ICARUS - A tool for managing future manned and unmanned aviation

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Abstract— **In manned aviation, an aircraft altitude is determined using pressure difference measurements; however, small drones use altitude determination based on measurements to GNSS satellites; barometric and GNSS based altitudes are totally independent and not compatible altitude systems. New methods and procedures are therefore needed to enable all airspace users and supervisory systems to place all aircraft in the same altitude reference system. The EU-funded ICARUS project introduced an innovative solution for common altitude reference inside very low-level airspace, defining new U-space services and validating them in real operational environments.**

Keywords-UAS, Drone, U-Space services, UTM, Common Altitude, Altimetry, GNSS

I. INTRODUCTION

In manned aviation, an aircraft altitude is determined using various pressure altitude difference measurements. In unmanned aviation, most of the aircraft are using Global Navigation Satellite Systems (GNSS) based services as a basic source of altitude. The connection between those two very different methods of altitude determination require external conversion system.

Aircraft (Figure 1) use the International Standard Atmosphere (ISA) for defining, reporting, and broadcasting vertical information. Above a locally specified "Transition Altitude", we express this altitude in Flight Levels (FL) based on the QNE of 1013.2HPa at "0 feet". FL can maintain vertical separation since they refer to a particular standard isobaric surface.

Below a locally specified "Transition Level", altitude is also computed using the ISA, but it is referred to either the pressure at the local airfield (where the aircraft will land) (QFE) or the regional value for the pressure at mean sea level (QNH). These values provide a reference compatible with ground obstacles and the runway [1].

Since all aircraft in the local airspace use the same QNE/QNH/QFE reference datums, this is adequate for achieving vertical separation of traffic.

Manned aviation is starting to adopt GNSS based altitude, but its use is not yet sufficiently standardised and the applicable rules of the air are still based on barometric altitude.

On the other hand, UAS (Unmanned Aircraft Systems) use ellipsoidal altitude derived from measurements to GNSS satellites (Figure 2). These can enable vertical separation of UAS/UAS traffic, and in combination with appropriate digital surface models (DSMs), ground obstacle avoidance. However, they are not compatible with the barometric references that manned aviation traffic relies on.

Barometric altimetry is not adequate for unmanned aviation operating in Very Low Level (VLL) for several reasons: (a) A small drone may take off and land almost from everywhere ("Home Point"), reducing in this way the original significance

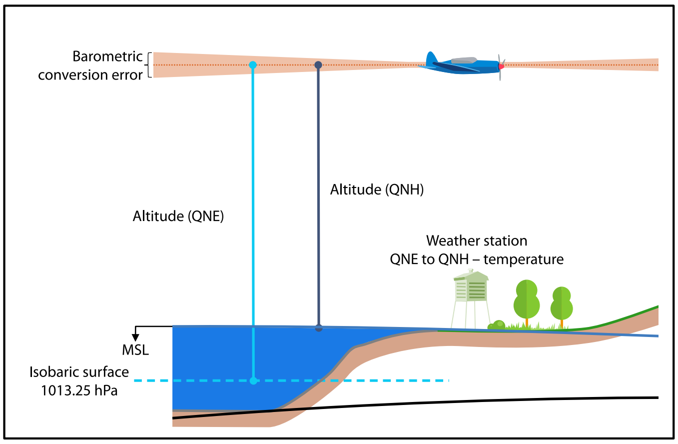

Figure 1. Manned aviation barometric altimetry.

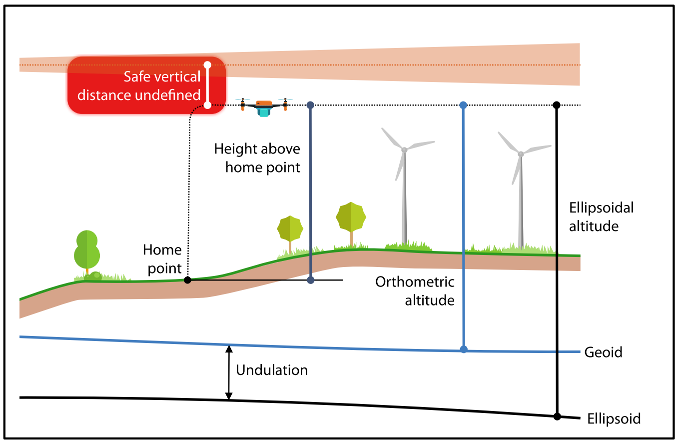

Figure 2. Unmanned aviation ellipsoidal (GNSS) altimetry.

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of QFE (altimeter setting for departing or arriving airfield), (b) Barometric pressure altitude is not accurate in VLL airspace, atmospheric pressure is difficult to measure over cities because of high temperature gradients: buildings radiate heat, in particular when there are large air-conditioning units on top of them, whereas nearby parks and lakes are cooler. This considerably affects the measurement of barometric altitude on UAS, (c) Air pressure is not constant but changes over time, so the (regional) QNH does as well. When using barometric altimetry for de-confliction between different airspace users, UAS need to know the evolution of QNH and adopt their QNH setting during the flight, (d) The certified resolution of the barometric measurement in manned aircraft is 25 ft, which is too coarse for VLL. In addition, such accuracy is only possible using equipment whose size is unfeasible for small drones, and (e) In traditional 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.

Therefore, to achieve interoperability and continuity of safe operation near or within manned aviation airspace, there is a need to deliver QNE/QNH based altitude information to UAS users, whereas QFE has very limited meaning for drones.

The ICARUS project has introduced an innovative solution for a common altitude reference inside VLL airspace, by defining new U-space services and validating them in real operational environments.

ICARUS provides the solution to these problems with a collection of services that:

- Introduces GNSS-based altitude measurement as a common vertical reference datum for UAS.
- Provides a tailored U-space service for ground obstacle mapping and terrain profile information.
- Provides a two-way height-altitude transformation service between GNSS and barometric reference systems.

II. High Level Objectives

Following the recommendations of the Eurocontrol UAS ATM Common Altitude Reference System (CARS) [2] ICARUS proposed the use of GNSS receivers with suitable requirements for the common UAS-UAS vertical reference. U-space is a set of new services relying on a high level of digitalisation and automation of functions and specific procedures designed to support safe, efficient, and secure access to airspace for large numbers of drones. Thus, the ICARUS project aimed at defining a new U-space service for altitude transformations for common UAS-manned aircraft reference, tightly coupled with the interface of existing U-space services, such as the Tracking and Flight Planning services.

Finally, the representation of the morphology of the Earth (surface including ground obstacle information) through DSM using ellipsoidal altitude was also an important element of the study.

The users of the ICARUS service will be remote pilots competent to fly UAS operations in Visual Line of Sight (VLOS) or Beyond Visual Line of Sight (BVLOS) in the Specific category, ultralight and general aviation 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 (U3) introduced by the Single European Sky ATM Research Joint Undertaking (SESAR JU).

With these considerations, ICARUS established the following four high-level objectives:

1. UAS-UAS Common reference at VLL: Define the technical requirements for high accuracy GNSS-based altitude measurement for drones, allowing a reliable and accurate common vertical reference (UAS-UAS).
2. UAS-Ground Obstacle awareness: Investigate the vertical accuracy and resolutions achievable by the actual Digital Terrain Models (DTM) or DSM services for ground obstacle and terrain profile within the geodetic WGS-84 (World Geodetic System) datum.
3. UAS-Manned Common reference: Design a tailored U-space service for altitude translation between ellipsoidal to barometric altitude for UAS and manned aircraft.
4. Enhance the VLL capacity in Urban Air Mobility (UAM) Scenarios: 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, paving the way for the enhancement of the VLL capacity and UAS separation for future BVLOS applications.

III. ICARUS Methodology

The ICARUS work plan included two administrative work packages, four research work packages and a transversal work package devoted to the definition of the business plan, communication, dissemination, and exploitation tasks.

A. ICARUS concept definition

ICARUS performed a critical review of the results of past and concurrent projects. The workable solution to the challenge of developing a CARS (Common Altitude Reference System) involved a multidisciplinary approach that included geodesy, geomatics, navigation, and ATM (Air Traffic Management) research, which was not always present in previous studies.

The ICARUS consortium was well balanced and possessed all the expertise needed to address this problem. It defined the requirements affecting both a GNSS-based altimetry approach in terms of accuracy, precision, continuity and integrity of service, and the requirements applicable to a DSM, including ground obstacles, in terms of resolution and accuracy.

The involvement of the U-space community of UAS pilots, drone operators, Unmanned Traffic Management (UTM) service providers and general aviation pilots, including those who were members of the Advisory Board, has enabled, through a dedicated web-based questionnaire, an assessment of the operational needs related to common altitude reference issues.

Five specific operational use cases of particular interest embodied the requirements identified, to highlight the ICARUS concept and its added value, and provided the information required to perform a preliminary safety assessment that was undertaken using state-of-the-art methodologies. The five use cases considered were:

1. Lineal infrastructure inspection
2. Drone delivery of spare parts to offshore platform
3. Industrial power-line inspection

4. Biological sample delivery in urban airspace
5. Airport-vertiport passenger transfer

The main output of this phase of the project was an analysis of the requirements of the service envisaged by the project, the identification of gaps to be filled to implement the solution, and a preliminary safety assessment of the use-cases, including an analysis of compliance with current EU regulations.

B. ICARUS as a collection of U-space services

The specification of the ICARUS concept led to the definition and design of a prototype solution. In this phase, we developed the system architecture of the service, considering the output of previous studies, with particular reference to the final architecture proposed by the CORUS project, to facilitate the integration of the ICARUS services into UTM (Unmanned Traffic Management)/USSP (U-Space Service Provider) implementations.

C. Development of simulated environment

To support the validation of the ICARUS services in the laboratory environment, the ICARUS team implemented a complete simulation of the system to perform preliminary tests. Each validated scenario used the real interface of the ICARUS prototype, with a particular configuration in accordance with the specific aims of the validation exercise.

D. Validation activities

The primary aim of the validation phase of the project is the proof of the ICARUS concept through validating the functionality of the system in a real operational environment.

The concept validation followed a stepwise approach, starting with the initial requirements. During the verification and validation phase of the ICARUS project, we performed several tests to verify the requirements, and the assumptions made in the first part of the project.

At the end of the project, we performed a second iteration of the requirements to adjust the conditions that had not verified previously and to adjust the performance of the system in operational conditions.

- ICARUS requirements: We defined five relevant use cases for ICARUS to support the requirements used to drive the design of the ICARUS service architecture and the flight trials (both simulated and real).
- Verification and validation plan: We established test cases, procedures, and the naming conventions to be used during the validation exercises.
- Validation scenario design: We described each validation scenario design, regarding the ICARUS microservices that were queried during the validation campaign.
- Operational activities and simulations: We provided significant operational details in advance about the validation campaigns and the exercises that were conducted.

To verify the correctness of the CARS algorithm, we performed two parallel UAS test flights at the same place (an Italian rural environment) and time. Both UAS flew in the same place, climbing with an altitude step of 10m up to 120m AGL (Above Ground Level).

During the test, we analysed the measured and converted values.

The UAS test flight specifications are:

- Both UAS were equipped with a calibrated RTK (Real-Time Kinematic) system to determine their exact height above the take-off point (AGL m).
- The blue UAS had an ADS-B (Automatic Dependent Surveillance – Broadcast) transmitter with its own barometric sensor that gave the altitude relative to the standard pressure (QNE).
- The orange UAS has been equipped with a 3G / LTE (Long Term Evolution) tracker with its own GNSS system that provides the altitude relative to the WGS-84 Ellipsoid.

The graphs (Figures 3 and 4) illustrate the efficiency of the CARS conversion regarding the conversion of values to the common denominators, which are Ellipsoid, QNH and QNE.

The plotted lines represent the values calculated for the blue and orange UAS described above. It should be emphasised that regardless of what is the source of the height/altitude information, the calculation process is performed with respect to every reference pattern.

E. Concept consolidation and recommendations

The project culminated with the collection and analysis of the data acquired during the validation campaign and the results achieved by the project. We presented the ICARUS concept and the conclusions of the study to the SESAR community and U-space / UTM stakeholders.

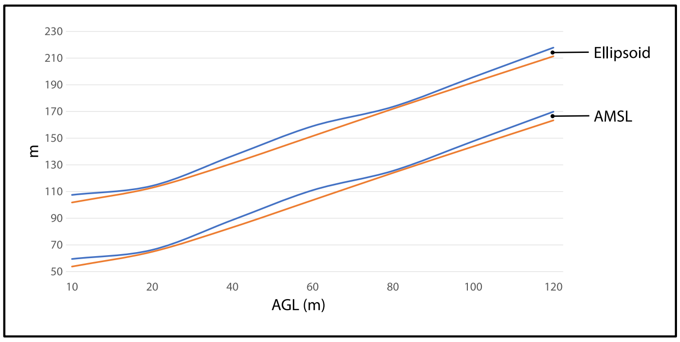

Figure 3. CARS conversion barometric vs GNSS in reference to ellipsoid and AMSL (Above Mean Sea Level).

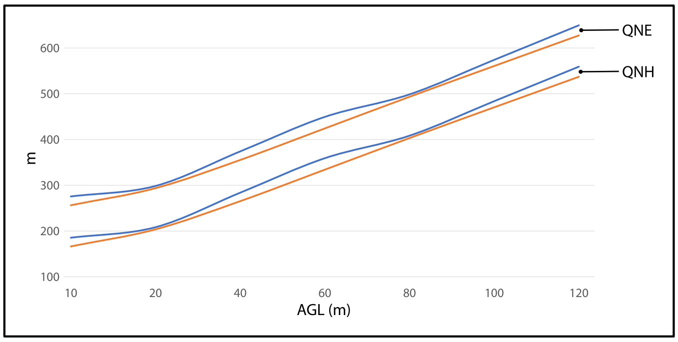

Figure 4. CARS conversion barometric vs GNSS in reference to QNE and QNH.

F. *Industry standards development*

ICARUS has ensured close coordination with Sub-Committee (SC) 16 (UAS) of the International Organization for Standardization (ISO) Technical Committee (TC) 20 (Aerospace) which is developing the series 23629-XX of international standards on UTM (called U-space in Europe). Among them, 23629-12 lists 30 digital U-space services, classified as 'safety-critical', 'safety-related' and 'operation support'. Since these standards are strongly recommended to industry and service providers, their inclusion signifies that the aviation community will use the results of the project.

The list already includes three additional services proposed by ICARUS:

- Real-time Geospatial Information Service (RGIS)
- Vertical Conversion Service (VCS).
- Vertical Alert Service (VALS).

The results of the ICARUS project consider EU 2021/664 [3], 2019/947 [4] and 2019/945 [6] regulations.

IV. ICARUS ARCHITECTURE AND DESIGN

Figure 5 shows a high-level view of the proposed architecture of the ICARUS system.

A. *Inputs*

ICARUS consumes and maintains instantly updated data from GNSS, GIS (Geospatial Information Service) and weather sources to support its conversion and alert algorithms. The data is collected in raw format and needs to be processed before using it in the functional modules.

B. *Application Programming Interface (API)*

ICARUS publishes APIs and open and interoperable protocols that are used by U-space service providers to query the system on behalf of U-space and general aviation users.

C. *Computational services*

- Geo-information module: The Geo-information module implements a set of services to support all the other subsystems by providing geographical information, typically associated with DSM, DTM and obstacle data.

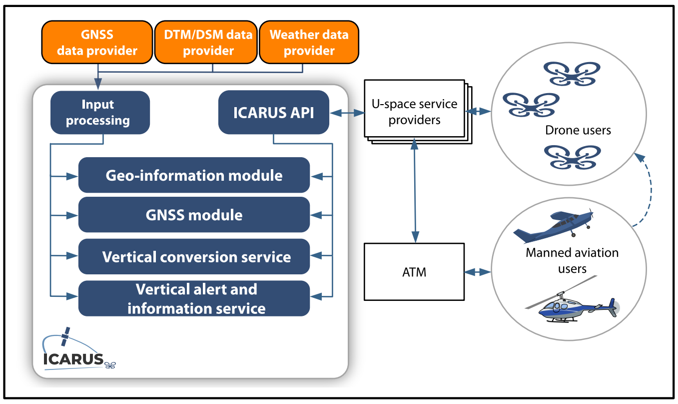

Figure 5. ICARUS high-level architecture.

  The Geo-information service receives input data from external data providers. Mission planning scheduling triggers data ingestion, causing data transfer from external interfaces and is stored in local memory.

- GNSS Module: The GNSS module provides the real-time information regarding the drone position and the integrity of the solution achieved to the other ICARUS subsystems. The unit performs a check of the quality of the GNSS signal in the geographical area of interest, through the monitoring of the progress of the integrity parameters, providing an usability flag to the users.

- Vertical Conversion Service module: The VCS module provides the Vertical Conversion Service, which converts the heights provided as input from a barometric to a geometric reference system, and vice versa.

  It directly interacts with the U-Space Service Provider, with the other internal ICARUS modules, and with the Weather Data Provider that gets data from a set of distributed weather reference stations.

  The VCS module can determine and share current aircraft altitude regarding the Earth's surface (buildings and ground obstacles), terrain, mean sea level, and ellipsoid models . The geoid model used was aproximated to MSL.

- Vertical alert service module: The VALS is a system that offers the UAS Pilot with information and alerts on detection of a potentially hazardous terrain situation, so that the UAS pilot may take effective action to prevent a crash event. The main idea is to define a 3D safety-space buffer, called the Forward-Looking Terrain Avoidance volume (FLTA), and raise an alarm whenever any type of obstacle breaches the defined FLTA.

- The tracks referred to the geometric datum WGS-84 were generated by two prototype boards for the UAS and for General Aviation/ultralight aircraft.

  The UTM Box Pollicino™ is equipped with a low-cost Dual Frequency Multi Constellation (DFMC) GNSS receiver that was used as a benchmark to estimate the added value for vertical accuracy of the high-end Multiple Frequency Multi Constellation (MFMC) GNSS receivers (such as Septentrio Mosaic X5) used during the validation campaigns.

  The mock-up of the Electronic Flight Bag (Figure 6) was developed in the frame of ICARUS project as a human machine interface (HMI) to general aviation pilots to provide local traffic information in the same altitude reference, exploiting the services implemented (VCS, VALS) not only for information about other UAS/manned traffic but also for ground obstacles warning.

  We used these boxes during the verification and validation activities of the project (Figure 7).

V. ICARUS SERVICES

ICARUS has developed and validated a new U3 service - Altitude Translation Service, to be used by UAS operators and general aviation pilots, that provides their current altitude, using a Common Altitude Reference, as well as the distance from the ground and known obstacles. This macro service is based on the following U-Space services:

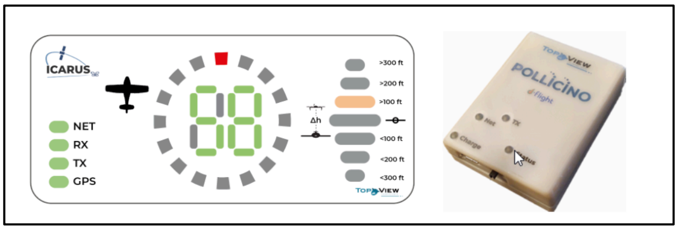

Figure 6. ICARUS Electronic Flight Box (left), Pollicino™ UTM Box (right).

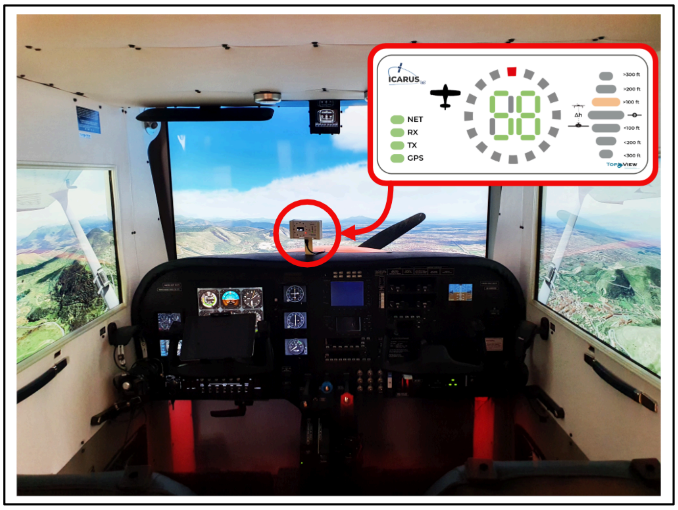

Figure 7. ICARUS Electronic Flight Box used as add-on of the Cockpit Simulator

- Real-time Geospatial Information Service (RGIS): Accurate cartography, DTM / DSM, 3D models of the ground obstacle provisioning service during the execution of flight (tactical phase), to provide real-time information of vertical distance to ground.
- Vertical Conversion Service (VCS): A new U-space service defined by ICARUS that provides drone altitude and height regarding the surface, converting drone altitude into barometric altitude, and converting manned barometric altitude to geometric altitude, to enable entry into a CARA (Common Altitude Reference Area). VCS converts any height/altitude input to all other height/altitude outputs.
- Vertical Alert Service (VALS): A new U-space service defined by ICARUS that alerts drones and manned aviation about their current vertical distance from the ground when it is small.
- Electro-Magnetic Interference Information Service (EMS) / Navigation Coverage Information: GNSS Signal Monitoring and Positioning + Integrity service that reports enhanced accuracy, performance estimation and integrity to UAS pilots or drones.

VI. TOTAL SYSTEM ERROR

To estimate the accuracy of the ICARUS system, we have evaluated all known sources of error, following the Performance-Based Navigation methodology defined by the International Civil Aviation Organisation (ICAO) [6] (See Figure 8).

- Total System Error (TSE): is the deviation of a flight's actual position away from the desired path. It is the sum of three major errors.
- Path Definition Error (PDE): occurs when the path defined in the flight plan differs from the actual path reported to U-space. Traditional aviation usually neglects the PDE, because it is not relevant for their operations. With drones, especially when planning missions that require a high level of detail, the PDE can be relevant.

  It originates in errors present in the geodetic datum used by the ground control station and the DSM used. Updating the DTM value by entering a "Home Point fix" before take-off can be a good mitigation strategy to limit this error.
- Navigation System Error (NSE): corresponds to the difference between the UAS position as estimated by the navigation sensor, the GNSS receiver in this case, and its actual position.

  We can use the error values provided by the GNSS service providers such as [7].
- Flight Technical Error (FTE): refers to the ability of the autopilot to follow the defined path or track, including any display error. The FTE can be determined using numeric simulation applied to representative models of a multi-rotor and fixed wing UAS in varying conditions of flight and wind speeds that are normal in real-world operations.

We assume that these three errors are independent, have a zero-mean (i.e., they don't have any systematic error), and have a Gaussian distribution. Therefore, the distribution of the TSE is also Gaussian, with a standard deviation equal to the root sum square of the standard deviations of these three errors.

A. *UAS-UAS separation*

The TSE determined in this way applied to both UAS corresponds to the total error budget for the UAS-UAS service.

B. *UAS-Ground separation*

Besides the TSE of the involved drone, the use of digital elevation models, digital surface models, and ground obstacles introduces another source of error that affects the total error budget.

The error introduced by a low-quality digital elevation model can be substantial. For that reason, ICARUS should use DSM of the highest quality.

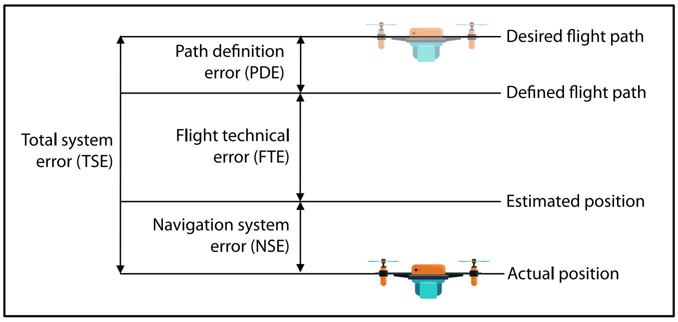

Figure 8. Total System Error.

C. *UAS-Manned separation*

For the common altitude reference for manned and unmanned aviation, the conversion between the different altimetry systems introduces two additional errors:

- The conversion from the DEM used to reference the barometric station used to determine the QNH or QFE references to make them compatible with GNSS height observations.
- The barometric to geodetic conversion required to transform the barometric reading from the manned aircraft to the geodetic height used by the drone reading from the manned aircraft to the geodetic height used by the drone.

Table 1 lists the values obtained for the Total System Error for the fixed wing and multi-rotor systems used for the three different scenarios considered.

TABLE I. TOTAL SYSTEM ERROR

Service	***System***	***Horizontal error (95% CI)***	***Vertical error (95% CI)***
UAS-UAS	Fixed wing	14.5 m	3.0 m
	Multi-rotor	10.0 m	3.0 m
UAS -Ground	Fixed wing	14.5 – 33.0 m	3.0 – 20.0 m
	Multi-rotor	10.0 – 31.5 m	3.0 – 20.0 m
UAS-Manned	Fixed wing	14.5 m	4.5 m
	Multi-rotor	10.5 m	4.5 m

VII. CONCLUSION

This paper presented a proposal for a Common Altitude Reference system for VLL airspace developed by the ICARUS consortium that all users of the airspace, manned and unmanned, can use. A comprehensive review of the existing limitations of the prevailing barometric altitude methods used in traditional aviation was conducted, resulting in the definition of four high-level objectives for the ICARUS solution. The requirements for the system were defined and its architecture and design were carried out. The validation of the solution included simulated exercises, to check the interoperability of the different components and real flights in relevant environments.

The following conclusions can be drawn from the ICARUS study:

A. *Conclusions on maturity of the solution*

Since the purpose of ICARUS was the development of a prototype, we achieved only high-level results. However, we should consider that the commercial implementation of the service, along with its certification, will still require large financial outlays. Thus, ICARUS focused on a Proof-of-Concept approach.

Reaching a Technology Readiness Level (TRL) 7 (Model demonstration in an operational environment) will require the development of documentation, certification, and proven highly scalable data models and algorithms. Because of the need to launch many new services (RGIS, VCS, VALS and EMS), achieving certification will demand a long time and further investment. Additional research and development activities in some specific areas are still needed:

- Standardisation, best practice and calibration of barometric sensors and certified source on ground (trusted source GIS / METEO).
- DTM/DSM undulation references.
- Need to add more data from land pressure stations to reduce the unknown error between real QNH Reference and calculated QNH reference.
- Certification of service provider.
- GNSS Integrity algorithms to be further investigated for real time application even with dissimilar technologies and cross check correlation.
- Certification of GNSS receivers for UAS operations.

B. *Conclusions on technical design, feasibility and architecture*

CARS is a real-time service. For this reason, its final production architecture must be reliable and scalable vertically and horizontally. The vertical development will be realised by increasing the computing power, while horizontal development will be performed through the multiplication of server instances.

In real-time systems, the weakest element determines the speed of the entire system. Therefore, during the development of the production system and the process of certification, the needs resulting from aviation safety will determine the requirements, technical or otherwise.

However, to prevent unforeseen limitations arising during the operation of the system, it is necessary to define fall-back and contingency procedures (both technical and procedural) to inform all users about the limitations of the CARS system, specially operating within a CARA.

C. *Conclusions on performance and benefit assessments*

The performance of the system will depend on the number of aircraft present in a volume of airspace and the frequency of location updates. The typical broadcast frequency of position information varies between 1 and 5 Hz. Thus, system performance should take extreme cases into account and should include a safety buffer in case the amount of information in a volume of space increases significantly.

D. *Conclusions on requirements*

After the validation activities were completed, we performed a requirement coverage exercise to analyse if the requirements had been met. The result of the exercise is that all the test cases had been successful, although in some cases the results were limited to the particular data sets used (and therefore the tests might have failed in other conditions).

E. *Recommendations for standardisation and regulation*

- Consideration of the concept of a CARA (Common Altitude Reference Area) by EASA in amendments to SERA.
- Consideration by the EU of a definition of altitude different from ICAO's, applicable to airspace type Zu, as defined in the CORUS ConOps;

- The development of specific Low-level Flight Rules (LFR) to cover the needs of UAM at VLL.
- Transposing the principles of AMC1 ARO.GEN.305(b);(c);(d);(d1) into the U-space context as an Acceptable Means of Compliance (AMC) to the forthcoming Commission U-space Regulation.

The adoption of a performance-based approach to regulation of altimetry in the coming "Part UAM" of AIR-OPS, considering that: the function of a barometric altimeter, especially in areas away from aerodromes where an accurate QNH may not be available, could be replaced by VCS, and the function of the radio altimeter, especially in obstacle-rich environments, could be replaced by RGIS.

Acknowledgment

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References

[1] Doc 8168 (PANS-OPS), Volume I, Flight Procedures - Part VI - Altimeter Setting Procedures - Chapter 3.

[2] UAS ATM Common Altitude Reference System (CARS): https://www.eurocontrol.int/publication/uas-atm-common-altitude-reference-system-cars.

[3] Commission Implementing Regulation (EU) 2021/664 of 22 April 2021 on a regulatory framework for the U-space.

[4] Commission Implementing Regulation (EU) 2019/947 of 24 May 2019 on the rules and procedures for the operation of unmanned aircraft.

[5] Commission Delegated Regulation (EU) 2019/945 of 12 March 2019 on unmanned aircraft systems and on third-country operators of unmanned aircraft systems.

[6] ICAO Doc 9613, Manual on performance-based navigation (PBN.

[7] European GNSS (Galileo) Services Open Service Quarterly Performance Report, April-June 2020.