EGNOS-based Navigation and Surveillance System to Support the Approval of RPAS Operations

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***Abstract*—This paper presents an EGNOS-based Navigation and Surveillance sensor designed, developed and integrated in a real RPAS in order to contribute to the approval of innovative RPAS operations, supported by a Safety Case overwhelmed by high levels of accuracy and integrity provided by EGNOS. On one hand, this research proposes an on-board navigation system and a procedure design criteria for RPAS, based on current procedure design provisions for manned aircraft. On the other hand, this work demonstrates the benefits that EGNOS can offer for the safe future integration of UAS, defining an RPAS RNP 0.02 navigation specification in the airspace and validated through more than 30 flights using the developed navigation and surveillance system.**

Keywords: EGNOS, navigation, GNSS, RPAS, UAS, surveillance.

I. Introduction

Civil Remotely Piloted Aircraft Systems (RPAS) are quickly developing worldwide and in Europe in particular. They represent the future of a high percentage of operations that are currently carried out by manned aviation or satellites. UAVs are becoming a powerful tool in strategic frameworks, not only for military use, but also regarding civil and commercial applications. In the last decade, UAVs have attracted significant interest in a wide range of applications, exploiting their ability to fulfil multiple mission types. Such applications include exploration [1] and inspection missions [2], surveillance or monitoring tasks like landmine detection [3] , border protection and law enforcement [4], infrastructure inspection [5], traffic surveillance [6], dumping detection of toxic substances and environmental disaster management [7]. The introduction of unmanned aircraft operations is probably the most revolutionary event in the aviation world from its early beginning. However, it is commonly recognized that Airspace Management and future ATM system will not be adapted to RPAS needs but rather, RPAS will need to fit in by complying with the rules and mandatory equipment to fly above 500 ft AGL under IFR or VFR. Conversely, SESAR-JU in Europe is developing the "U-Space", focusing on heights below 500 ft AGL, where services, procedures and equipment might perhaps be designed specifically for UAS/RPAS. In this U-Space, according to EUROCONTROL [8] special routes for RPAS may emerge in the future. Clearly the protection volume around the route would be smaller as a function of the accuracy and integrity of the navigation system.

Nowadays RPAS civil operations Beyond Visual Line of Sight (BVLOS) are usually limited to segregated airspace, while VLOS is allowed by several EU States, at least in uncontrolled airspace at a certain distance from aerodromes. UAS operators and manufacturers are still not so much concerned about the integration of certified avionics on-board since, in the 'specific' category, airworthiness certification is not necessary according to EASA [9]. Nevertheless, based on the fact that RPAS will be required to comply with certain functionalities and minimum operational performance like other airspace users in the same airspace volume, a future need for low weight certified avionic equipment is foreseen. In fact, in mentioned [9], proposed rule UAS.SPEC.110, already envisages the use of certified equipment (e.g. accompanied by an ETSO Authorization) on-board of non-certified unmanned aircraft. Once approved, this rule would legally apply to civil and not to public UAS operations. However, since in any case the ETSO Authorization is voluntary, market forces will decide whether manufacturers would benefit, for their business purposes, from such authorizations. ETSO articles suitable for relatively small UAS, may in the future also include navigation systems based on GNSS/SBAS, for which EASA ETSOs are already available [10]. Should these ETSOs not be perfectly adapted to drones, the EASA rules allow manufacturers to propose adaptations in the form of 'deviations', before ETSOs specific for drone equipment may emerge in the future. The main navigation technology present on most RPAS is GNSS. Using this type of receivers together with augmentation systems like SBAS (EGNOS) is an opportunity to increase the level of safety and performance of RPAS navigation. One of the positive consequences of the navigation performance requirements for RPAS could be the possibility to fly IFR procedures in accordance with its equipment, increasing the safety of the operation. Nowadays there is no criteria about instrument flight procedure design for RPAS but an adaptation from the current provisions for manned aircraft is proposed in this work.

In order to demonstrate the effective benefits and the applicability of GNSS augmented services to RPAS, REAL project started with the development a Concept of Operations whose main objective was to describe the operational and regulatory environment for unmanned aircraft thereby ensuring a common understanding inside the project of the challenges, and aims to achieve safe and regulatory compliant VLL BVLOS operations on UAS, supported by EGNOS.

On one hand, the objective of this research is to propose an instrument flight procedure design criteria for RPAS based on current procedure design provisions for manned aircraft. This new criteria should take into account the physical and operational unmanned aircraft differences with manned aircraft, as well as considering the REAL project scenarios as the initial application areas. On the other hand, this research aims at demonstrating the benefits that EGNOS can offer for the safe future integration of UAS in the airspace. These benefits may include:

- Greater accuracy and integrity in following the planned flight path and so enhanced safety for third parties in the air and on the ground;
- Greater situational awareness for neighbouring air traffic equipped with ADS-B in;
- Cooperative behaviour with manned large airplanes equipped with ACAS; and
- Reduced risk of losing the unmanned aircraft due to Controlled Flight Into Terrain (CFIT), which, although not strictly required by current safety regulations on UAS, is nevertheless a benefit for UAS operators, manufacturers and insurers.

With the aim of validating the navigation operation and in order to demonstrate the benefits that EGNOS could provide to RPAs operations, almost thirty flights in two different campaigns have been performed along this research.

II. EGNOS AND ITS APPLICATION TO RPAS NAVIGATION SYSTEMS

Global Navigation Satellite Systems (GNSS) have been the main positioning source in most applications over the last three decades. However, applications are progressively requiring higher accuracy requirements and, at the same time, lower price levels. For example, there are cases in remote sensing applications where it is necessary to achieve a level of accuracy below the meter. In the User Guide for EGNOS application developers [11], it is presented that the expected performance of the GPS signals uses to be between 7 and 13 meters, the conclusions of this study are presented in Table I.

TABLE I: GPS ACCURACY

	GPS Specifications	Real expected performance
Horizontal Accuracy	< 17 meters (95 %)	7.1 meters
Vertical Accuracy	< 37 meters (95 %)	13.2 meters
Time Accuracy	< 40 ns (95 %)	12 ns

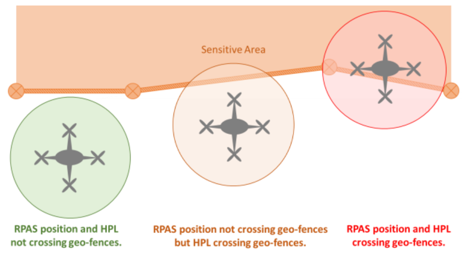

Figure 1. RPAS horizontal protection levels interference with geo-fencing.

In order to complement the GPS performance, numerous augmentation systems have been launched in the last decades. EGNOS (European Geostationary Overlay Service) is a SBAS system designed to complement the GPS positioning system improving the integrity and the positioning and timing service accuracy. The use of the EGNOS system jointly with GPS can provide a horizontal accuracy better than 3 meters and a vertical accuracy better than 4 meters at 95 % of the time. The use of EGNOS in navigation also is beneficial in the RPAS approach and landing phases. In these phases, EGNOS can enable a higher precision using procedures similar to LPV-200 [12]. This allows safer operations in flights Beyond Visual Line Of Sight (BVLOS) where the pilot is not able to see the aircraft during the landing phase. The high-level performance of EGNOS system can support in demonstrating the safety of this type of operations. By last, EGNOS also can help to improve the geo-fencing capabilities of the guidance module. Geo-fencing concept aims to use geographical information to establish boundaries or fences, to prevent hazardous RPAS flights in sensitive areas. This could be used to limit flights near airports, or above certain altitudes. The navigation positioning solution, based in EGNOS, provides the means to better determine whether the RPA is crossing a geo-fence by assessing not only the position computed, but the protection levels. Hence, even if the RPAS calculated position is outside a sensitive area, the protection levels may lay inside, meaning that RPAS may be really crossing a geo-fence area (see Figure 1).

III. RPAS NAVIGATION SPECIFICATION ASSESMENT

Airspace concepts are the operations performed within an airspace aimed to fulfil strategic aviation objectives such as safety and efficiency improvement, air traffic increase or environmental impact mitigation. In order to satisfy these objectives, specific requirements have to be achieved by the airspace concept itself. Navigation requirements can be satisfied using different tools, such as conventional or performance-based navigation (PBN). The former (conventional) approach prescribes a list of receivers to be carried on-board (e.g. ADF, ILS, VOR, etc.). With the progress of technology, since around 1990 ICAO is promoting PBN (initially labelled RNP). Current EASA rules prescribe indeed a navigation performance, but not a list of receivers. Therefore, the PBN concept is chosen for RPAS navigation, considering that GNSS is the most widely used navigation technology in the RPAS sector. Then, this section aims to define a first proposal of a navigation specification (NAVSPEC) tailored to the performance of a drone equipped with the Navigation Surveillance System (NSS) developed in this project.

A GNSS RNAV NAVSPEC (RNAV and RNP) defines the size of the areas that protect the instrument flight procedure designed trajectory in the horizontal domain. The RNP NAVSPECs define the lateral total system error (TSE) value limits where aircraft must be contained for at least 95% of the total flight time (i.e. for RNP 0.3, lateral TSE and along-track error will not exceed ±0.3 NM for at least 95% of the total flight time). The TSE is dependent upon position estimation error (also known as navigation system error (NSE)), path definition error (PDE) and flight technical error (FTE):

$$TSE = \sqrt{FTE^2 + NSE^2 + PDE^2} \quad (1)$$

- **PDE** occurs when the path defined in the aircraft database does not correspond to the desired path. PDE is usually sufficiently small that it could be safely ignored, even in accuracy –demanding approach phase of flight.
- **NSE** refers to the difference between the aircraft's estimated position and the true position. It is defined at the output of the navigation receiver and therefore it includes both Signal In Space (SIS) and airborne equipment error. This is dependent on the accuracy of the inputs to the position solution, such as the accepted accuracy of GNSS measurements. For GNSS-based RNP systems, the NSE is small and the FTE is the dominant component.
- **FTE** refers to the ability of aircrew or autopilot to follow the defined trajectory, including any display error. The FTE component value is assumed based on data from flight tests as mentioned in RTCA MOPS for GPS which are too conservative with respect to current navigation systems as it will be commented later on.

Figure 2 shows graphically how it is calculated the Total System Error.

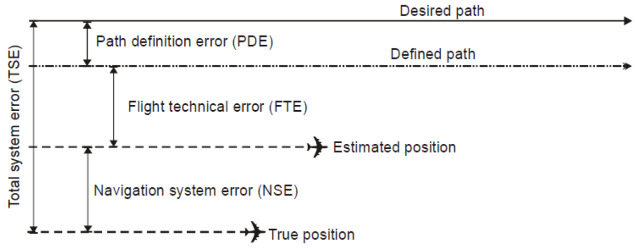

Figure 2. Total System error.

The criteria followed to demonstrate that the new horizontal and vertical protection parameters values are adequate for small RPA performance and characteristics is validated from the data gathered through the first campaigns of flight validations. With these data, it was possible to define the TSE suitable for small drones basing on the following assumptions:

- FTE considered is the highest value of the 95-percentile HFTE values obtained in all the flights previous to the final test campaigns performed during the project REAL. Thus, the **FTE is 11.45 meters**. A safety parameter multiplying this value is considered due to the small number of flights performed to obtain it, which is not representative at all to model the FTE correctly. The **safety margin parameter selected is n = 3**.
- **NSE assumed value is 3 meters**, which corresponds to the EGNOS Safety-of-Life horizontal accuracy 95-percentile value described in EGNOS Service Definition Document.
- **PDE is neglected**.

Finally, and using all the parameters described above, the computed TSE is 34.48 meters (0.02 NM), which is translated into RNP 0.02 NAVSPEC.

IV. EQUIPMENT

This section briefly describes the different systems and equipment used along this research work. It is important to note that two different RPA were used, one for each campaign of flights. This decision was taken in order to evidence that the developed navigation system can be easily integrated and used in any platform. Also this decision gives the opportunity of obtaining data from different flight dynamics and locations.

A. Drone used during the first campaign: AIRCATEC

The drone used during the first campaign of flights was a completely electrical 4-rotor multicopter. This drone has a maximum takeoff weight of 24kg and a payload of up to 16 Kg. It was specifically designed for being able to fly up to 48 minutes. In Figure 3 it is shown this RPA.

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Figure 3. AirCATEC RPA deployed in ATLAS test area.

B. Drone used during the second campaign: Sharper A6 RPA

This aircraft is a 6-rotor vehicle powered by electric motors driving fixed-pitch propellers with a takeoff weight of 18kg. It is capable of fully automated consolidated inspection missions having a flight time for inspection up to 30 minutes with full sensor payload.All GPS and communication antennas are external of the carbon fiber aircraft body, aligned for maximum signal propagation. Figure 4 shows the Sharper A6 from SharperShape.

Figure 4. Sharper A6 RPA deployed in Kirkkonummi test area.

C. EGNOS-based Navigation and Surveillance System

This system has been developed as an independent module capable of being installed easily into any type of RPAS as payload. The Navigation and Surveillance System (NSS) has been designed using a general purpose ABS plastic instrument case, which is manufactured using two-part clam shell construction. The front panel holds all the different connectors used to interface with it, while the back panel provides a glass window to check the battery status together with a small micro USB connector for its charge. This system is presented in Figure 5.

Figure 5: NSS front view.

The NSS is composed of the following elements:

- **GNSS multi-constellation, multi frequency, professional receiver:** This is the GNSS receiver used by the platform to receive GNSS data and compute the aircraft position during its operation.
- **Mass market GNSS receiver:** This is the GNSS low cost receiver which performances have been compared with professional multi-frequency and multi-constellation GNSS receiver results.
- **High-end Inertial Aided GPS Sensor:** a high-performance, miniature, Inertial Aided GPS Navigation System (GPS/INS) that combines micro inertial sensors and a high-sensitivity embedded Global Positioning System (GPS) receiver.
- **On-board processor:** This is the processor unit that is used by the platform to run the software packages and to interface with the GNSS receivers.

D. GNSS Simulator

This is a portable and versatile multi-constellation Global Navigation Satellite Simulator which is able to record and replay real world data, allowing realistic and repeatable testing to be carried out under controlled conditions. Labsat 3 was used to record GNSS data on ground during the conduction of demonstrations and was also integrated in the RPA for post-flight analysis.

E. Drone Controller

AIRCATEC drone is equipped with the Pixhawk autopilot (see Figure 6), a high-performance autopilot-on-module suitable for fixed wing, multi-rotors, helicopters, cars, boats and any other robotic platform that can move. In this project, it has been used as the controller of the UAV motors. The communication of this system with the NSS and GCS was done by the Mavlink protocol. Also, it has integrated accelerometers, gyroscopes, magnetometers and barometers and all its telemetry is logged during the flight.

Figure 6. AIRCATEC Pixhawk autopilot.

V. FLIGHT TEST SCENARIOS AND PROCEDURES

One of the main objectives of REAL was to obtain as much data as possible from multiple experiments to verify that the developed EGNOS based navigation system is able to improve the performance of those navigation systems whose positional solution remains only in the GPS constellation. In order to increase the casuistry of the data obtained, the experiments were planned in different dates, and different weather conditions.

A. *Scenario*

The first experimental flights were conducted in ATLAS [13] (Air Trafic Laboratory for Advanced unmanned Systems), a Test Flight Centre located in Villacarrillo (Jaen, Spain) which offers the international aerospace community an aerodrome equipped with excellent technological-scientific facilities and airspace ideally suited to the development of experimental flights with unmanned aerial vehicles. The second campaign was conducted in a rural area of Kirkkonummi, located at 26 km from Helsinki. The area, crossed by a power line, is a space where researchers usually perform test flights.

B. *Flight Data Analysis*

During the flight campaign, several flight plans were created in order to study the results obtained from different routes, velocities, locations, etc. This section performs an analysis of the flight data extracted from the navigation system box. Due to during this research more than twenty flights were carried on, in this article just a flight per procedure will be shown.

1) *ATLAS LONG ROUTE*

This flight procedure is part of the ATLAS flight campaign. It consists of a departure, a route and an approach. The purpose of conducting this procedure is to execute a flight plan similar to the one that could be used in a firefighting activity, where the RPAs shall departure from a base station, follow a route to the emergency location, and then come back to the base station. This procedure was conducted just one time because of its large length (6 km) and the limited RPAs operation time. In Fig. 7 it is shown the commanded route and the trajectory followed by the drone. In this figure it is also shown the basic information of the flight procedure.

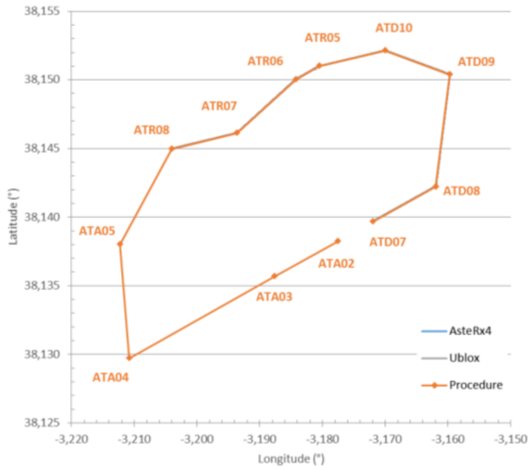


Figure 7. Flown trajectory and theoretical procedure of ATLAS_LONG_ROUTE. Due to the large dimensions of the trajectory, and the small deviations, there is no significant differences between the flown trajectory and theoretical procedure).

2) *ATLAS MEDIUM ROUTE*

This procedure corresponds to a medium-size route, formed by four segment legs deployed around the departing point. These aim to emulate a reduced version (1700m) of ATLAS_LONG_ROUTE, allowing performing multiple flights without RPAS operation time limitations. This procedure was conducted 8 times using different configurations. Fig. 8 depicts the flight plan loaded in the navigation system and the trajectory followed by the drone in the flights performed.

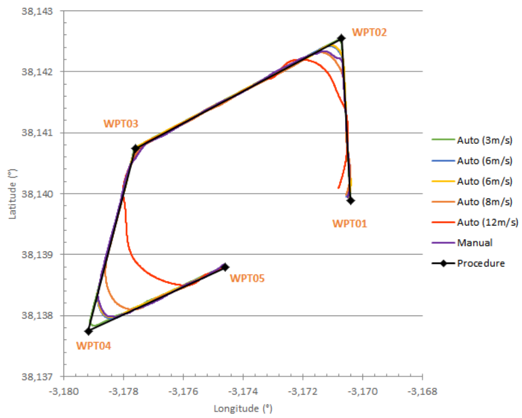


Figure 8. Flown trajectory and theoretical procedure in the different flights of ATLAS_MEDIUM_ROUTE.

3) *ATLAS SHORT ROUTE*

This flight procedure corresponds to a short procedure (419m), formed by three segment legs of 150m length, deployed around the departing point. This short procedure was designed aiming to be used during the first validation flights, while keeping the RPA close to remote pilot for safety reasons. This procedure was conducted one time. Fig. 9 shows the basic information about this procedure.

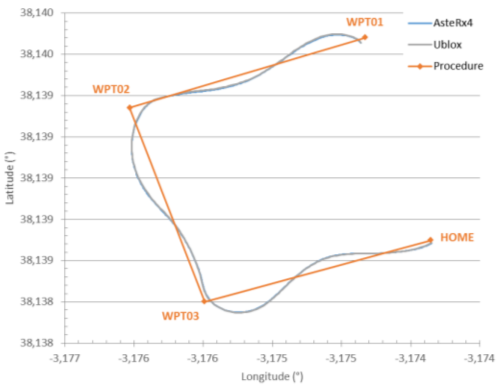


Figure 9. Flown trajectory and theoretical procedure of ATLAS SHORT ROUTE.

VI. RESULTS

In order to conduct a detailed presentation of the analysis outcomes, these are gathered under the following subsections together with the identified drawbacks and the lessons learned.

A. *Flight Deviations*

The tables below gather the HFTE and VFTE per each flight with the aim to facilitate the comparison and procurement of general results.

TABLE II. Horizontal Flight Technical Error Or HFTE (M). LR Stands For Long Route; MR For Medium Route And SR For Small Route

Flight	LR 6m/s	SR 8m/s	MR 3m/s	MR 6m/s	MR 6m/s	MR 8m/s	MR 12m/s	Manual
Maximum	8,68	4,82	4,00	3,52	4,40	5,09	8,29	11,20
Minimum	0,00	3,30	0,01	0,00	0,02	0,00	0,00	0,01
Average	2,32	4,14	1,89	1,18	1,74	1,41	2,70	2,25
Median	2,30	4,19	2,11	1,12	1,67	1,23	1,74	1,67
Percentile 95%	4,25	4,75	3,10	2,32	3,32	3,97	7,76	5,95

By analysing the flight trajectories and the calculated FTE parameters the following statements can be highlighted:

- In the lateral plane, the HFTE are quite low, and the error variations when transitioning from a straight segment into a turn are relatively small. This is thanks to the improvement of the NSS Box guidance algorithm during the turns.
- There is no significant correlation between RPA speed and HFTE. Average HFTE keeps below 2m, except for 12m/s.
- In the vertical plane, it is observed a relevant deviation in most of the flights, indicating that the GNSS altitude is always a few meters below the desired altitude (negative VFTE). One of the factors that was causing this effect was the altitude difference between both local reference positioning solutions (NSS Box and RPAs autopilot). As this issue was solved, the remaining factor related to vertical deviations is the difference between the altitude computed by NSS Box and the one computed by RPA autopilot.

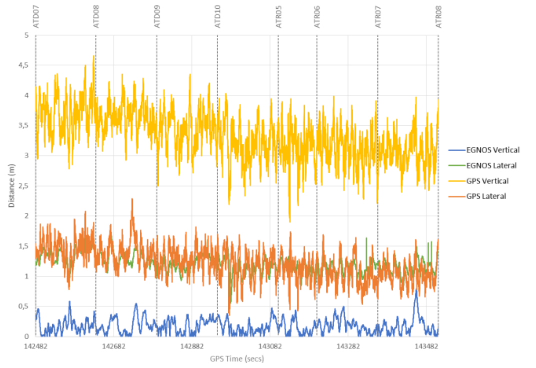
TABLE III. Vertical Flight Technical Error (M). LR Stands For Long Route; MR For Medium Route And SR For Small Route

Flight	LR 6m/s	SR 8m/s	MR 3m/s	MR 6m/s	MR 6m/s	MR 8m/s	MR 12m/s	Manual
Maximum	4,04	11,3	12,63	8,38	4,53	11,05	14,12	-
Minimum	0,00	0,03	6,33	3,80	0,00	7,90	10,87	-
Average	2,13	4,60	8,09	5,73	1,17	9,40	12,08	-
Median	2,20	4,19	7,29	5,69	0,82	9,49	12,13	-
Percentile 95%	3,62	10,6	11,76	8,02	4,44	10,86	12,89	-

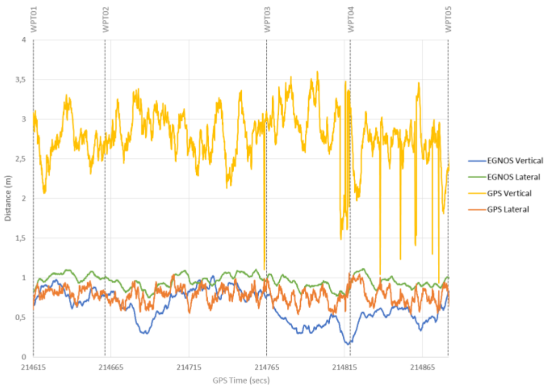
It is important to note that the RPA does not only rely on GNSS but also on other systems (inertial measurement unit, barometer) in order to compute its global position. Hence, this position is a mix of multiple solutions which are internal balanced by the RPA to obtain a global one which, in some cases, differs from the GNSS solution. Then, it shall be considered that the VFTE assessed and presented in this report is not purely based on GNSS altitude reference.

B. *GPS vs EGNOS-based navigator*

Aiming to assess which are the benefits provided by EGNOS during the RPAs operation, it was computed the GPS trajectory solution (without using EGNOS) for a couple of flights per campaign. This solution was processed based on the GNSS raw data recorded by the professional GNSS receiver processed through the GNSS Eurocontrol toolset PEGASUS [14]. At the same time, the precise trajectory followed by the RPA was obtained through a post-processed kinematic (PPK) assessment, performed with Novatel Inertial Explorer version 8.70 in differential processing mode using both GPS and GLONASS constellations when available. Two base stations and precise GNSS files were used for each trajectory processing. Solutions in forward & reverse directions were calculated and combined. In this framework, the diagrams and tables below aim to present the differences between the precise trajectory and the positioning solution computed by each GNSS receiver. Figure 10 aims to present the differences between the precise trajectory and the positioning solution computed by using EGNOS and the GPS solution in two flights of the first campaign.



(a)

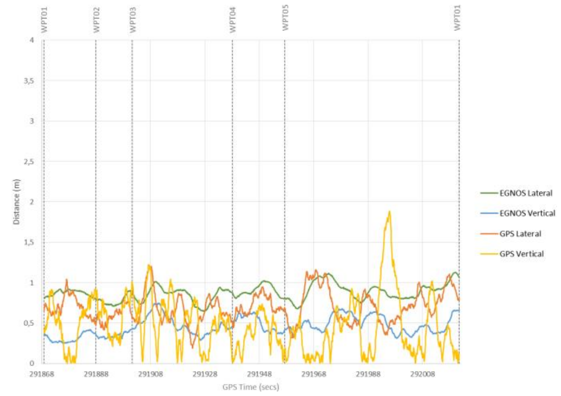


(b)

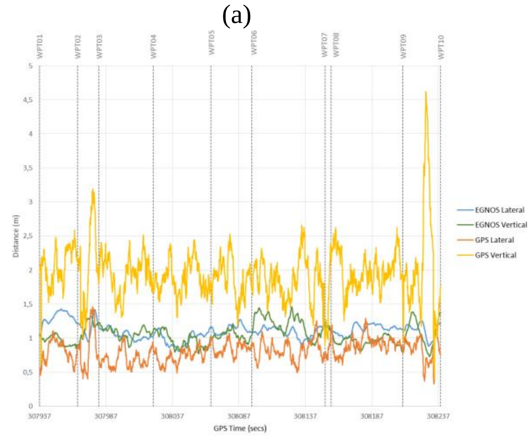
Figure 10. Difference between PPK trajectory and EGNOS/GPS positioning solutions in (a) flight 2 and (b) flight 4 of the first campaign of flights.

As can be observed, lateral deviations from both solutions are similar on the average values; however, in GPS solution, the value dispersion is slightly higher, obtaining a small increment in the 95th percentile. On the other side, noticeable differences are obtained in the vertical axis, where GPS solution increases the error between 2m and 3m from EGNOS solution. The results for the second campaign of flights are shown in Figure 11.

As can be observed, in flight 4 the deviations from both solutions are similar on the average values; however, on the vertical axis, GPS reaches a maximum of 1.8m while EGNOS solution maximum remains at 0.7m. Then, in flight 15, noticeable differences are obtained in the vertical axis, where GPS solution increases the average error around 1m from EGNOS solution, while reaching maximums of 4.6m. To summarize the obtained results, in Table IV it is shown the numerical difference between the PPK trajectory and the EGNOS/GPS positioning solutions.



(a)



(b)

Figure 11. Difference between PPK trajectory and EGNOS/GPS positioning solutions in (a) flight 4 and (b) flight 15 of the second campaign of flights.

TABLE IV. Difference Between PPK Trajectory And EGNOS/GPS Positioning Solutions

	C1 Flight 2				C1 Flight 4			
	EGNOS		GPS		EGNOS		GPS	
	H	V	H	V	H	V	H	V
Maximum	1,68	0,79	2,29	4,66	1,83	2,16	1,82	5,47
Minimum	0,55	0,00	0,36	1,90	0,67	0,00	0,43	0,00
Average	1,20	0,17	1,22	3,34	1,04	0,75	1,00	2,72
Median	1,20	0,15	1,21	3,33	1,07	0,70	0,95	2,79
Percentile 95%	1,47	0,39	1,65	3,97	1,18	1,23	1,51	4,24
	C2 Flight 4				C2 Flight 13			
Maximum	1,13	0,75	1,21	1,88	1,43	1,46	1,46	4,62
Minimum	0,64	0,25	0,19	0,00	0,81	0,73	0,33	0,39
Average	0,87	0,46	0,69	0,47	1,11	1,05	0,81	1,94
Median	0,88	0,43	0,67	0,44	1,12	1,03	0,81	1,92
Percentile 95%	1,07	0,65	1,07	1,04	1,32	1,34	1,07	2,48

VII. CONCLUSIONS

Summarizing, from the results obtained, it has been possible to define an RPAS RNP 0.02 navigation specification, a value below the challenging RNP 0.1 which was defined at the beginning of the project. Apart from that, By comparing EGNOS versus GPS positioning solution, it is identified that EGNOS provides noticeable benefits, especially on the vertical axis by reducing the error around 2m. In that way, it is possible to conclude that EGNOS improves the navigation and surveillance functions of a RPA by introducing the following benefits:

- In the RPAS approach and landing phases, EGNOS can enable higher precision using procedures similar to LPV-200. This allows safer operations in BVLOS where the pilot is not able to see the aircraft during the landing phase. The high level performance of EGNOS system can support in demonstrating the safety of this type of operations.
- The use of EGNOS improves the accessibility to sites affected by low visibility and improved safety through EGNOS vertical guidance and reduced landing minima.
- The use of EGNOS could improve significantly the accuracy of the geo-fencing mechanism thus increasing the level of safety.
- EGNOS could improve the reliability and accuracy of the information transmitted to other airspace users using ADS-B. This could in turn support a safer traffic separation function, either under ATC or RPA pilot responsibility.

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