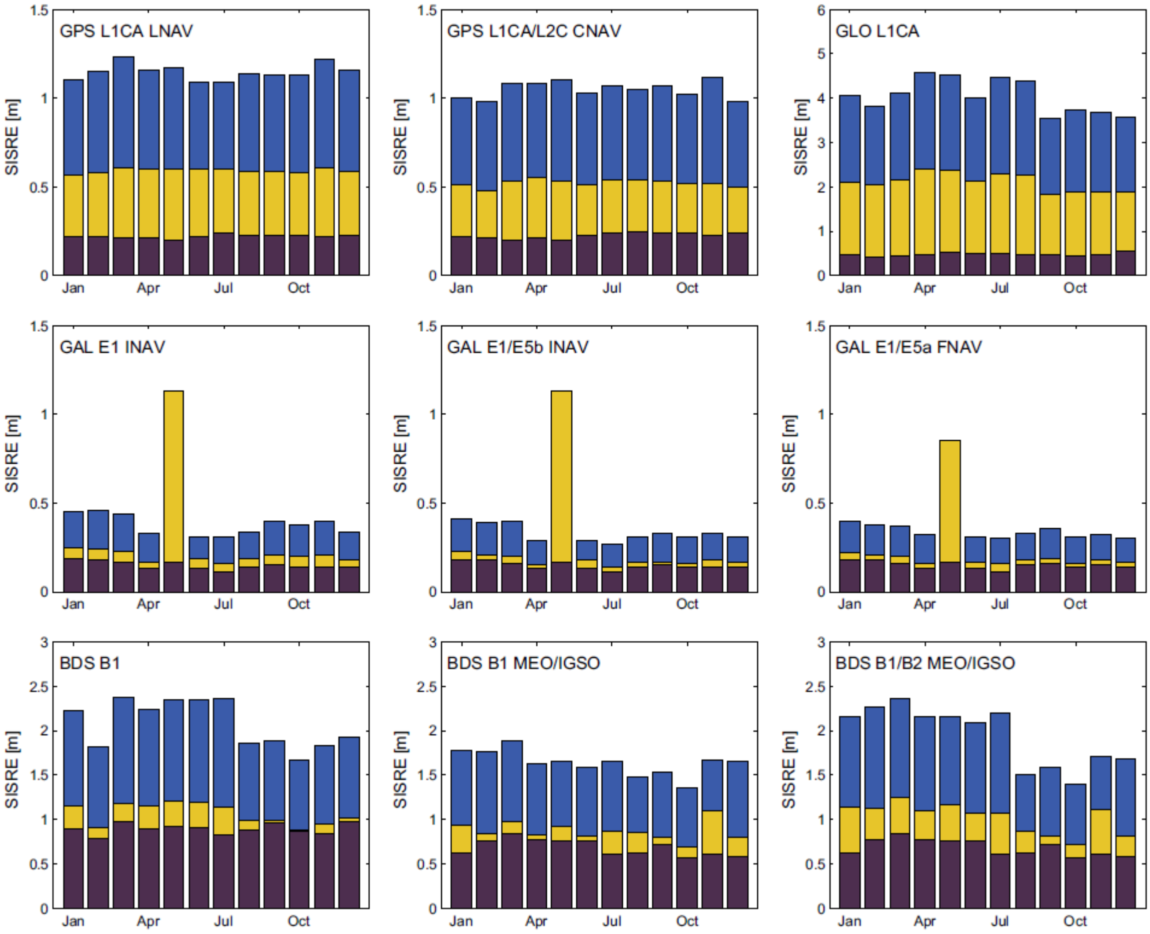


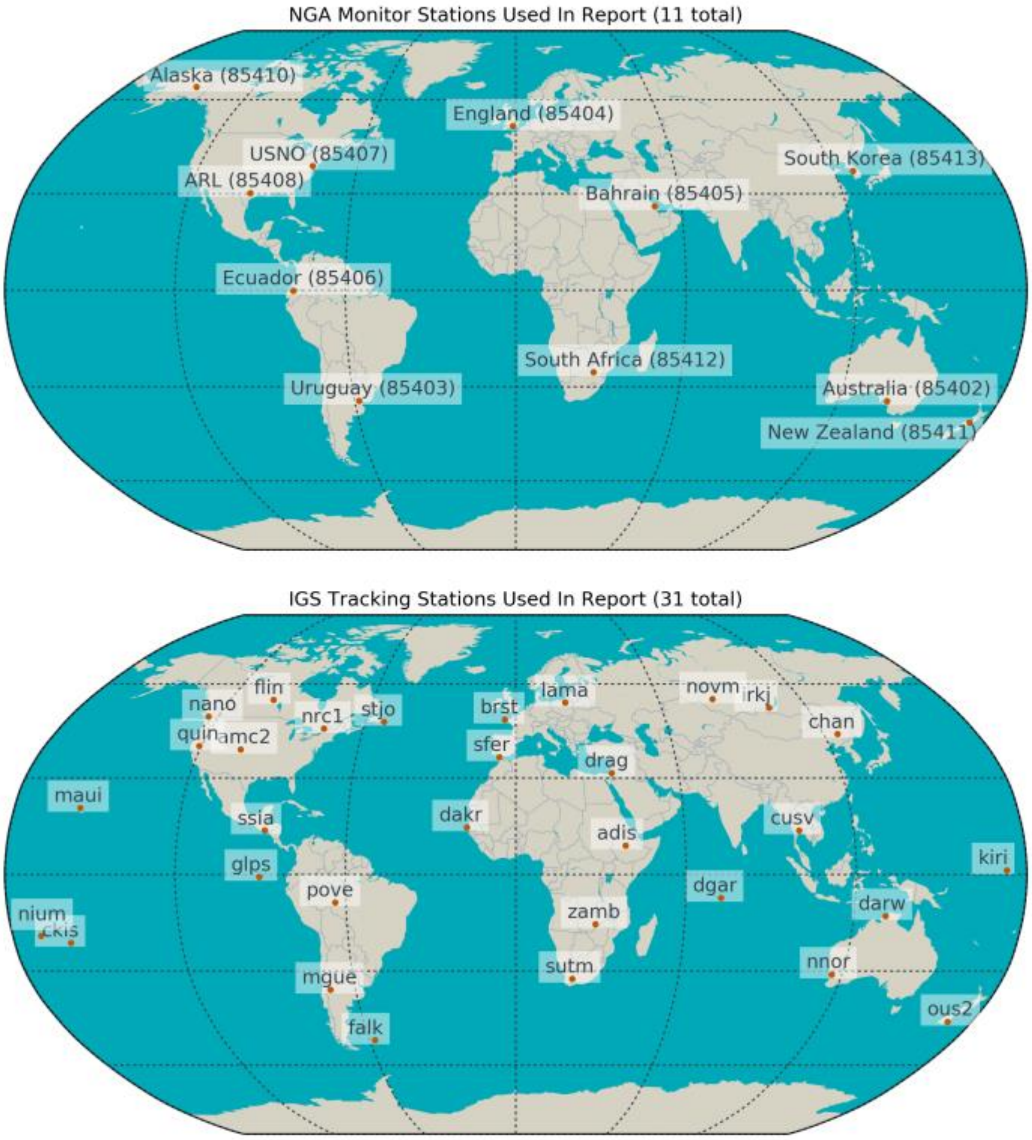
Figure 9-5: Monthly signal-in-space range errors of the four major navigation satellite systems for January to December 2017.

The top of the blue part in the charts in Figure 9-5 is the overall SISRE 95th percentile.

All the considerations made so far demonstrate that it is very difficult to allocate a precise a-priori error budget for the NSE, even with theoretical considerations and standard performance specifications. In the absence of an extensive test campaign, therefore, the accuracy will be assessed as follows, based on data published in the periodic reports of the GPS and Galileo operators ([9], [10]). It should be noted that the conditions in which the data are collected for the performance reports are quite different from the context of the ICARUS project: the receivers used are fixed, the antenna is calibrated and georeferenced, and there is generally an “open sky” environment. For this reason, some precautions should be applied to the accuracy data obtained for building the error budget allocation.

9.3.2.3.1 GPS

Data from the reference stations shown in Figure 9-6 were used in [8] for analysing the year 2019.


NGA Monitor Stations Used In Report (11 total)

IGS Tracking Stations Used In Report (31 total)

Figure 9-6: Maps of the Network of Stations Used in [8]

The following horizontal and vertical accuracy figures, referred to as Single Frequency (L1) Standard Positioning, are published in the yearly analysis, together with several different Key Performance Indicators:

Statistic	Horizontal		Vertical	
	IGS	NGA	IGS	NGA
Mean Error [m]	2.10	1.09	3.76	1.46
Median Error [m]	1.25	1.09	2.12	1.45

Maximum Error [m]	33.63	1.25	72.95	1.63
Error Standard Deviation [m]	3.60	0.03	6.71	0.05

Table 9-9: Daily Average Position Errors for 2019

Statistic	**Horizontal**		**Vertical**	
	IGS	**NGA**	**IGS**	**NGA**
Mean Error [m]	8.36	2.88	8.82	4.18
Median Error [m]	3.77	2.87	6.65	4.10
Maximum Error [m]	160.71	3.94	437.25	6.40
Error Standard Deviation [m]	17.00	0.16	28.39	0.43

Table 9-10: Daily Worst Site 95th Percentile Position Errors for 2019

Moreover, [9] gives the performances related to the second quarter of 2020. The data are obtained from a subset of the Wide Area Augmentation System (WAAS) and the International GNSS Service (IGS) reference station networks. The results are presented in graphical form, related to Single Frequency (L1) Standard Positioning, in the following figures.

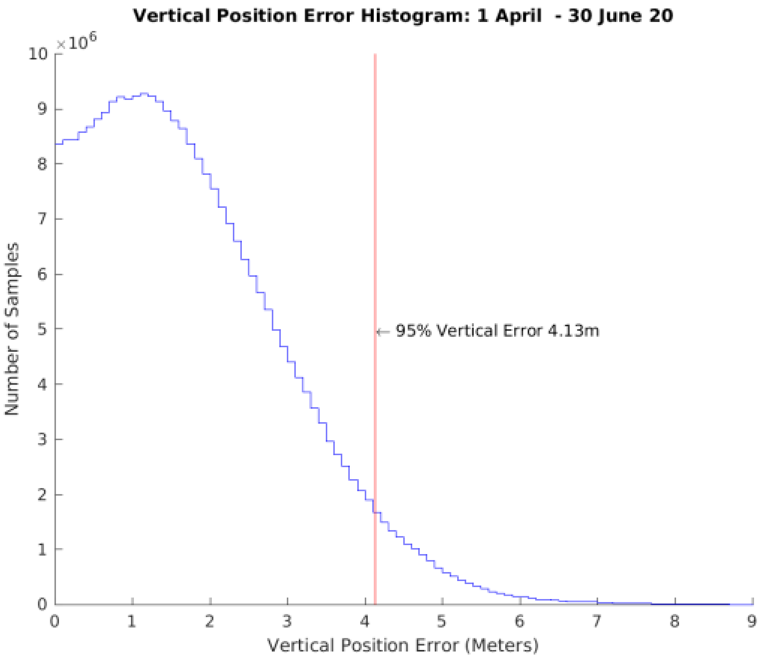


Figure 9-7: Global Vertical Error Histogram

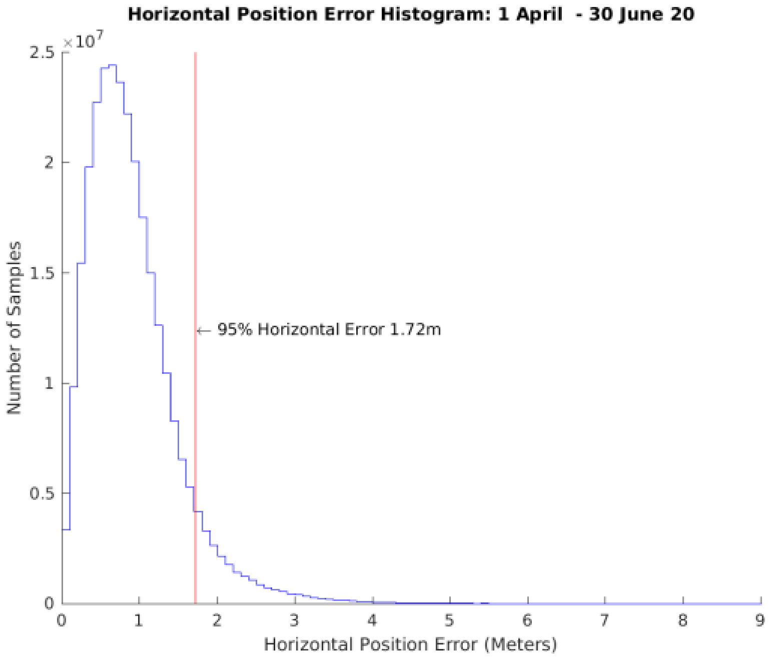
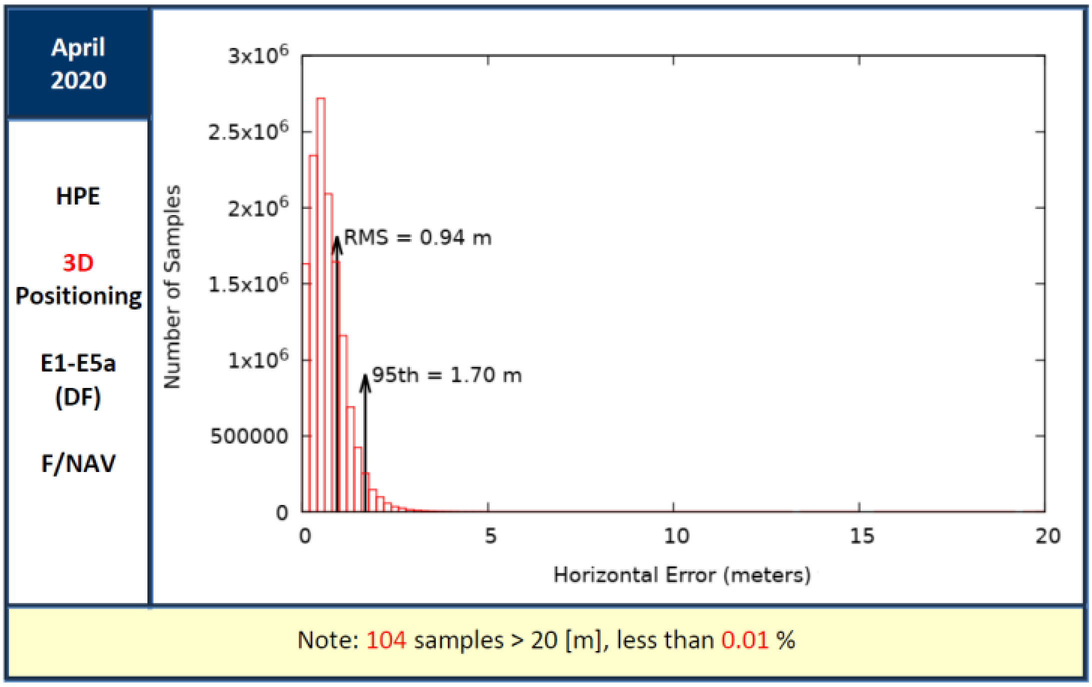


Figure 9-8: Global Horizontal Error Histogram

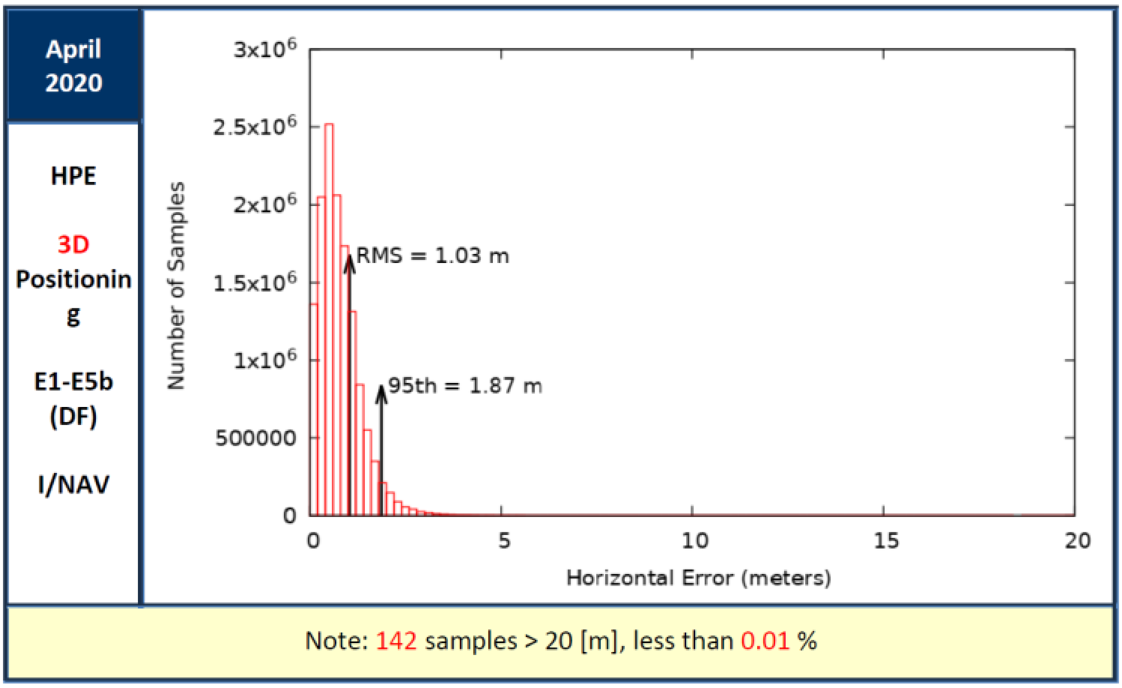
9.3.2.3.2 Galileo

The second quarter of 2020 is analysed in [10]. The results are heterogeneous with respect to the published GPS data: they are presented on a per-month basis (and not aggregated), and are related to a Dual Frequency Ionospheric-free Positioning (for E1/E5a and for E1/E5b signal combinations). The following figures show only one representative month (April).



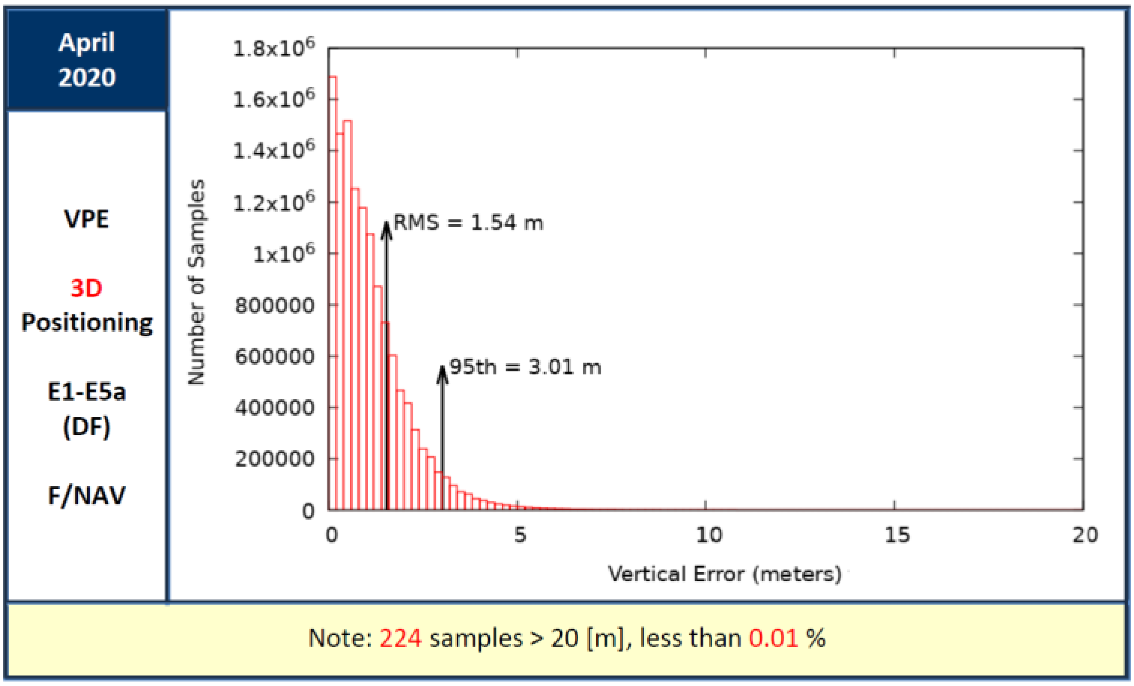
Note: 104 samples > 20 [m], less than 0.01 %

Figure 9-9: Horizontal Positioning Error for “Galileo-only” users in April 2020 using E1/E5a combination



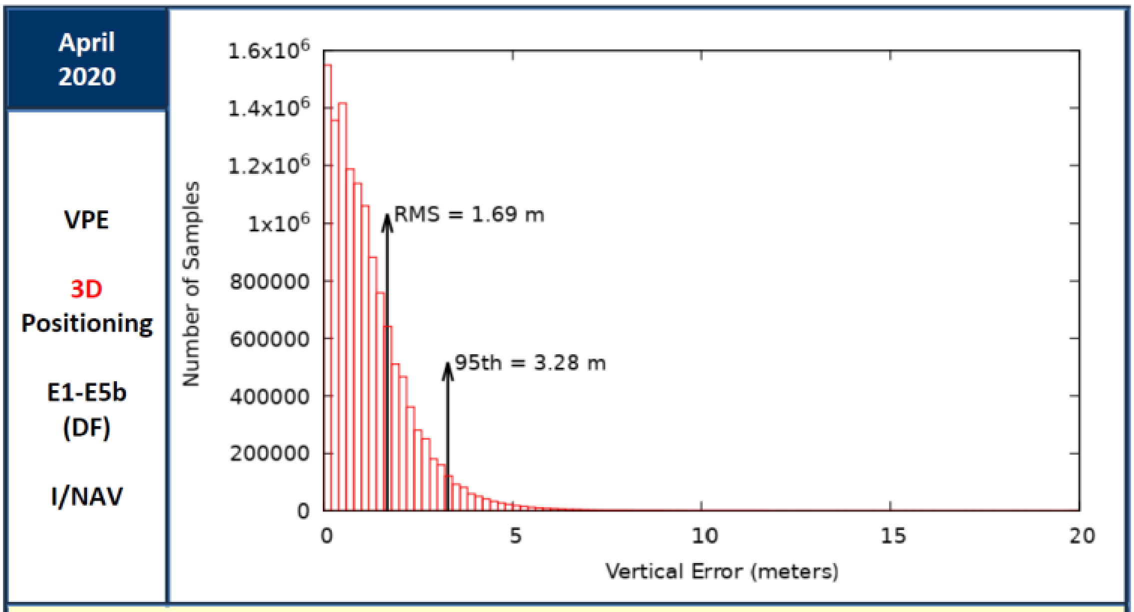
Note: 142 samples > 20 [m], less than 0.01 %

Figure 9-10: Horizontal Positioning Error for “Galileo-only” users in April 2020 using E1/E5b combination



Note: 224 samples > 20 [m], less than 0.01 %

Figure 9-11: Vertical Positioning Error for “Galileo-only” users in April 2020 using E1/E5a combination



Note: 392 samples > 20 [m], less than 0.01 %

Figure 9-12: Vertical Positioning Error for “Galileo-only” users in April 2020 using E1/E5b combination

9.3.2.3.3 EGNOS

The year 2019 is analysed in [13], using data from the reference stations shown in Figure 9-13.

The horizontal accuracy results for all the stations remained below 1.4 metres (95%), and the vertical accuracy below 2.4 metres (95%); Open Service EGNOS processing was applied for improving the accuracy of the GPS solution.

The performances for the individual stations are given in Table 9-11.

Station	HNSE 95% (metres)	VNSE 95% (metres)	Station	HNSE 95% (metres)	VNSE 95% (metres)
Aalborg	0.9	1.4	Lappeenranta	0.8	1.6
Agadir	0.8	1.4	La Palma	1.0	1.5
Alexandria	1.1	1.8	Lisbon	0.9	1.4
Athens	0.7	1.3	Madeira	0.8	1.2
Berlin	0.8	1.2	Malaga	0.8	1.0
Canary Islands	1.1	1.4	Palma de Mallorca	0.7	0.9
Cork	0.9	1.2	Reykjavik	0.9	1.8
Catania	0.7	1.2	Roma	0.7	1.1
Djerba	0.9	1.1	S. de Compostela	0.9	1.0
Egilsstadir	0.7	1.7	Sofia	1.2	1.9
Glasgow	1.0	1.4	Swanwick	1.1	1.6
Golbasi	0.9	1.5	Toulouse	0.8	1.1
Gävle	0.8	1.6	Trondheim	0.7	1.5
Haifa	1.3	2.2	Tromsoe	0.9	2.2
Jan Mayen	1.1	2.3	Warsaw	0.9	1.4
Kirkenes	0.8	1.8	Zürich	0.8	1.3

Table 9-11: EGNOS Open Service Accuracy (95%) for the considered year

Figure 9-13: stations used in EGNOS performance evaluation

9.3.2.4 Error Budget Allocation

As seen in the previous paragraph, the data are still heterogeneous; for this reason, we can try to infer a budget allocation for the NSE from the available data. Since the conditions of the flight of a drone cannot be considered to be as good as those of the reference network stations (good sky visibility, antenna dimensioned to minimise multipath, static, georeferenced, using an expensive receiver, etc.), conservative figures are given. It should be emphasised, however, that the availability of the signals, the DOP, and hence the accuracy, are better in the dual-constellation configuration than in the single-constellation.

Configuration	Processing	Horizontal Error Budget (95%) [m]	Vertical Error Budget (95%) [m]
GPS + EGNOS/EDAS	Single frequency (L1) Accuracy augmentation from EGNOS/EDAS LPV-200 Integrity provision through EGNOS/EDAS	2.0	3.0
GPS + Galileo + ARAIM	Ionosphere-free dual frequency (E1/E5a, L1/L5) LPV-200 Integrity provision through ARAIM application	2.5	3.5

Table 9-12: NSE Budget Allocation

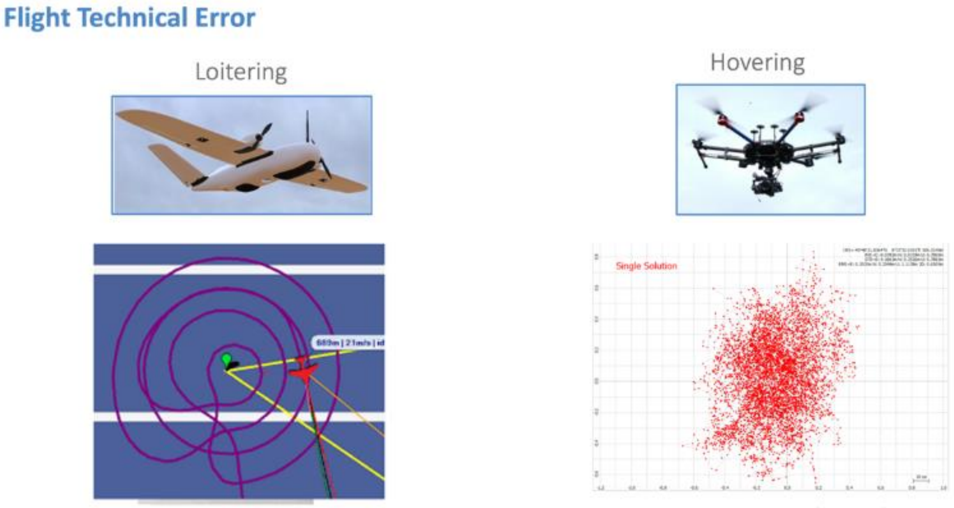
Once again, it is important to note that the accuracy performance of a receiver can only be precisely determined after an extensive and in-depth measurement campaign, since it is strictly related to the receiver implementation. Moreover, since the accuracy figures are statistic quantities and not guarantees, should not be used to define any kind of horizontal/vertical alert service definition; since human safety requirements are involved, the integrity parameters (i.e. protection levels) must be used.

9.3.3 Flight technical error

The Flight Technical Error (FTE) is additional error in, or deviation from, the reference trajectory (additional to the navigation system error), due to the process of physically flying the drone under operational circumstances. Due to external circumstances (such as wind and turbulence) and the aircraft's performance, the pilot (or the autopilot) cannot keep the aircraft exactly on the reference trajectory. This aspect will become increasingly important as reference trajectories get more complicated. Flight paths that now basically consist of straight-line segments connected by fixed radius turns will be replaced increasingly sophisticated curved segments, especially for rotorcraft drones flying in VLL in close to ground obstacles.

Flight Technical Error is expected to be the main contributor for determining the Total System Error. According to ICAO, the FTE is defined as the capability of the pilot/crew to keep the planned trajectory. The following assumption is made to enable the same concept to be transposed to the unmanned world:

For this reason, the FTE can be interpreted as the capability of the specific drone/autopilot to keep its trajectory, despite external disturbance such as wind or wind gusts. From a "Theory of Systems" point of view, the FTE provides a measurement of the specific drone/autopilot *transfer function in* response to external stimulus.



50 m radius (lateral), vertical to be assessed

Horizontal: < 1 m (2 sigma)
Vertical: 1,6 m (2 sigma)

Figure 9-14: Fixed wing drones and copters has in general different FTEs

A feasible strategy for assessing the FTE is through numeric simulations, exploiting flight simulation engines provided by the drone manufacturers (both proprietary and open source) that can be typically configured in "Hardware-in-the-Loop" or "Software-in-the Loop". Such platforms have been integrated or reused from other projects to assess both vertical and horizontal FTE.

Since FTE is the main contribution to the TSE, we want to analyse its sensitivity by varying:

- The drone's speed (GS)
- Wind speed (i.e. cross wind-gusts)

In particular, having fixed a time interval Δt when the wind gust hits the drone, its lateral shift (FTE) depends on the wind speed w and on the speed of the drone v:

$$\varepsilon_{FTE} = f(v, w)$$

The function f depends essentially on the drone specifications, its ground speed, and on the wind gust's duration.

9.3.3.1 FTE Simulator for multicopters

There are several autopilot systems for drones on the market. They can be closed box systems developed by the drone manufacturer, but there are also a few open-source systems available. As these systems differ, it is hard to declare an expected value for the FTE in general. The FTE function has been investigated using the simulator system shown in Figure 9-15, using the following components:

- a DJI S900 drone;
- a Windows PC, running the DJI Assistant 2 program, version 1.2.4, connected through a USB cable to a DJI N3 Flight Controller mounted on-board the drone;
- a Raspberry PI 3 board connected to the DJI N3 through a Controller Area Network (CAN) cable;

- a DJI Lightbridge Ground Control Controller with a tablet running the DJI GO application.

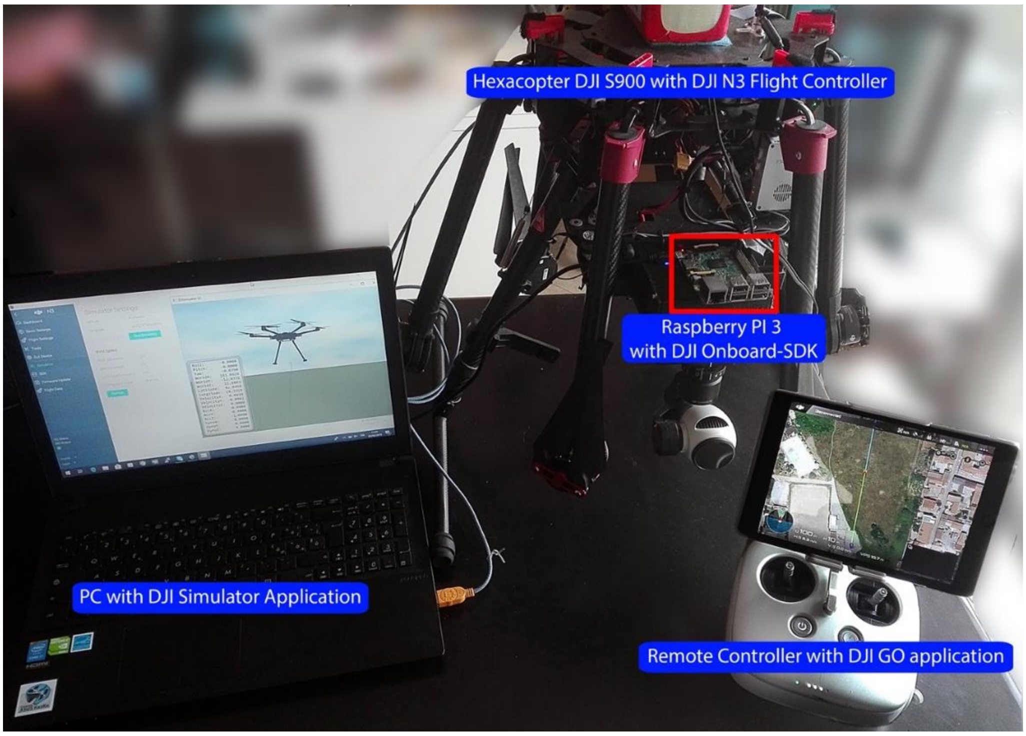
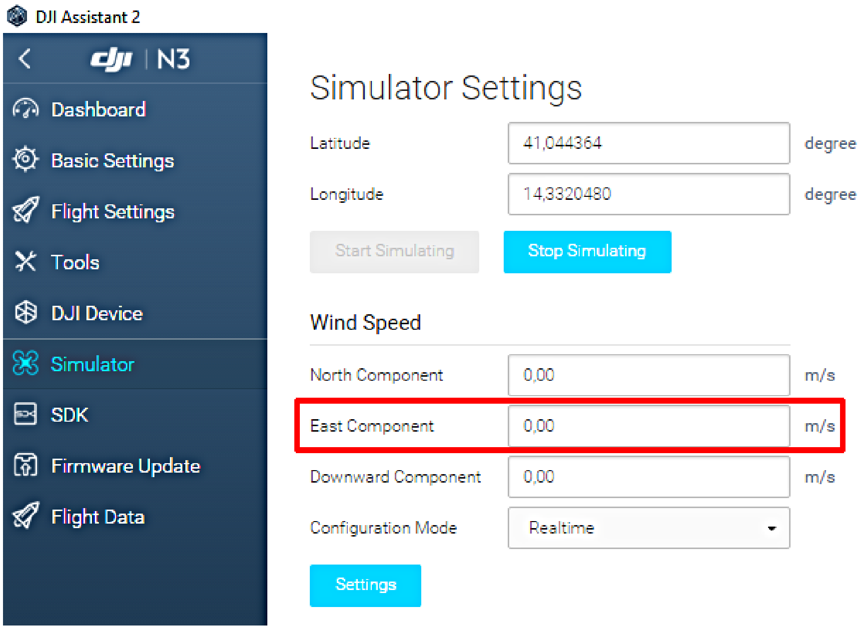


Figure 9-15: Simulation system setup used for TSE sensitivity analysis

A simple flight scenario (straight trajectory) was developed using the DJI On-board SDK on a custom C++ application running on the Raspberry PI 3 board; the flight path was created using two waypoints with known positions in Earth-Centred, Earth Fixed (ECEF) coordinates, flying north to south.

Several automatic flights were performed using different wind speeds (5, 8, 10 and 15 m/s) and various drone speeds (3, 5, 7 and 10 m/s). During the tests, different wind gusts were simulated by entering the wind speed on the simulator program on the east-west component field (cross wind), as shown in Figure 9-17, for approximately 5 seconds, making sure that the drone had reached the expected speed. During each automatic mission, the trajectory of the drone was logged and the positions of the flown path were compared with the planned trajectory.



Simulator Settings

Latitude 41,044364 degree

Longitude 14,3320480 degree

Wind Speed

North Component 0,00 m/s

East Component 0,00 m/s

Downward Component 0,00 m/s

Configuration Mode Realtime

Figure 9-16: DJI Assistant 2 simulation program with wind speed settings

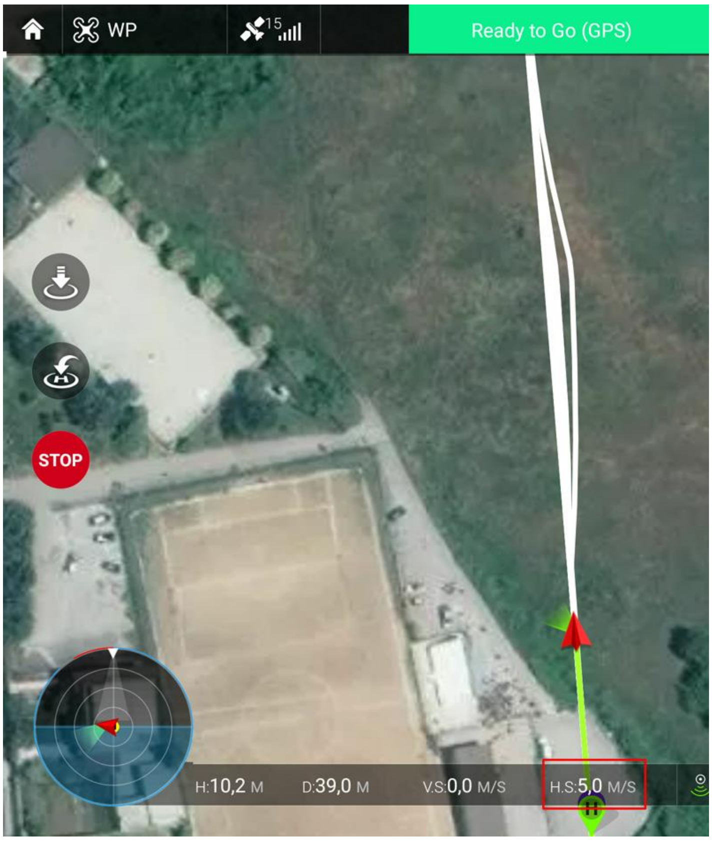


Figure 9-17: Effect of wind tested by simulator and the popular pilots' applications DJI GO

The figures above show the application used by the pilot to monitor a flight route and the simulated wind speed. The different paths traced during various flights can be seen in white; in this flight the drone speed is 5 m/s as highlighted in the red box.

9.3.3.2 Test results

For every simulation, the maximum lateral shift (the distance between the drone's centre of gravity (CG) and the line that joins the start and the end points of the defined path) was calculated. The data were processed using MATLAB software with the following results:

Horizontal FTE [m] (5 second wind-gust duration)				
	w = 5 m/s	w = 8 m/s	w = 10 m/s	w = 15 m/s
v = 3 m/s	0.30	0.72	1.16	3.10
v = 5 m/s	0.38	0.83	1.31	3.33
v = 7 m/s	0.47	0.97	1.48	3.47
v = 10 m/s	0.61	1.21	1.83	4.79

Table 9-13: FTE (maximum value) with various wind velocities and drone speeds

The $f(v,w)$ function was estimated by fitting a two-dimensional third-order polynomial to the data in Table 9-13:

$$f(v,w) = p_{00} + p_{10}\,w + p_{01}\,v + p_{20}\,w^2 + p_{11}\,v\,w + p_{02}\,v^2 + p_{30}\,w^3 + p_{21}w^2v + p_{12}w\,v^2 + p_{03}\,v^3$$

The estimated coefficients of the function are given in Table 9-14.

Coefficients of the sensitivity function *f(v,w)*									
p_{00}	p_{10}	p_{01}	p_{20}	p_{11}	p_{02}	p_{30}	p_{21}	p_{12}	p_{03}
-2.083	0.3169	0.7911	-0.01204	-0.06945	-0.08832	0.0008573	0.001706	0.004144	0.003178

Table 9-14: Coefficients of the sensitivity function $f(v,w)$

The RMS error between the values reported and those calculated with the estimated sensitivity function $f(v,w)$ is 0.05 m. Figure 9-18 gives a plot of the function $f(v,w)$ for wind speeds between 5 and 15 m/s and for drone speeds between 3 and 10 m/s. The plot clearly shows how the sensitivity of the FTE to the wind speed increases with increasing drone speed.

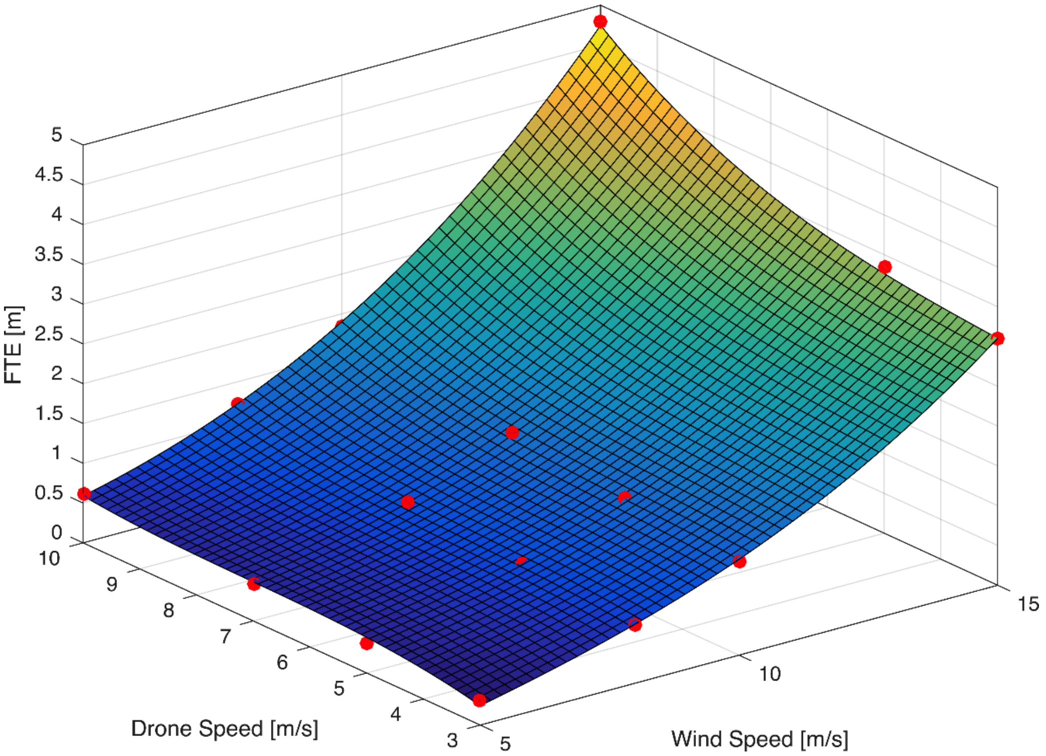


Figure 9-18: Sensitivity function for FTE of a 20kg Hexcopter

The sensitivity function $f(v, w)$ binds the maximum value of FTE to the wind speed (w) and to the drone speed (v). The sensitivity function in Figure 9-18 is for wind gusts of 5-second duration. The red dots represent the calculated values from the simulated data reported in Table 9-13.

The following figures show some tests of the hexcopter flying at a ground speed of 5 m/s with different wind gusts profiles.

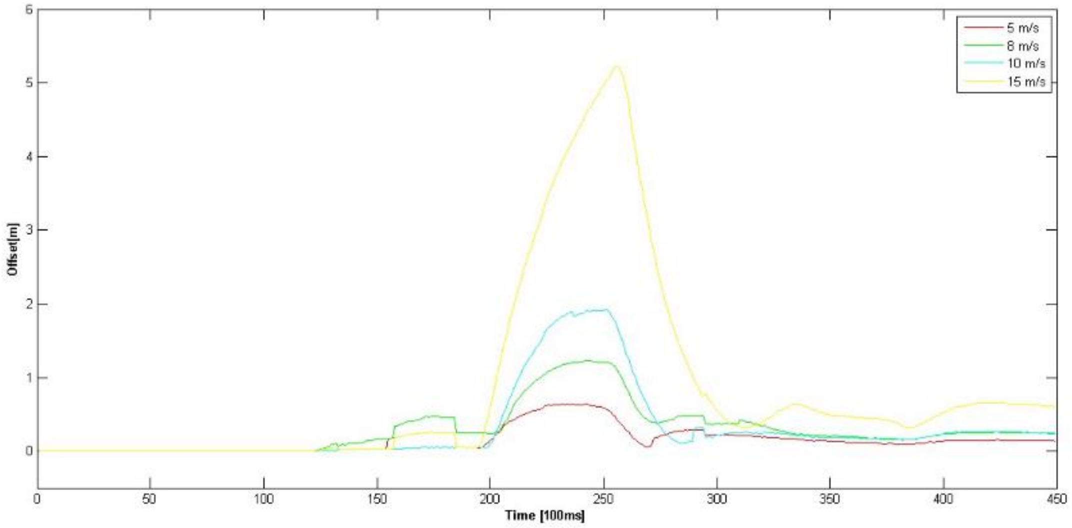


Figure 9-19: Flight Technical Error (FTE, “offset” in the plot) at different wind speed

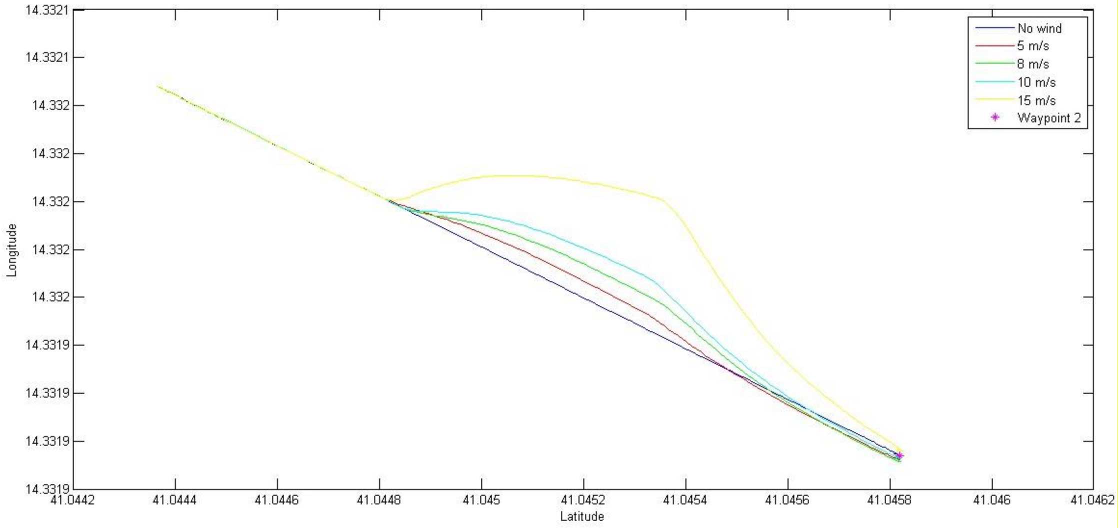


Figure 9-20: Impact on drone path expressed in Geographical Coordinates with respect to planned route

Figure 9-21: Impact on drone path on pilot's HMI

Following the same approach, the test was repeated for the vertical axis where updraft was applied with different intensities. Table 9-15 gives the discrepancies of the trajectory and the registered vertical positions from the vertical profile.

It must be noted that, since the simulator in unaffected by NSE, all the contribution can be put down to FTE.

Vertical FTE [m] (5 second wind-gust duration)				
	w = 5 m/s (updraft)	w = 8 m/s (updraft)	w = 10 m/s (updraft)	w = 15 m/s (updraft)
v = 3 m/s (GS)	0.019	0.043	0.065	0.140
v = 5 m/s (GS)	0.022	0.047	0.069	0.142
v = 7 m/s (GS)	0.027	0.053	0.074	0.153
v = 10 m/s (GS)	0.034	0.061	0.085	0.166

Table 9-15: FTE (vertical) with various wind velocities (updraft) and drone ground speeds.

The most interesting result of these tests is the great resilience of multirotors in keeping their height, even in presence of strong updrafts or downdrafts. This is logically due to their ability to generate vertical draft in combination with strong control algorithms used by the autopilot.

Some results of the vertical behaviour of the multirotor are given in the following figures.

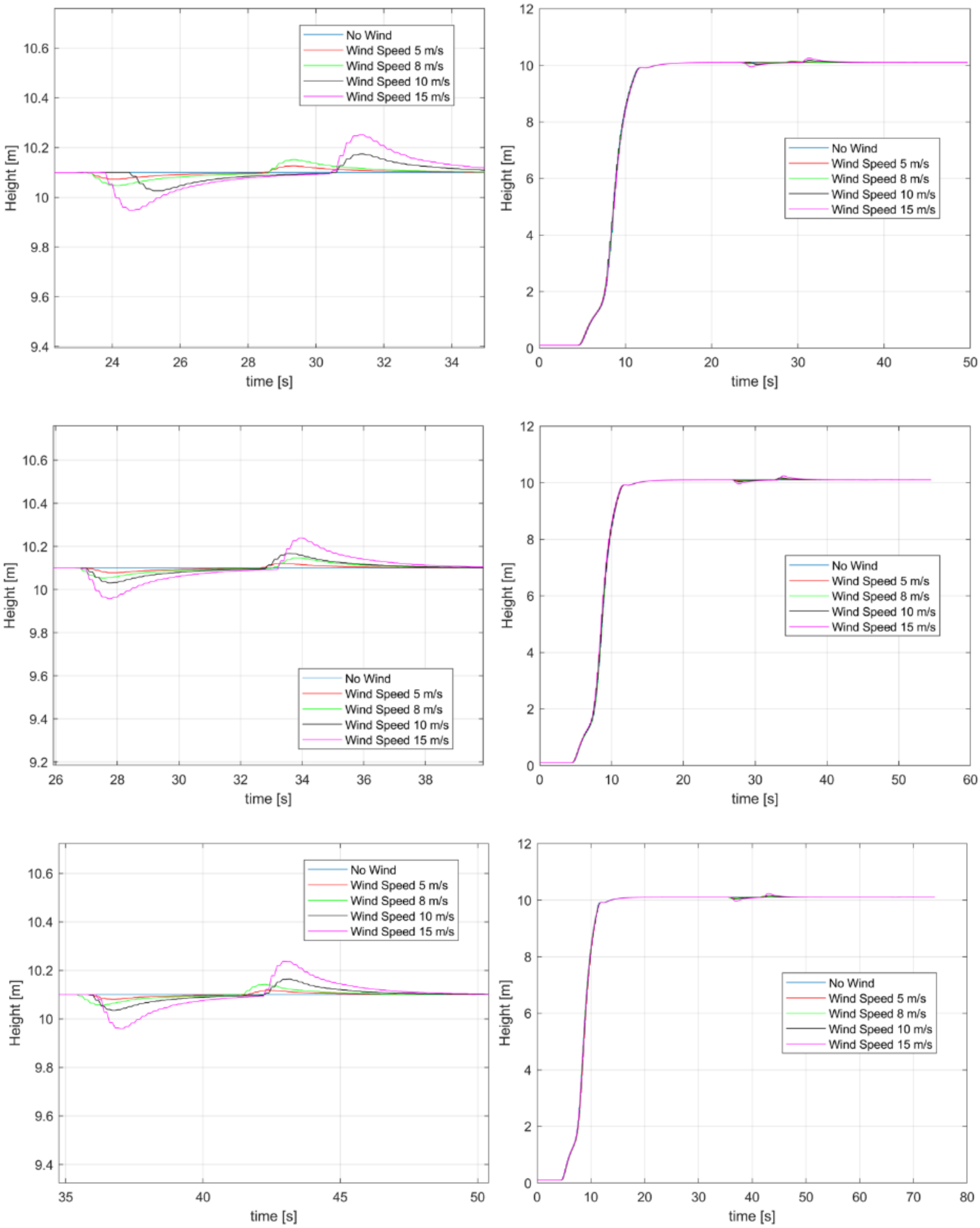


Figure 9-22: Error in height with different updraft wind intensity

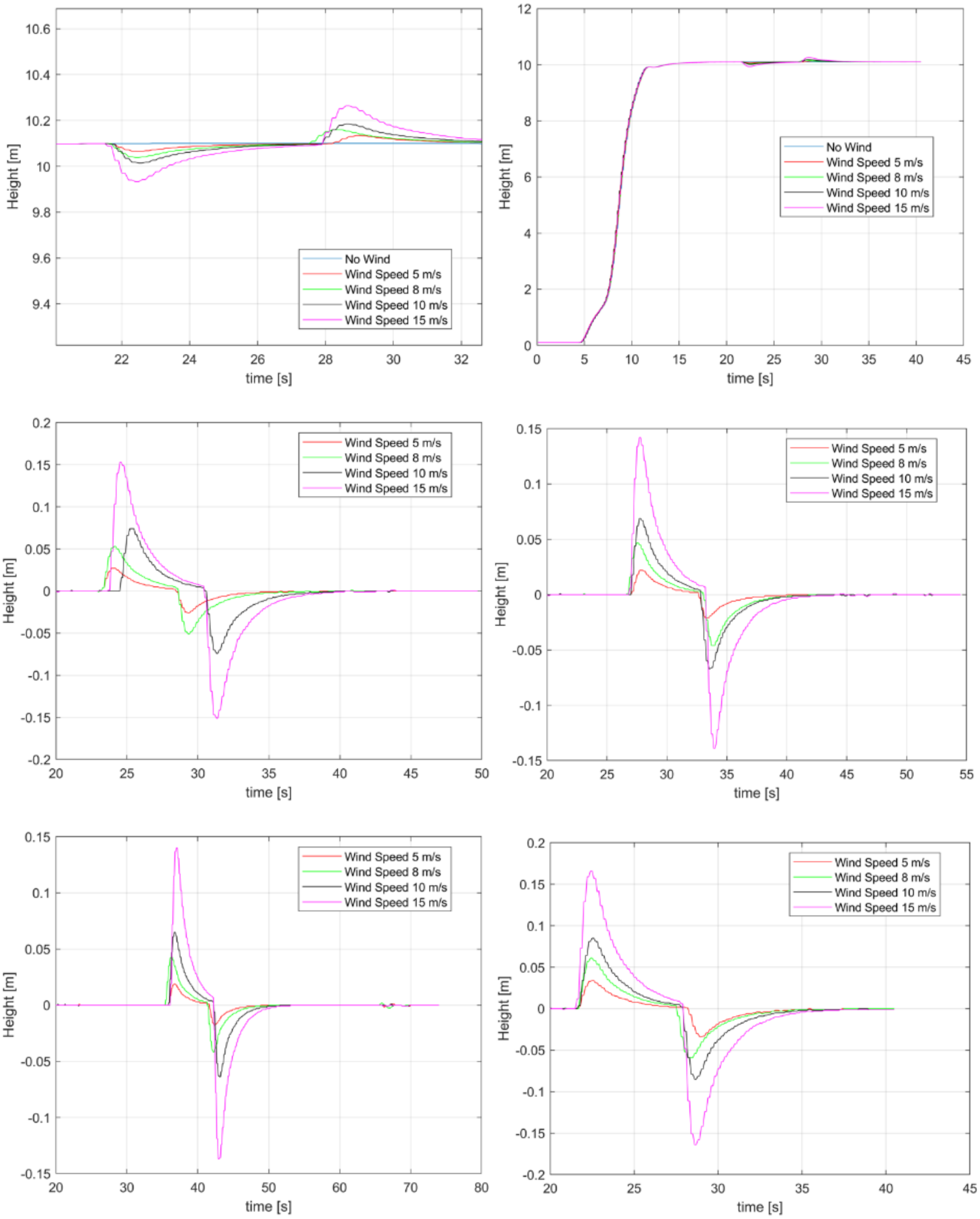
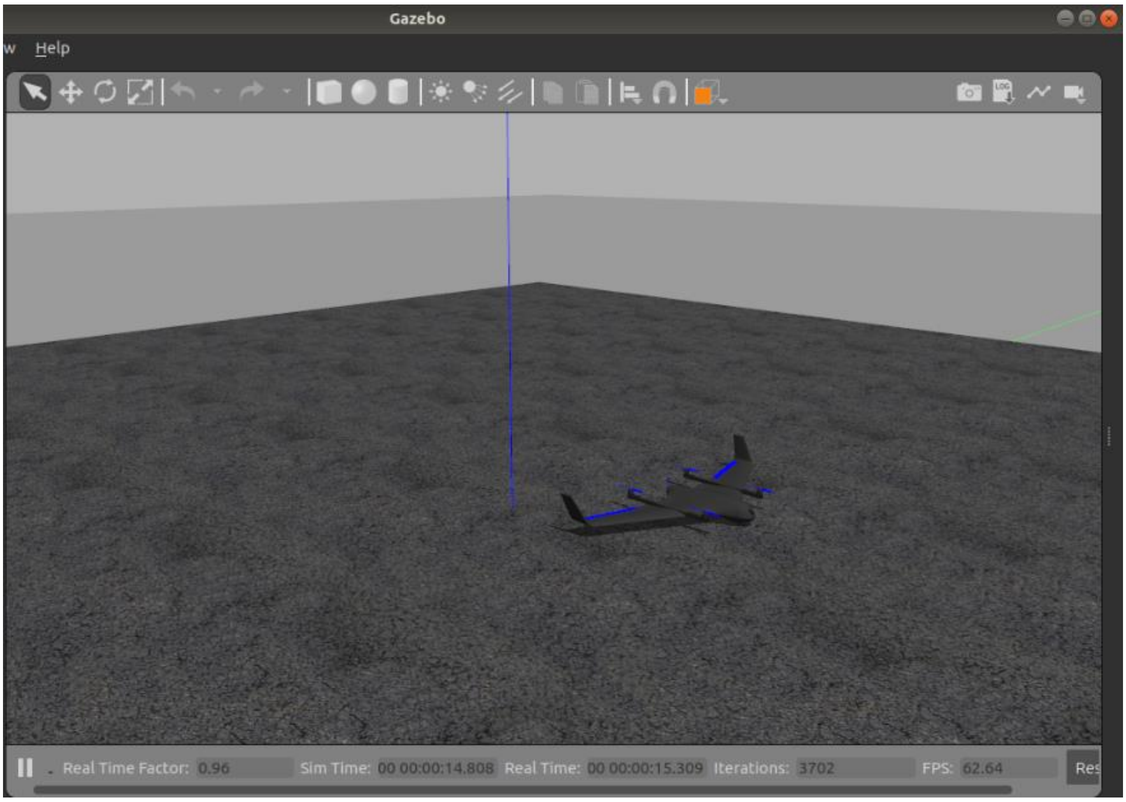


Figure 9-23: Details of the error in height with different updraft wind intensity

9.3.3.3 FTE Simulator for Fixed-wing drones

Two open-source flight simulation engines were used to assess FTE for fixed wing drones: ArduPilot and PX4, configured in Software-in-the-Loop (SITL) mode in conjunction with Gazebo, a well-known robotics simulator used for displaying the vehicle in 3D and for the dynamic modelling of wind (Figure 9-24).



Real Time Factor: 0.96 Sim Time: 00 00:00:14.808 Real Time: 00 00:00:15.309 Iterations: 3702 FPS: 62.64

Figure 9-24: Gazebo simulator with the VTOL vehicle ready to take-off.

The flight scenario chosen for the simulation was the delivery of spare part to an offshore oil & gas platform in the Adriatic Sea as previously described in use case I. The offshore platform selected for the simulation is the ENI gas platform named “PORTO CORSINI M W C” located at about 7 km from the coast, near Marina di Ravenna as shown in Figure 9-25.

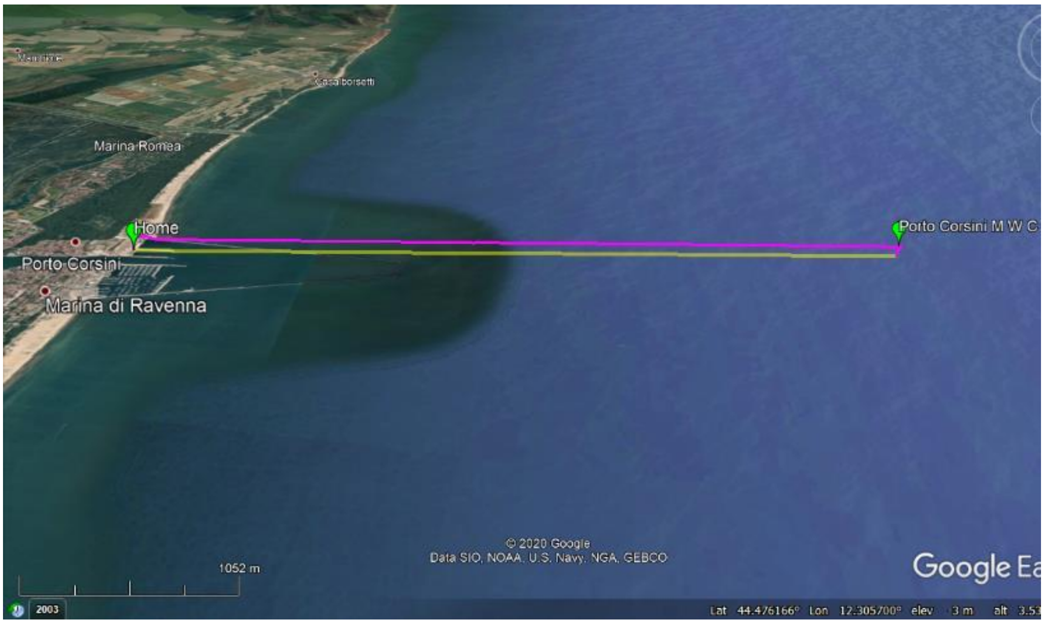


Figure 9-25: Planned flight path

Several automatic flights were performed using different wind speeds (5, 8, 10 and 15 m/s) and various VTOL fixed wing drone speeds (20, 25 and 30 m/s). During the tests, some wind gusts were simulated using a custom Python application running on the Linux simulation PC; the flight path was created using two waypoints with known positions (Home Location: 44.4950449, 12.2847878; Offshore Location: 44.508981, 12.37289) at a cruise altitude of 110 m.

During each automatic mission, the trajectory of the VTOL fixed-wing drone was logged and the positions along the flown path were compared with the planned trajectory.

9.3.3.3.1 Test Results

For every simulation, the maximum lateral shift (distance between the drone's centre of gravity (CG) and the line that joins the start and the end points of the defined path) was calculated. The data were processed using MATLAB software with the following results:

FTE [m] Horizontal				
	w = 5 m/s	w = 8 m/s	w = 10 m/s	w = 15 m/s
v = 20 m/s	2.43	3.21	4.78	8.46
v = 25 m/s	1.88	3.27	4.24	7.05
v = 30 m/s	1.95	3.35	3.77	6.04

Table 9-16: (maximum value) with various wind velocities and drone speeds (wind gust duration 5 seconds)

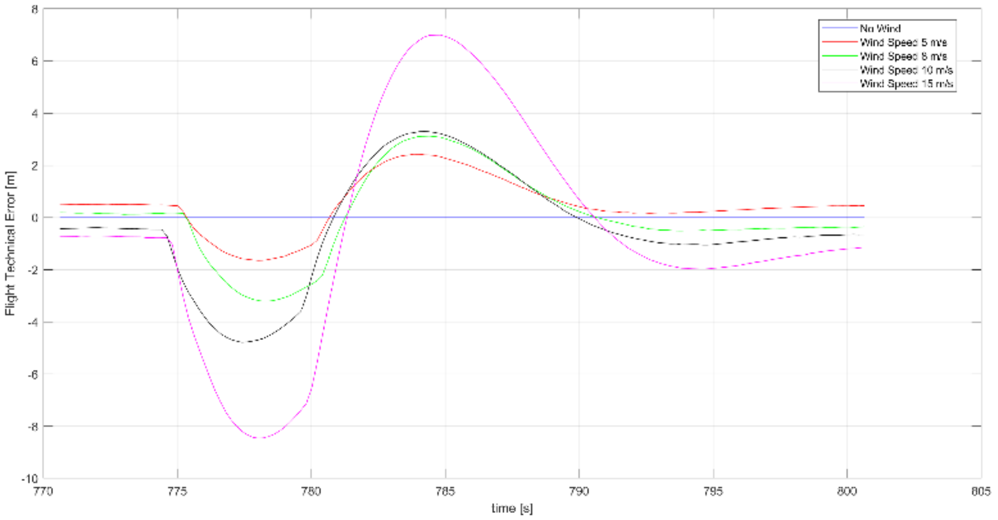


Figure 9-26: Horizontal FTE Drone speed 20m/s

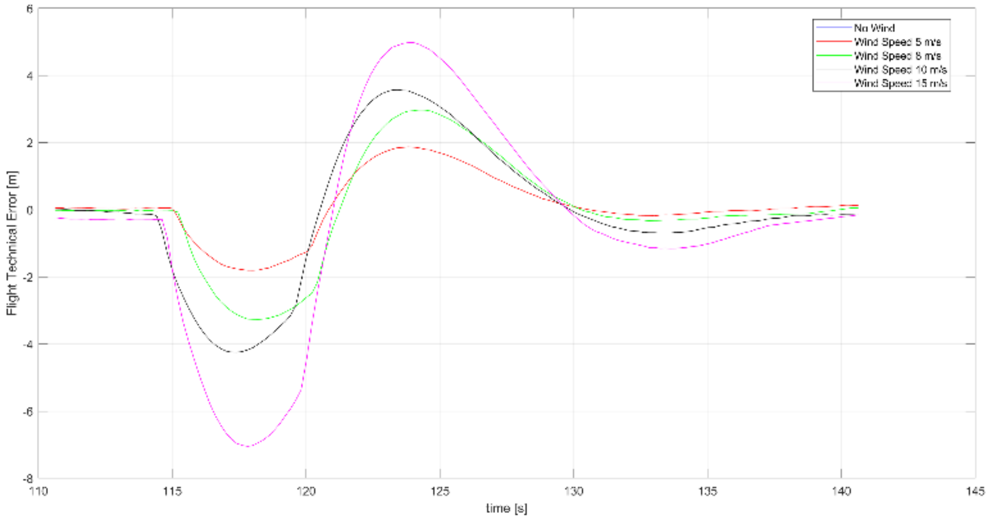


Figure 9-27: Horizontal FTE Drone speed 25m/s

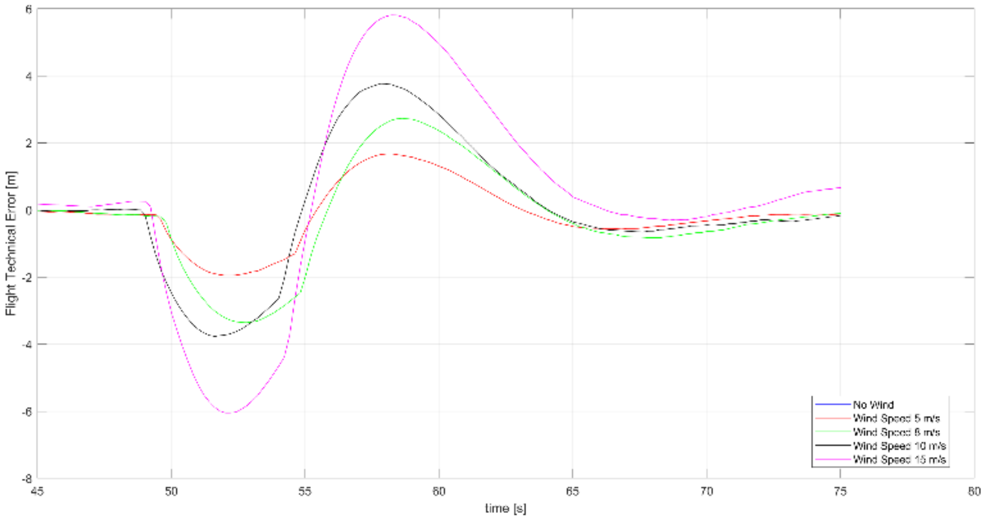


Figure 9-28: Horizontal FTE Drone speed 30m/s

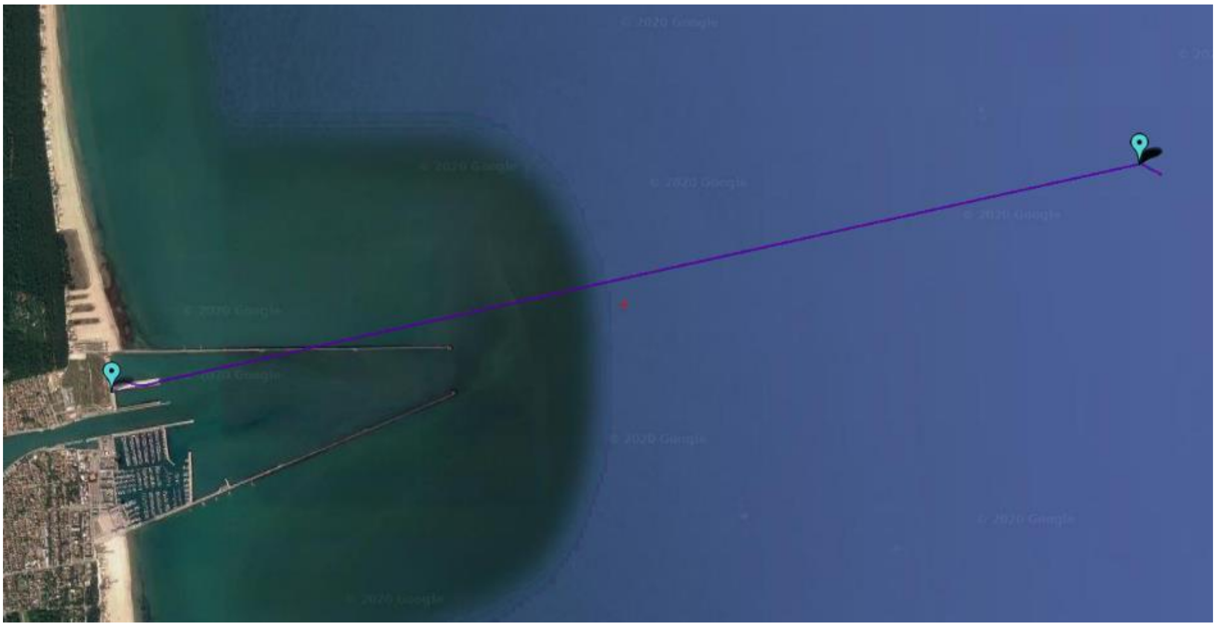


Figure 9-29: Flight Mission to the offshore with 20m/s drone speed and 12 m/s wind speed

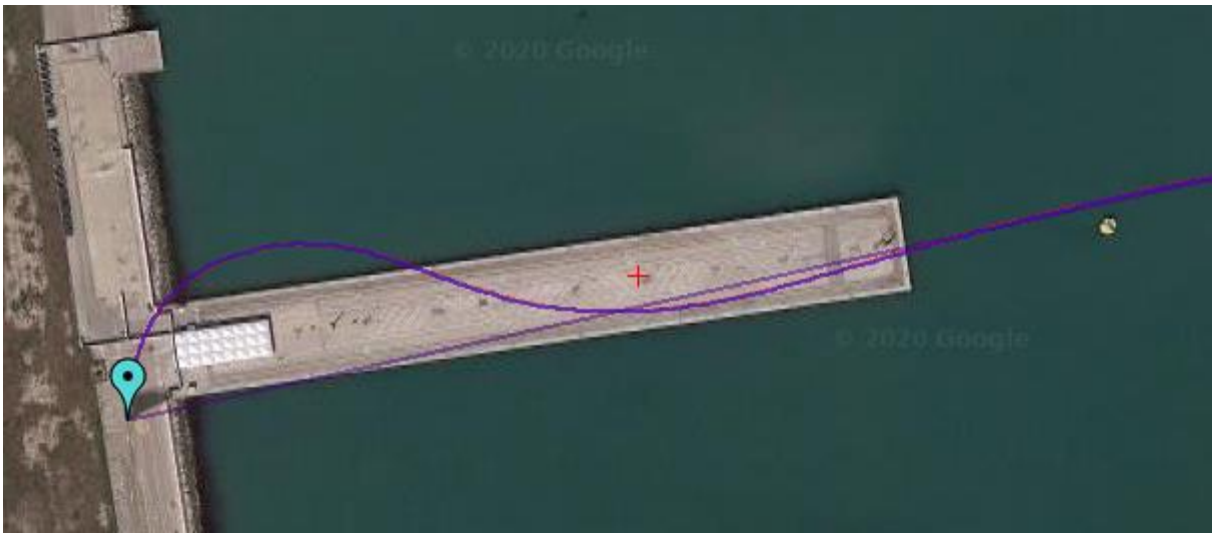


Figure 9-30: Transition between multirotor and fixed wing mode

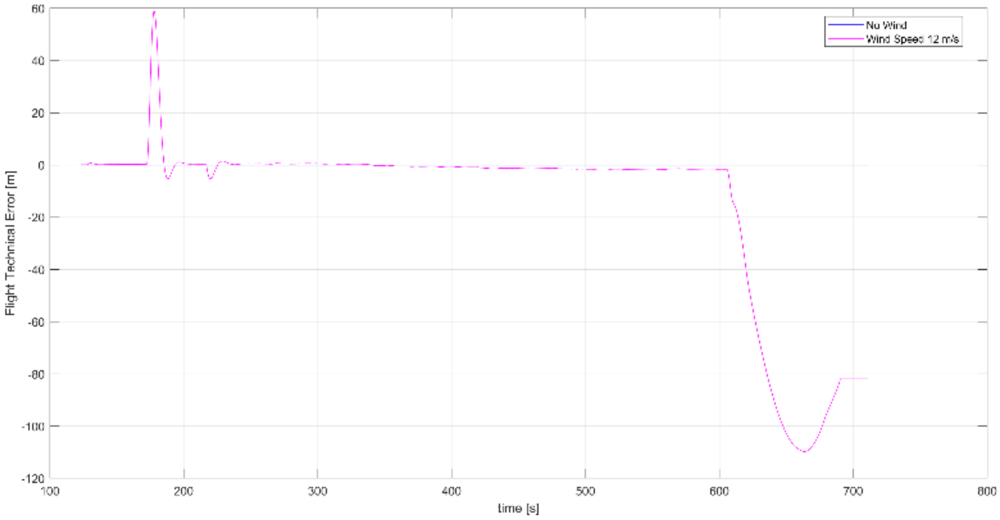


Figure 9-31: FTE during the whole mission to the offshore with a wind speed of 12 m/s

It is to be noted that the take-off and landing phases are affected by higher errors, considering the transition phase from quadcopter to fixed-wing and vice-versa.

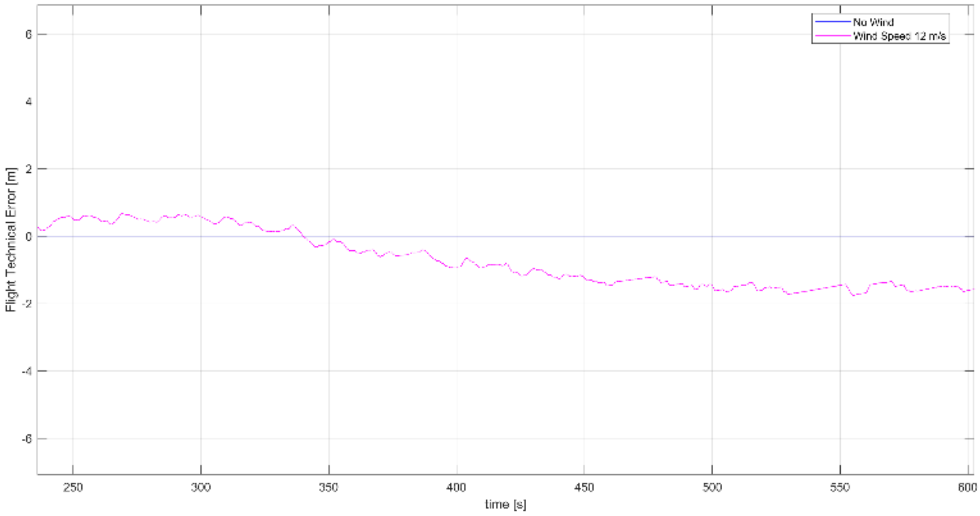


Figure 9-32: Zoom of the horizontal FTE when the drone has reached the expected speed of 20 m/s

Following the same approach, the test was repeated for the vertical axis where different intensity updrafts were applied.

FTE [m] Vertical				
	w = 5 m/s (updraft)	w = 8 m/s (updraft)	w = 10 m/s (updraft)	w = 15 m/s (updraft)
v = 20 m/s (GS)	0.791	0.757	1.169	1.445

Table 9-17: FTE (vertical) with various wind velocities (updraft) and drone's Ground speeds. The wind gust duration is 5 seconds

Some results of the vertical behaviour of the fixed wing are given in the following figures.

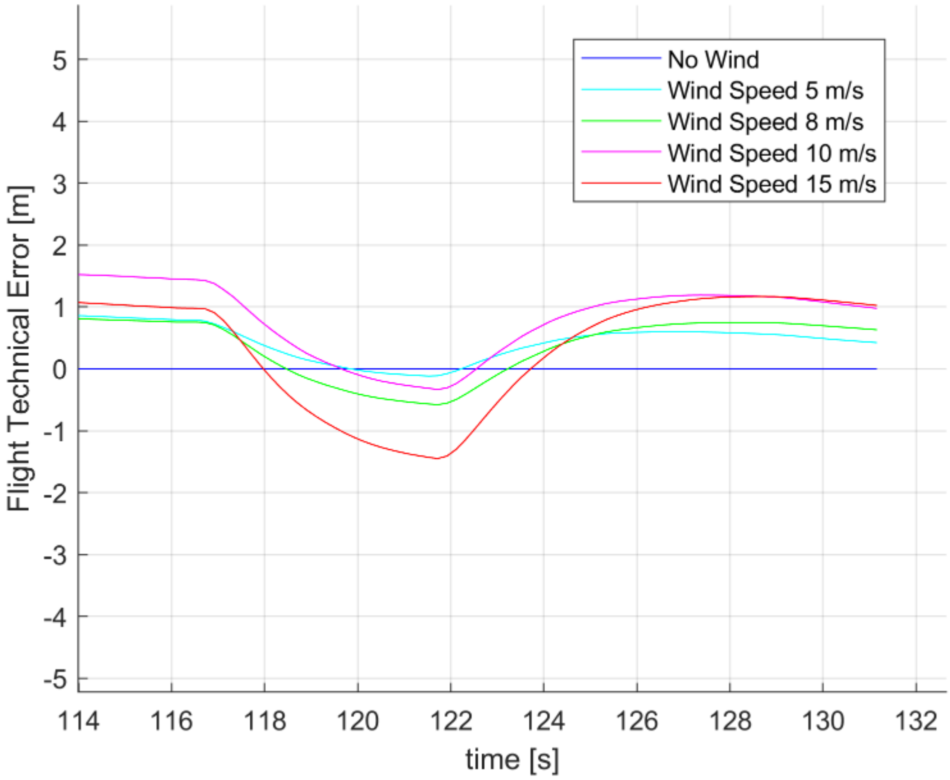


Figure 9-33: Vertical FTE - drone speed 20m/s

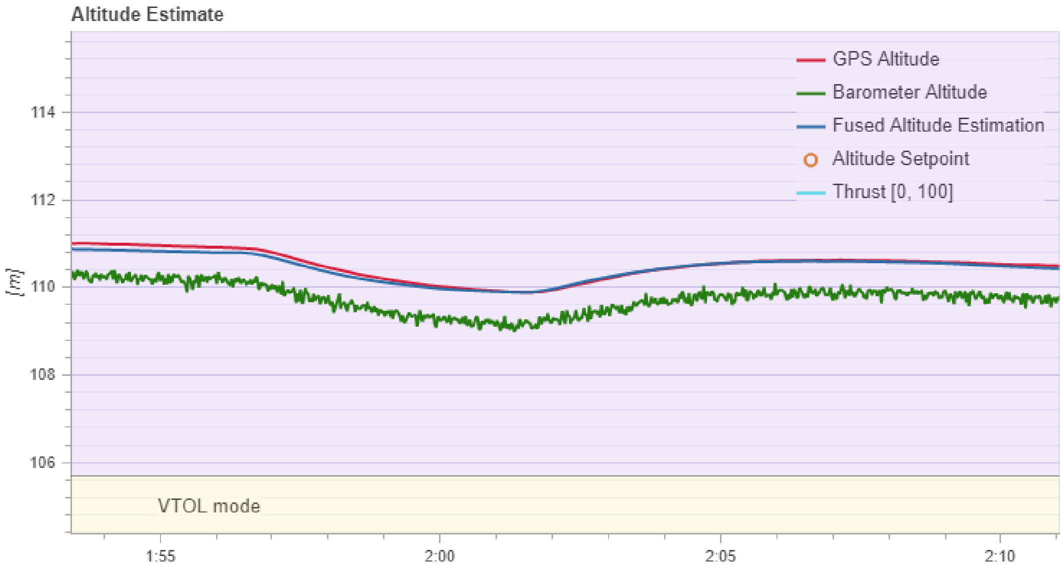


Figure 9-34: Drone speed 20m/s - Wind speed 5m/s (Autopilot logs during simulation)

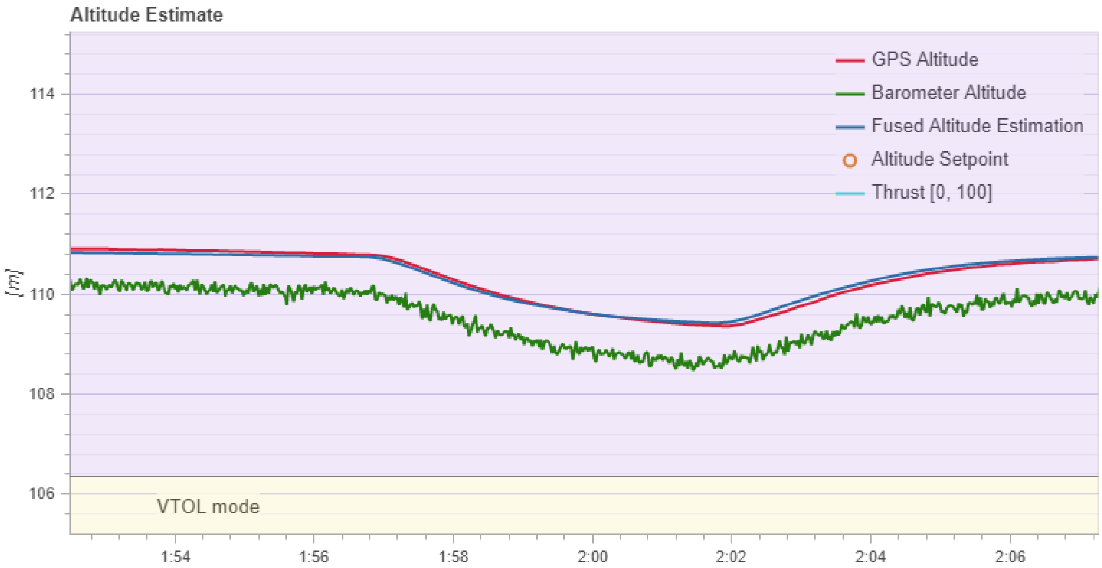


Figure 9-35: Drone speed 20m/s - Wind speed 8m/s (Autopilot logs during simulation)

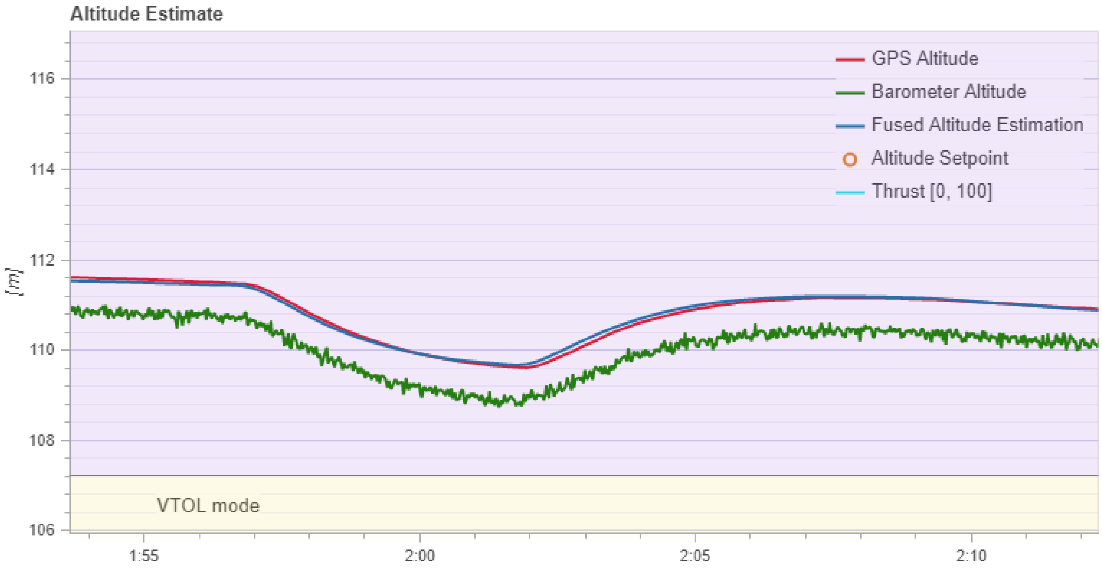


Figure 9-36: Drone speed 20m/s - Wind speed 10m/s (Autopilot logs during simulation)

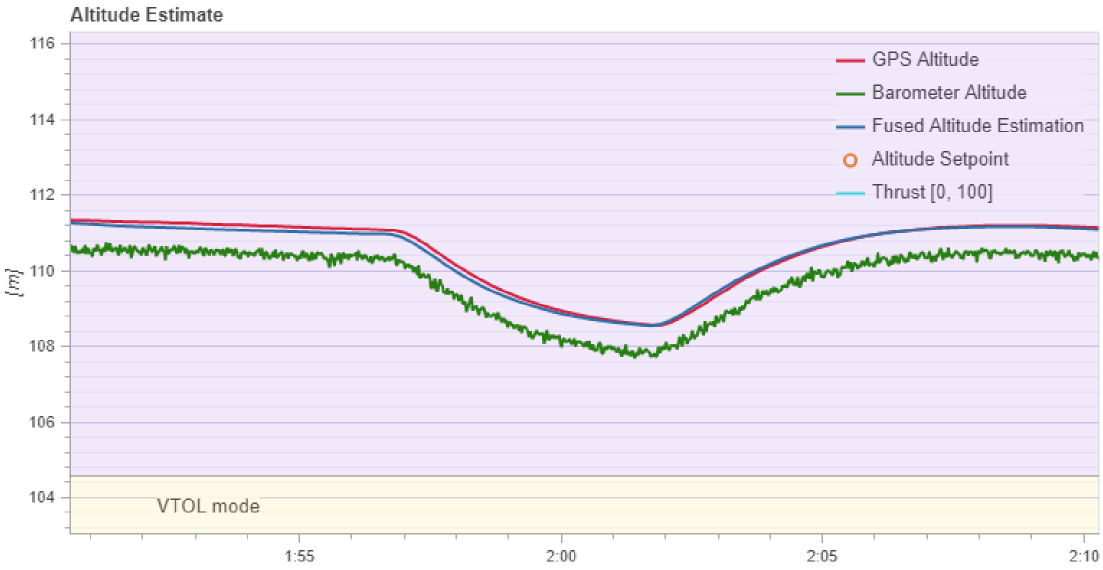


Figure 9-37: Drone speed 20m/s - Wind speed 15m/s (Autopilot logs during simulation)

9.3.4 Conclusions

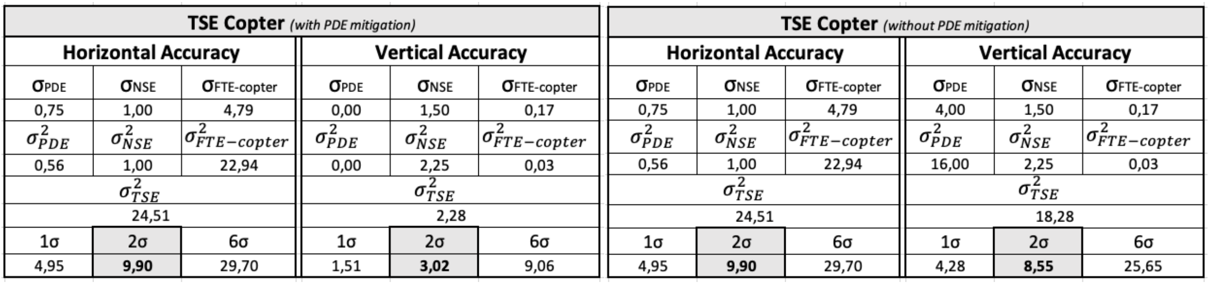
The first case (UAS-UAS) is concluded with a summary table with all the errors estimated for two UAS (multicopter and Fixed-wing drone), flying in a given airspace volume with a waypoint-to-waypoint trajectory over a common WGS-84 datum. A PBN approach is followed.

The main conclusions refer to the identified limitations by which vertical (and horizontal) UAS-UAS separation is possible.

Error source	Statistical characterization	Examination	Horizontal accuracy (95%)	Vertical accuracy (95%)	Notes and Limitations
PDE	Normal distribution	Analysis	1,50 m	8,00 m negligible *using DFMC GNSS Receiver and proposed operational mitigation*	Not Negligible for very precise UAS operations (typically where RTK is required). Cartography errors may depend by the mission planning software used and its related maps (horizontal maps, 3D models for DSM). **Mitigation for the vertical accuracy:** the home point calculated by drone's DFMC GNSS receiver can be used to provide additional measurements to the USSP, for enhancing the accuracy of the vertical elevation model.
NSE Conf. 1	Normal distribution	Analysis	2,00 m	3,00 m	DFMC (GNSS + EGNOS/EDAS)
NSE	Normal distribution	Analysis	2,50 m	3,50 m	DFMC

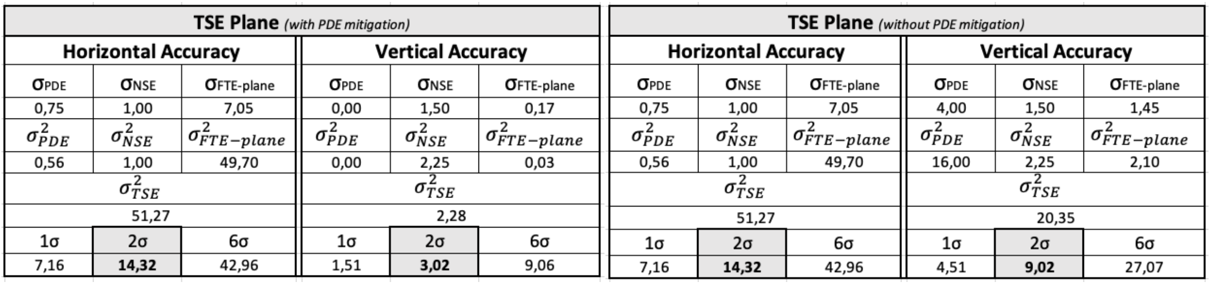
Conf. 2					(GNSS + Galileo +ARAIM)
FTE (Copter)	Normal distribution	Simulation	9,58 (worst case according with simulation)	0,34 m	Cross wind component (horizontal): 15 m/s Drone GS: 10 m/S Updraft component (vertical): 15 m/s Drone GS: 10 m/S
FTE (Fixed Wing)	Normal distribution	Simulation	14,10 m (worst case according with simulation)	2,90 m	Cross wind component (horizontal): 15 m/s Drone GS: 25 m/S Updraft component (vertical): 15 m/s Drone GS: 20 m/S

Table 9-18: summary of error budget allocation in UAS-UAS common reference case



TSE Copter *(with PDE mitigation)*						**TSE Copter** *(without PDE mitigation)*					
Horizontal Accuracy			**Vertical Accuracy**			**Horizontal Accuracy**			**Vertical Accuracy**		
σ_{PDE}	σ_{NSE}	$\sigma_{FTE\text{-}copter}$	σ_{PDE}	σ_{NSE}	$\sigma_{FTE\text{-}copter}$	σ_{PDE}	σ_{NSE}	$\sigma_{FTE\text{-}copter}$	σ_{PDE}	σ_{NSE}	$\sigma_{FTE\text{-}copter}$
0,75	1,00	4,79	0,00	1,50	0,17	0,75	1,00	4,79	4,00	1,50	0,17
σ_{PDE}^2	σ_{NSE}^2	$\sigma_{FTE-copter}^2$	σ_{PDE}^2	σ_{NSE}^2	$\sigma_{FTE-copter}^2$	σ_{PDE}^2	σ_{NSE}^2	$\sigma_{FTE-copter}^2$	σ_{PDE}^2	σ_{NSE}^2	$\sigma_{FTE-copter}^2$
0,56	1,00	22,94	0,00	2,25	0,03	0,56	1,00	22,94	16,00	2,25	0,03
σ_{TSE}^2			σ_{TSE}^2			σ_{TSE}^2			σ_{TSE}^2		
24,51			2,28			24,51			18,28		
1σ	2σ	6σ	1σ	2σ	6σ	1σ	2σ	6σ	1σ	2σ	6σ
4,95	**9,90**	29,70	1,51	**3,02**	9,06	4,95	**9,90**	29,70	4,28	**8,55**	25,65

Table 9-19: Total System Error estimation for copters



TSE Plane *(with PDE mitigation)*						**TSE Plane** *(without PDE mitigation)*					
Horizontal Accuracy			**Vertical Accuracy**			**Horizontal Accuracy**			**Vertical Accuracy**		
σ_{PDE}	σ_{NSE}	$\sigma_{FTE\text{-}plane}$	σ_{PDE}	σ_{NSE}	$\sigma_{FTE\text{-}plane}$	σ_{PDE}	σ_{NSE}	$\sigma_{FTE\text{-}plane}$	σ_{PDE}	σ_{NSE}	$\sigma_{FTE\text{-}plane}$
0,75	1,00	7,05	0,00	1,50	0,17	0,75	1,00	7,05	4,00	1,50	1,45
σ_{PDE}^2	σ_{NSE}^2	$\sigma_{FTE-plane}^2$	σ_{PDE}^2	σ_{NSE}^2	$\sigma_{FTE-plane}^2$	σ_{PDE}^2	σ_{NSE}^2	$\sigma_{FTE-plane}^2$	σ_{PDE}^2	σ_{NSE}^2	$\sigma_{FTE-plane}^2$
0,56	1,00	49,70	0,00	2,25	0,03	0,56	1,00	49,70	16,00	2,25	2,10
σ_{TSE}^2			σ_{TSE}^2			σ_{TSE}^2			σ_{TSE}^2		
51,27			2,28			51,27			20,35		
1σ	2σ	6σ	1σ	2σ	6σ	1σ	2σ	6σ	1σ	2σ	6σ
7,16	**14,32**	42,96	1,51	**3,02**	9,06	7,16	**14,32**	42,96	4,51	**9,02**	27,07

Table 9-20: Total System Error estimation for planes

From the analysis and simulations performed, we can conclude that:

- During BVLOS operations, for a straight trajectory (waypoint-to-waypoint), it is possible to reach a navigation accuracy performance with a TSE of about:
  - 10 metres for the horizontal accuracy for multicopters (better than RNP0.01);
  - 3 to 9 metres for the vertical accuracy for multicopters (better than RNP0.005);
  - 14 metres for the horizontal accuracy for fixed-wing planes (better than RNP0.01);
  - 3 to 9 metres for the vertical accuracy for fixed-wing planes (better than RNP0.005);
- The vertical FTE has been proven to be very similar for both multicopters and fixed-wing planes with comparable MTOM and the same flight and environmental conditions, but substantially different on the horizontal plane in favour of multicopters.

- UAS flying BVLOS in the same air volume, in automatic flight and with same WGS-84 datum, could be possibly stay "well clear" of each other by considering a minimum vertical distance (6 sigma) of 27 m
- UAS flying BVLOS in the same air volume, in automatic flight and with same WGS-84 datum, could be possibly stay "well clear" of each other considering a minimum vertical distance (6 sigma) of 43 m
- A "Home Point" update procedure before take-off for the vertical altitude measurement through a DFMC GNSS receiver is a possible mitigation strategy to control the DTM /DSM errors provided through a U-space geo-awareness service
- EGNOS is a "must have" technology for EGNSS integrity monitoring; some UAS speed limitations may be considered to keep the time-to-alert (offered by design with EGNOS) compatible with the horizontal and vertical alert limits, in the absence of U-space navigation monitoring services.

9.4 UAS-Ground obstacle awareness

In addition to the error components of the drone flight described in paragraph 9.1, another source of error affecting the total error budget is the one introduced by the use of digital terrain models, digital surface models, and ground obstacles.

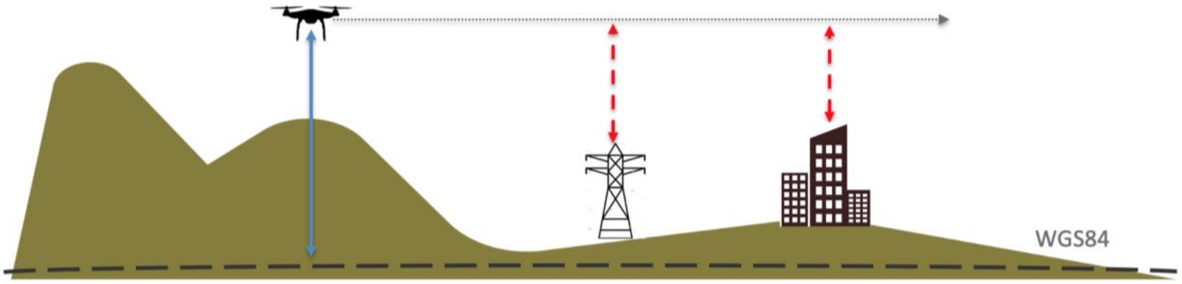


Figure 9-38: UAS-Ground obstacles case

9.4.1 Digital terrain model, digital surface model, ground obstacles

The description of the errors affecting the different models used is provided for each implementation in the corresponding paragraphs of the chapter 4.

Table 9-21 gives a summary of the accuracy of the different digital models.

NOTE – The statistical indices most often used for horizontal and vertical accuracy are CE90 and LE90 respectively. Where necessary (values marked with *), the conversions from CE90/LE90 to CE95/LE95 are calculated assuming Gaussian distributions (see paragraph 4.6), even if the error distributions, especially for the vertical accuracy, are generally leptokurtic; in any case, the conversion provides a good approximation.

Error source	Horizontal accuracy (95%) CE95 (m)	Vertical accuracy (95%) LE95 (m)
SRTM	11*	9*

ASTER GDEM3	< 30	< 20
AW3D30/AW3DStd - MERIT DEM	12*	10*
TanDEM-X DEM/WorldDEM	< 11*	< 12*
EU-DEM (latitude (φ) < or > 60°)	11*(φ < 60°) - 30 (φ > 60°)	9*(φ < 60°) - 20 (φ > 60°)
Euro-Maps 3D DSM	6-11*	6-12*
Regional/Local DEMs (off-the-shelf and on demand)	> 0.1-0.2	> 0.1-0.2

Table 9-21: Accuracy of the different Digital Terrain and Surface Models

9.5 UAS-Manned Flight reference

A final source of error affecting the total error budget is the conversion between the different reference systems used to represent the heights.

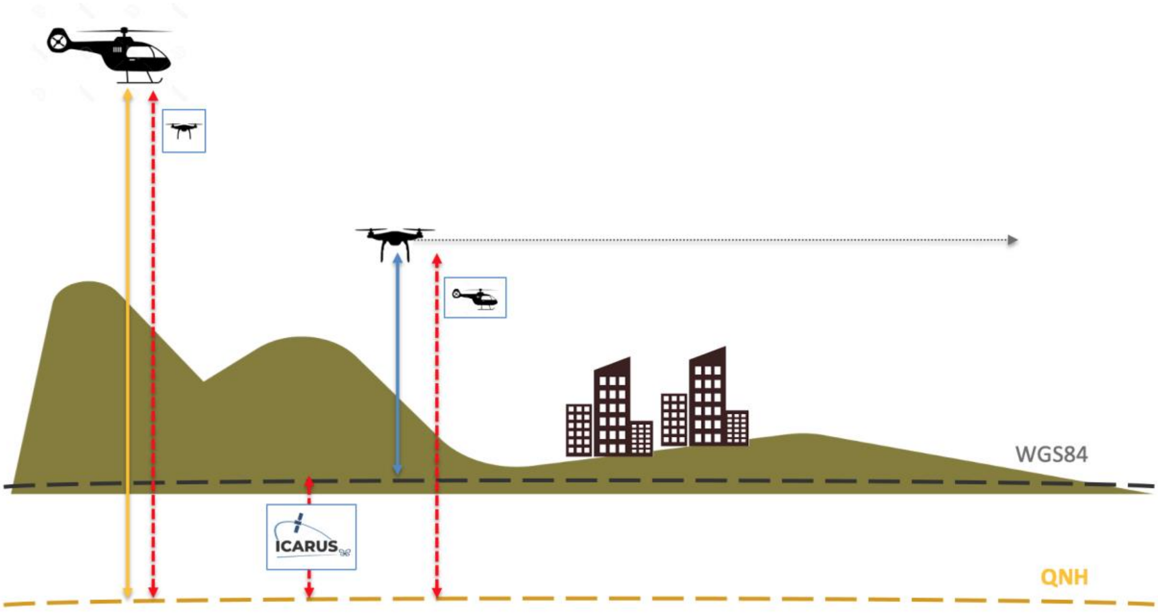


Figure 9-39: UAS-Manned flight case

9.5.1 Height system conversion error

In this paragraph, the conversions between the different height reference systems described in chapter 5 are reconsidered in terms of the errors they introduce.

In particular, we considered two main conversions:

1. orthometric / normal to ellipsoidal height and vice versa, to be used for converting the DTM /DSM reference system, the reference barometric station (used with the QFE) and the mean sea level (used in QNH) to make them compatible with GNSS height observations;
2. barometric to orthometric / normal height, to be used for determining the QFE or QNH-based barometric height to be communicated to general aviation aircraft that cannot directly use GNSS instruments.

The first conversion is based on a geoid / quasi-geoid model. It is recommended to verify that the model used for the conversion is consistent with the reference frame adopted by data, because both orthometric and normal heights are often identified with the term “altitude above sea level” (asl altitude). The height datum of the geoid model should also be verified and attention must be paid especially when using global models or purely gravimetric local geoid solutions.

The second conversion is based on the ideal gas law (see chapter 5) and attention must be paid to model errors due to lateral pressure variations.

The error sources of the two conversions are given in the following tables.

Geoid/quasi-geoid model	Expected Accuracy	Possible systematic errors
Global	0.30 m	< 1 m, if a non-consistent model, e.g. w.r.t. DTM, is used for the transformation < 0.50 m, if the geoid model is wrongly used as a quasi-geoid model or vice versa
Continental	0.08 m	
Regional	0.03 m	

Table 9-22: Conversion errors for orthometric / normal to ellipsoidal height and vice versa

Error source	Expected accuracy
GNSS-derived height of the reference barometric station	< 0.3 m
Mis-modelling of the pressure-height equation and pressure measurement error	< 3 m
Lateral pressure variation (if not modelled according to chapter 5)	~ 10 m / 1hPa

Table 9-23: Conversion errors for barometric to orthometric / normal height and vice versa

9.6 Error Budget summary

Case	Error Sources Considered	Horizontal total error budget (95%)		Vertical total error budget (95%)	
		Fixed wing	Copter	Fixed wing	Copter
UAS-UAS	PDE (Path Definition Error) NSE (Navigation System Error) FTE (Flight Technical Error)	14.5 m	10 m	3 m	3 m
UAS-Obstacles	PDE (Path Definition Error) NSE (Navigation System Error) FTE (Flight Technical Error) Digital terrain/surface/obstacles	14.5 m to 33 m[13]	10 m to 31.5 m[13]	3 m to 20 m[13]	3 m to 20 m[13]

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[13] Depending on the DSM/DTM/Obstacles precision (see 9.4.1)

UAS-Manned	PDE (Path Definition Error) NSE (Navigation System Error) FTE (Flight Technical Error) Height system conversion	14.5 m[14]	10.5 m[14]	4.5 m[14]	4.5 m[14]

Table 9-24: Error Budget summary in the three cases depicted

9.7 References

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10 ICARUS Requirements analysis

10.1Requirements Analysis

This chapter summarises the main findings of this document in a set of requirements that have been gathered in the form of an excel file (attached).

Most requirements have been defined inside this document, others have been collected in previous U-space projects and harmonised with ICARUS findings. In both cases, the traceability from the parent requirement has been kept.

The types of requirement identified at this stage are:

- General
- Functional
- Performance
- Operational

For each requirement, a verification method has been proposed as follows:

<u>Verification Methods</u>

- ✓ TEST (T): Compliance with requirements is validated by executing an item under controlled conditions, configurations, and inputs in order to observe the response. Results are quantified and analysed in dedicated test reports;
- ✓ ANALYSIS (A): Compliance with requirements is determined by interpreting results using established principles such as statistics, qualitative design analysis, modelling and computer simulation.
- ✓ REVIEW OF DESIGN (ROD): Compliance with requirements is validated by using existing records or evidences such as validated design documents, approved design reports, technical descriptions, engineering drawings
- ✓ INSPECTION (I): Compliance with requirements is determined by visual determination of physical characteristics which include constructional features, hardware conformance to document drawings or workmanship requirements, physical conditions, software source code conformance with coding standards

The verification of the requirements proposed will be addressed during the verification stage in WP6, where test cases will be defined in compliance with verification method specification.

All findings will contribute for the definition of the final recommendations and ICARUS CONOPS.

Finally, the results of the user survey are given in the following paragraphs, as part of the contribution for determining ICARUS requirements.

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10.2Requirements collected from User Survey

As part of the activities planned to define the ICARUS concept and requirements, a web survey was designed to provide the consortium with the point of view of potential users of the ICARUS service. This section presents the survey and its results.

The main goals of the survey were:

- Understanding the main differences between the two categories of user: UAS and GA operator.;
- Investigating the most critical issues concerning GNSS and barometric altitude measurements;
- Collecting feedback and input about operational needs concerning a common altitude reference system in VLL airspace;
- Exploring users' acceptance of Geometric Altitude Mandatory Zones, the use of an altitude translation service, and the use of a common "Zero" altitude in VLL Airspace.

Starting from these objectives, the survey's targets were users of VLL airspace, including both unmanned aviation pilots and operators, and manned aviation pilots (also considering ultralight pilots), the objective being to collect information from a purely operative point of view. Other groups of stakeholders - representative of U-space service providers, ATM service providers, CA authorities, and regulators - were involved in the first Advisory Board (AB) where participants were asked the most important questions of the survey.

In this perspective, therefore, three different categories are considered:

- UAS/unmanned aviation: Drone pilots and operators, both private and public entities;
- Manned aviation: General Aviation pilots;
- Advisory Board: participants in the first AB.

10.2.1 Methodology

The survey was submitted to UAS / unmanned aviation and manned aviation categories via the web using the Google Forms tool from 15th October to 25th November 2020. Third category participated during the first online AB meeting.

Even if the topics were the same, the number of questions was different to fit with the specificity of each category. In particular:

- 14 questions to UAS / unmanned aviation;
- 11 to manned aviation;
- 5 to the AB.

The questionnaire was divided into three sections: User profile (except for AB), common altitude reference, and threats to flight and ground obstacles. It encompassed different types of question and answers, depending on the category of the respondents. The questionnaire included some introductory material (video and/or brochure) to help respondents focus on the subject.

10.2.2 Results and Requirements

In total, there were 194 participants:

- 136 unmanned aviation;
- 37 manned aviation;
- 21 AB participants.

The aggregate answers to the main questions from the sections “Common altitude reference” and “Flying threats and ground obstacles”, that are most useful for the purpose of this document are presented in Figure 10-1.

- Issues related to Barometric altitude measurement

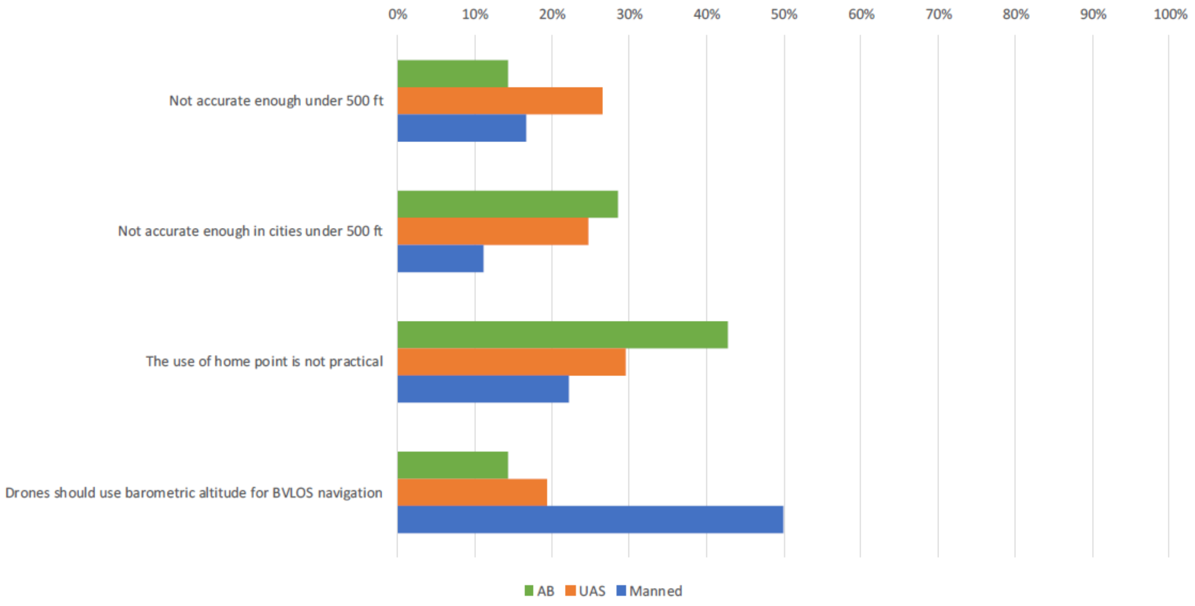

Figure 10-1: Survey results, Issues related to barometric altitude measurement

The AB and unmanned aviation stakeholders focused on the idea that “The use of home point as ‘Height 0’ for drones is not practical when addressing a great number of UAS flights”, while manned aviation thinks that “Drones should use barometric altitude for BVLOS navigation”, someway adapting to the way things are traditionally done.

- Issues related to satellite positioning (GNSS) altitude

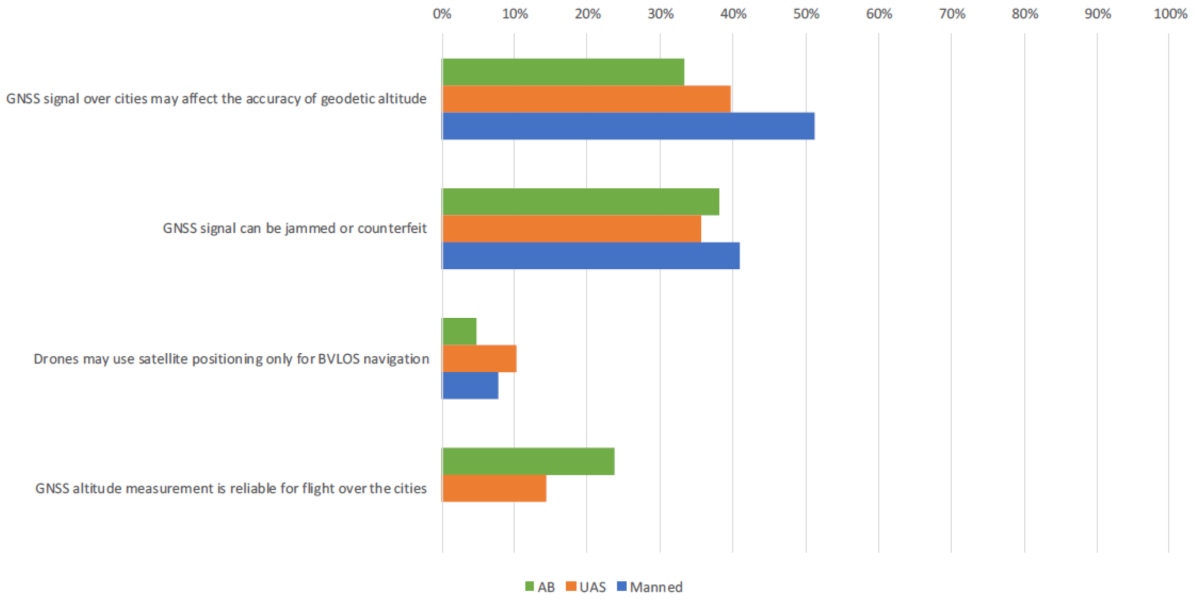

Figure 10-2: Survey results, Issues related to satellite positioning (GNSS) altitude

All the respondents agree, with some small differences, about accuracy and integrity of satellite (GNSS) altitude measurement, especially in an urban environment.

- Use of Geometric Altitude Mandatory Zones

  Participants were told that ICARUS proposes to establish "Geometric Altitude Mandatory Zones" (GAMZ) to overcome the problems with barometric altitude estimation in Very Low-Level airspace. In these zones the altitude reference for UAS and manned aviation would be geodetic (i.e. based on satellite positioning) rather than barometric. They were asked if they agree with this proposal.

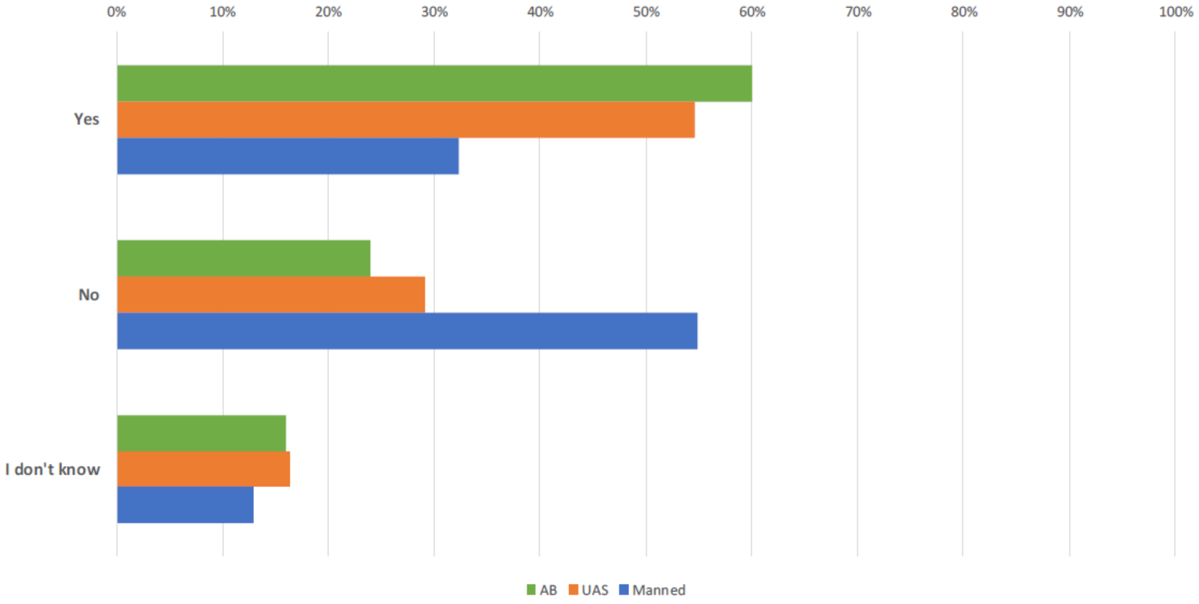

Figure 10-3: Survey results, GAMZ acceptance

While manned aviation strongly disagrees with the concept of GAMZ, it is appreciated by unmanned aviation and AB participants.

- Concerning the use of an altitude translation service

  Participants were asked for their opinion of the concept of a real-time service providing altitude translation from barometric to geodetic altitude data, and vice versa. For UAS, a drone pilot would request this via a U-space service; for manned aviation, a pilot would request access to the GAMZ via VHF.

  The formulation of the second part of the question reflects the different interfaces to the possible service.

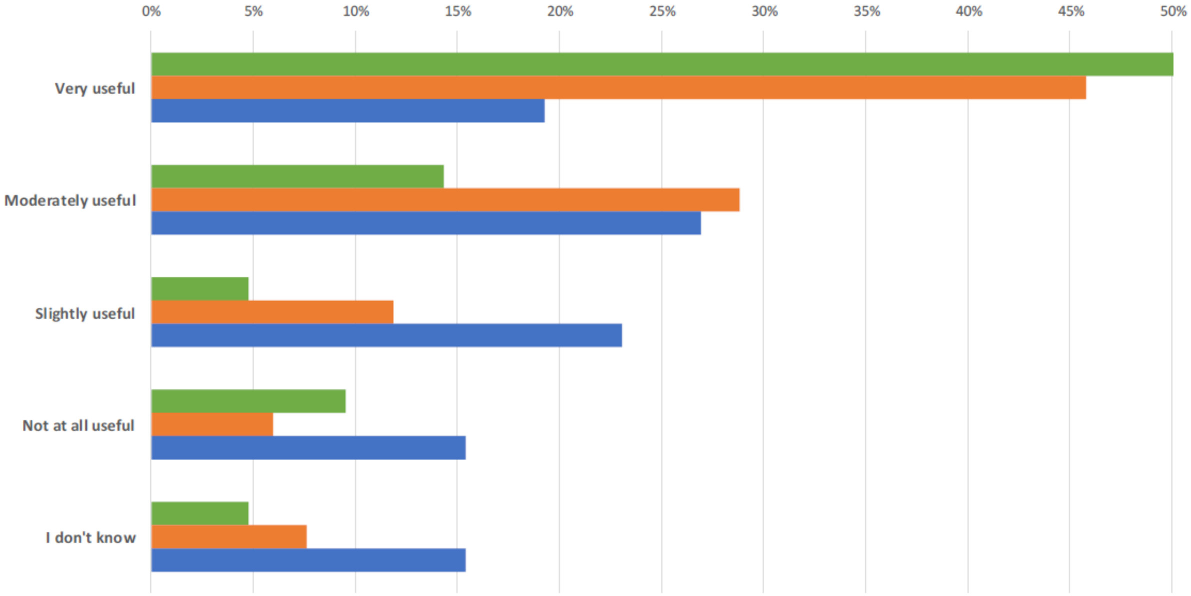

Figure 10-4: Survey results, translation service acceptance

Unlike GAMZ, the translation service received overall acceptance from all categories of respondent.

- About reporting obstacles

  Participants were asked how they would rate the possibility of reporting (whether manually or automatically with a U-space tracking service) the presence and position of ground obstacles?

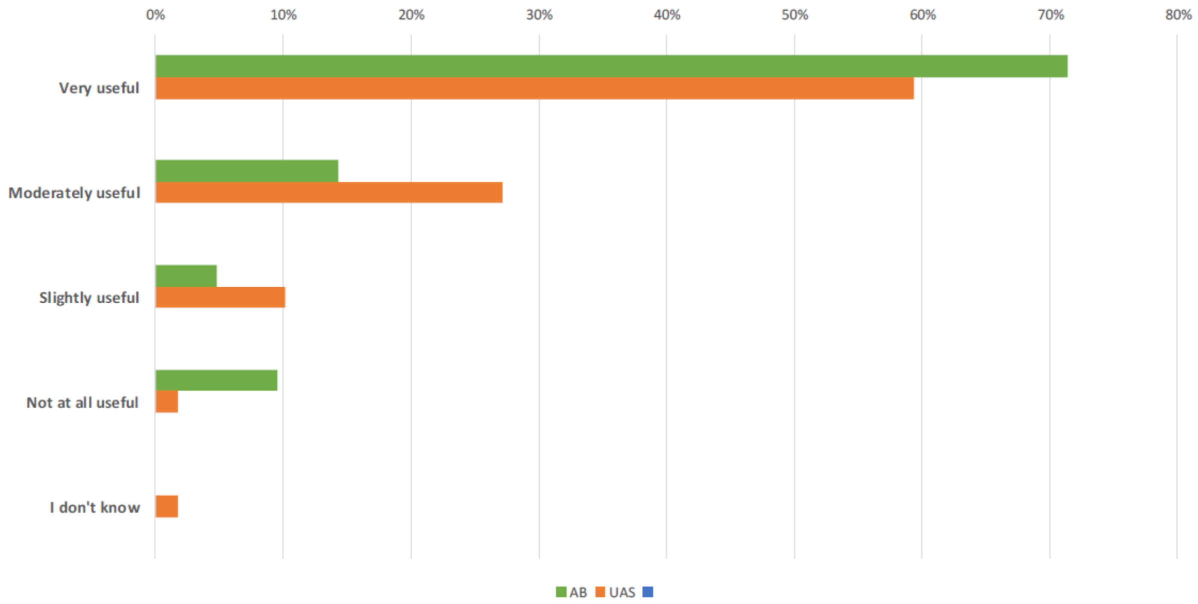

Figure 10-5: Survey results, ground obstacles' presence and position reporting service

Only unmanned and AB participants were asked this question, and gave positive feedback.

By merging these results, we can summarise some features of the "ideal" ICARUS concept as follows:

- Resolve the issue of the home point's being 'Height 0', which is not practical when addressing a large number of UAS flights;
- Consider (and mitigate) the GNSS signal multipath in urban environments;
- Acceptance of GAMZ in the community;
- Provide a real-time service that translates between geodetic and barometric altitudes;
- Provide drones with the possibility of reporting the presence and position of ground obstacles.

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