CONTRIBUTION TO THE OPERATIONAL EVALUATION OF EGNOS AS AN AERONAUTICAL NAVIGATION SYSTEM

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Keywords: *satellite navigation, operational evaluation, flight testing*

Abstract

This paper describes the Portuguese contribution to the European Geostationary Navigation Overlay Service (EGNOS) operational validation, within the EGNOS Data Collection Network (EDCN). The network and the methodology used are briefly presented, as well as some static performance results. A more detailed description will be devoted to early flight trials, with a description of the procedure and preliminary results.

1 Introduction

The European Geostationary Navigation Overlay System (EGNOS), the European Satellite-Based Augmentation System (SBAS) to GPS, is currently in its final phase of testing and will be operational in Spring 2007. This Wide Area DGPS (WADGPS) will be capable of providing GPS single-frequency users in Europe, namely from the aviation domain on the European Civil Aviation Conference (ECAC) area, with integrity information and position accuracy down to one metre.

The European Organisation for the Safety of Air Navigation (EUROCONTROL), as a part of its commitment to the European Tripartite Agreement with the European Commission and the European Space Agency (ESA) [1], is responsible for the coordination of EGNOS operational validation for civil aviation, including all the activities that will demonstrate that EGNOS is ready to be used and to support the flight operations for which it is intended. The involvement of EUROCONTROL occurs in collaboration with the European Air Traffic Service Providers (ATSP) aiming to validate and offer navigation services based on EGNOS in their airspace. Two workgroups have been established (GOV Working Group and ESV Task Force) and two distinct areas of work have been identified as required and complementary to support the implementation of EGNOS services for civil aviation in European airspace.

- Technical validation of the performance that can be achieved using the EGNOS system. This will include a demonstration that the implemented system is compliant with the requirements defined by civil aviation in the International Civil Aviation Organization (ICAO) Global Navigation Satellite System (GNSS) Standards and Recommended Practices (SARPs) document [2]. Those requirements are expressed in terms of Required Navigation Performance (RNP) parameters for each phase of flight, from En-Route to CAT-I precision approach. The RNP parameters are accuracy, availability, integrity and continuity of service.
- Definition of operational rules and procedures for aircraft to use the system for a particular application.

The work presented in this paper is mainly related to the first point, the technical validation. EUROCONTROL is contributing to this validation with the establishment of EGNOS Data Collection Network (EDCN) [3], which has the responsibility for defining and implementing a methodology to assess and validate the performance that can be achieved using the EGNOS system, i. e., the EGNOS operational validation.

The Portuguese contribution for the EGNOS operational evaluation, occurs in the frame of EDCN and involves the Portuguese Flight Test Workgroup (*Grupo de Trabalho de Ensaios em Voo* - GTEV), from the Technical University of Lisbon, in collaboration with the Portuguese Air Force (PoAF) and the Portuguese ATSP, NAV Portugal. They are responsible for the EGNOS data collection and evaluation in Portugal, including the Madeira and Azores islands, using the established methodology with long term static evaluations. Additionally, they are also responsible for doing flight trials, using several PoAF instrumented aircrafts.

The paper briefly describes the EDCN and adopted methodology for the EGNOS operational evaluation. The experimental setup used in Portugal and some results, from static evaluation and flight trials, will also be described.

2 EGNOS as an Aeronautical Satellite Navigation System

The primary design objective of the EGNOS satellite navigation system, which is to become operational by 2007, is improvement of safety, allowing its application in the aviation domain. As mentioned before, EGNOS is the European Satellite Based Augmentation System (SBAS) covering the ECAC area and is being developed by the ESA in co-operation with the European Commission and EUROCONTROL.

In an SBAS system, as EGNOS, a ground segment collects and processes the augmentation information. This information is transmitted to the users by geostationary satellites, in a GPS-like signal, allowing range measurements and containing correction data to be applied on the visible satellites navigation data, as for example pseudorange and ionospheric corrections, enabling users to compute their position with one metre accuracy level. Particularly relevant for aviation applications, as safety-of-life application, the augmentation signal contains also integrity information. This integrity information provides users with a certified error bound for their position estimate and is structured in such a way that it is able to meet a six-second time-to-alarm.

EGNOS is currently in its initial operation phase (IOP) and is being handed over to a commercial operator, the European Satellite Services Provider (ESSP) [4], and is arriving to nominal operation status and stabilization of the Signal-In-Space.

3 EGNOS Operational Evaluation

Before the deployment of the EGNOS system, ESA implemented the EGNOS System Test-Bed (ESTB) [5] as a limited EGNOS prototype, with a limited number of monitor stations. From February 2000, the ESTB has been providing a Signal-In-Space supporting the system development as well as giving potential users an opportunity to gain experience with EGNOS-like signals. This allowed the initiation of various activities in preparation for the EGNOS validation, namely in the frame of the GNSS-1 Operational Validation (GOV) Working Group [6]. EUROCONTROL has developed some tools for the evaluation of the EGNOS system performance and has coordinated data collection campaigns. Two major conclusions result from these initial developments [7]:

- data collection and processing must be standardised;
- data collection must be performed on a more regular basis, in order to establish a good understanding of performance of an SBAS Signal-In-Space over a longer time period and over an area with a good geographical distribution.

Presently, the EGNOS Signal-In-Space Validation (ESV) Task Force, established by the EUROCONTROL, coordinates all activities necessary to assess the performance achievable with a Radio Technical Commission for Aeronautics (RTCA) Minimum Operation Performance Standards (MOPS) DO-229 [8] compliant receiver over the European Civil Aviation Conference (ECAC) Area. The objective of this performance assessment is to support the use of EGNOS, namely on aviation domain, as a navigation satellite system providing guidance up to the so-called APV-II approach operations (APV - Precision Approach with Vertical Guidance), as defined by ICAO. The ESV Task Force will coordinate and agree with the EGNOS Certification Task Force the required input to provide evidence that the EGNOS Signal-In-Space meets integrity and continuity requirements and can be used for safety critical applications.

From these activities resulted the establishment by EUROCONTROL of the EGNOS Data Collection Network (EDCN), as a standardized data collection environment to perform continuous EGNOS performance assessment.

3.1 The EGNOS Data Collection Network

The EDCN (figure 1) presently includes six Universities, each one related with a data collection site, Barcelona, Budapest, Delft, Lisbon, Sofia and Toulouse, assuring the performance evaluation over an area with a good geographical distribution. The overall coordination is assured by PILDO LABS, and additionally some other data collection sites, as one in the EUROCONTROL Experimental Centre and those controlled by the ATSP, are contributing to the overall performance evaluation. The added value of this work lies in the independence of the data collection sites with respect to the EGNOS Ranging and Integrity Monitoring Stations (RIMS) locations and a greater diversity of the receivers and analysis tools.

For each data collection site, the data collection environment was assessed and a normalized setup was implemented, composed of a L1/L2 antenna, a SBAS receiver connected to a computer, with the needed software to log and process the data from the receiver installed. The antenna position coordinates were precisely surveyed at centimetre level, and a multipath assessment was done to identify:

- best antenna location for each site;
- conformity related to the multipath figures defined on the RTCA MOPS DO-229 document, and related to a typical application in a aircraft;
- to characterize its possible error effect on the measurements.

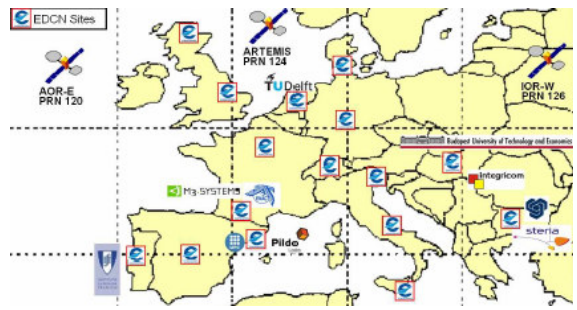

Fig. 1. The EGNOS Data Collection Network

3.2 Methodology

The EDCN structure, with all other additional EGNOS data collection sites, will be the baseline for the validation monitoring activities that will be performed in the frame of the EGNOS operational validation, aiming to demonstrate the user's requirements defined in ICAO SARPS. According to the adopted methodology, a series of static measurements will be made over extended periods in order to:

- establish the performance of the system that would be experienced by a potential user;
- verify the stability of the performance in a certain time period.

These long-term static data collection campaigns are performed in several monitor stations, basically consisting in a receiver, an antenna and a computer set, with the ability to receive GPS L1/L2 and EGNOS signals.

All data processing, analysis and reporting are done automatically in a daily basis, according with the RTCA MOPS DO-229 standard and using some software developed by EUROCONTROL. As shown in figure 2, the EGNOS performance is evaluated according to the Required Navigation Performance (RNP) requirements, *up axis*, involving several assumptions in the definitions of those parameters from the ICAO SARPs document. As mentioned before, these RNP requirements are defined in terms of accuracy, availability, integrity and continuity of service. Additionally, any anomalies identified are analysed in detail, *down-left axis*, to assess the cause, the probability of re-occurrence and possible mitigation techniques from the user's side. Finally a global assessment is performed based on the local and daily data sets, *down-right axis*, addressing the spatial and temporal stability of the system performance by combining the measured results on different locations with extrapolation of the results.

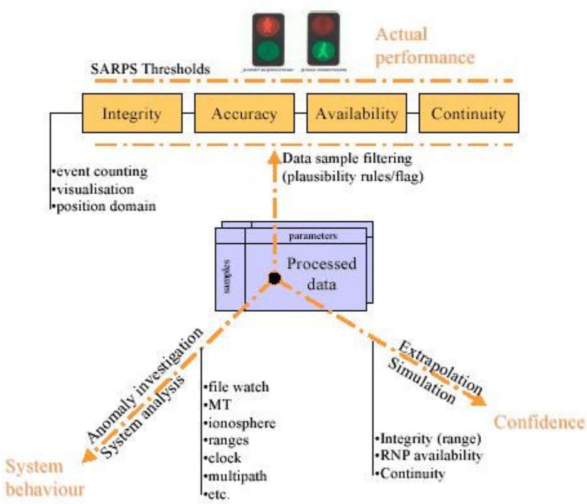

Fig. 2. EGNOS data analysis methodology

Flight experiments are necessary and performed to validate the applied methodology, verifying that the performance experienced on static survey is also achieved in the dynamic conditions representative of a typical airborne user.

4 EGNOS Operational Evaluation in Portugal

One of EDCN members is the Portuguese Flight Test Workgroup (*Grupo de Trabalho de Ensaios em Voo* - GTEV) from the Technical University of Lisbon. GTEV, in collaboration with the Portuguese Air Force (PoAF) and the Portuguese ATSP, NAV Portugal, is responsible for the EGNOS data collection and evaluation in Portugal, including the Madeira and Azores islands, using the established methodology with long term static evaluations.

4.1 Lisbon EGNOS Monitor Station

In Lisbon one permanent static monitor station was setup near the EGNOS RIMS station, located in Lisbon Airport. In this location, a NOVATEL MILLENIUM OEM3 receiver is normally used, with a NOVATEL L1/L2 600 antenna (IST3 reference site). This is a L1/L2 receiver with 10 GPS channels and 1 geosatellite channel. Data are collected using a computer with the NOVATEL SLOG program with a special script.

Alternatively, in this same location, a SEPTENTRIO POLARX-2 receiver (IST4 reference site) could also be used. This is a L1/L2 receiver with 12 GPS channels and 3 geosatellite channels. Data are collected using one computer and the SEPTENTRIO RXCONTROL program.

The SEPTENTRIO receiver includes a real-time processing program that generates a navigation solution according with MOPS but this EGNOS navigation solution is not usually used. EGNOS data collected in this permanent site are automatically processed, analysed, reported and transferred to the EUROCONTROL. To allow these operations EUROCONTROL DOIT and PEGASUS [9] software packages are used. The later one includes the GNSS SOLUTION program, which is a software receiver computing position and integrity solution in accordance with the RTCA MOPS DO-229 standards, from the receiver raw data.

The multipath figures in this location were evaluated, with the support of the team from the Technical University of Delft (TU Delft) using its strong experience in this domain. The result figures (figures 3 and 4) exhibit several sources of multipath, mainly due to east ground reflections, that could be minimized using an antenna choke ring or a different location of the antenna.

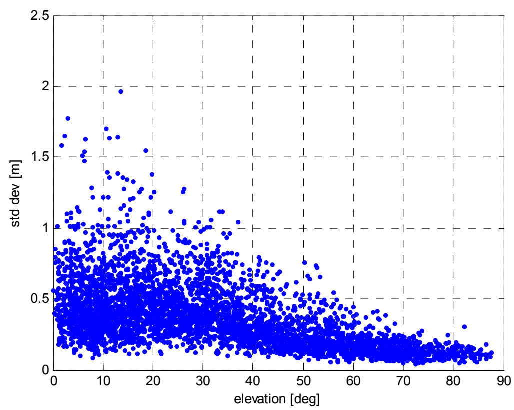

Fig. 3. Multipath standard deviation versus satellite elevation

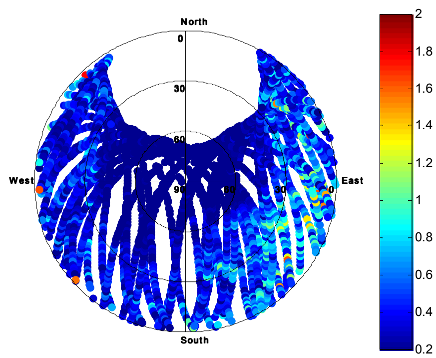

Fig. 4. Multipath standard deviation skyplot

The overall conclusion is that exhibited multipath figures are acceptable when compared to RTCA MOPS DO-229 requirements.

4.2 Example of Daily Results

The EGNOS performance exhibited in Lisbon is exemplified by results obtained from data collected in the Lisbon permanent monitor station on 9 June 2006, with EGNOS data broadcast by geosatellite IOR-W PRN126 and using the SEPTENTRIO POLARX-2 receiver. In the graph on figure 5 are presented the horizontal position error (HPE - blue), horizontal protection level (HPL - green) and number of satellites used to generate the EGNOS navigation solution (NSV - pink). The 95th percentiles are 1.24 m (HPE) and 22.94 m (HPL). Figure 6 shows results for vertical situation. The 95th percentiles are 1.74 m (VPE) and 35.41 m (VPL).

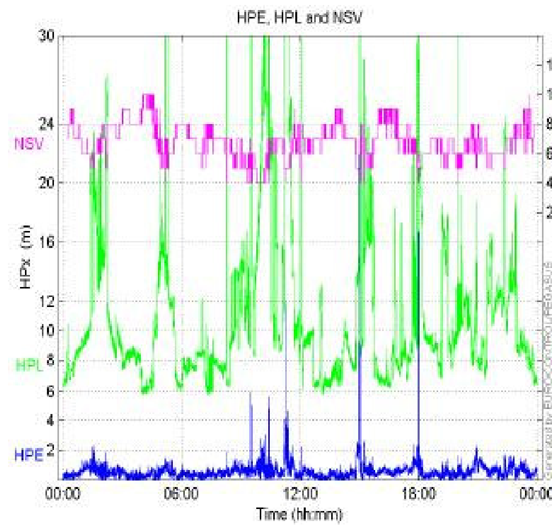

Fig. 5. Horizontal EGNOS performance versus time

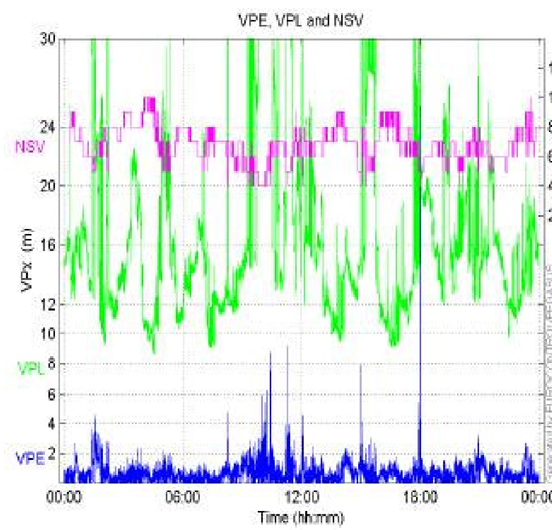

Fig. 6. Vertical EGNOS performance versus time

For each specific flight operation category, SARPS defines the Alert Limits (AL), for both horizontal and vertical situations (HAL and VAL). If in a given instant the Navigation Error is smaller than corresponding Protection Level and this is smaller than Alert Limit, then in this instant EGNOS provides a valid navigation solution for the corresponding flight operation type. Note that when the EGNOS system will be used on aircraft approaches of a given precision type, if the Protection Level exceeds the corresponding Alert Limit, an alarm is raised and the approach can not proceed. If the approach has already begun, this condition implies a continuity failure and a missed approach procedure must be conducted.

Otherwise the system is declared unavailable for that period.

If in a given instant Position Error exceeds Protection Level, this means a Misleading Information (MI) occurrence. If Position Error is larger than Protection Level and also larger than required Alert Limit, for a specific flight operation, than this is a case of Hazardous Misleading Information (HMI), which could lead to dangerous situations.

The presented figures show that daily EGNOS system performance in Lisbon was bad in several periods. This was due to local effects related to poor GPS satellite geometry exhibited during these periods, which leads to a small number of used satellites, only four in several periods. This was due to the fact that in that periods only this number of satellites had more than ten degrees elevation related to Lisbon. Then the produced EGNOS navigation solution exhibited high navigation errors and high protection levels, allowing to a non-availability of the system for the planned flight operation modes. In a near future, the EGNOS geosatellites will broadcast ranging information allowing its usage on the EGNOS navigation solution as navigation satellites. This situation has to be tested but since the number of satellites used on the EGNOS solution will be greater and some of these satellites, as they are geosatellites, have fewer errors associated with its position, the produced EGNOS navigation solution will have smaller errors and protection levels and the performance system results will be better.

The availability Stanford plot for the vertical axis (figure 7) shows the relation between the VPL, VPE and AL for the same daily EGNOS dataset. Only the vertical situation is showed, because it is the most demanding for aeronautical applications. On horizontal axis is the VPE and on vertical axis is the corresponding VPL, for each computed EGNOS navigation solution. Horizontal and vertical lines, corresponding for the VAL associated with each flight operation type, precision approach CAT-1 (12m), non-precision approach APV-II (20m) and APV-I (50m), are also represented. The colour of each point in the graph tabulates the number of occurrences of a specific pair. Note that the colour scale is logarithmic.

The presence of points on the right of the leading diagonal corresponds to dangerous situation, i. e., MI or HMI occurrences. For the presented EGNOS daily dataset no MI or HMI have occurred, as desired.

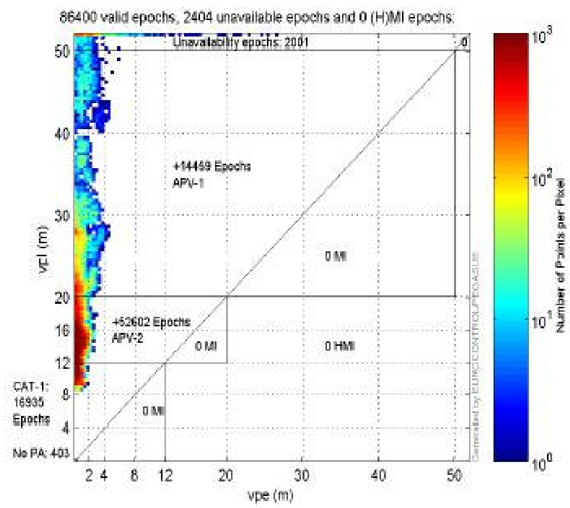

Fig. 7. Availability Stanford plot for the vertical axis

The graph demonstrates also the availability of the system for each flight operation type, by the location of each pair sample. The number of samples for which the EGNOS system is available is respectively 16935 (CAT-I), 69537 (APV-II) and 83475 (APV-I) which corresponds to a measured 19.6%, 80.5% and 96.6% availability figures. These values are well below the required availability values, which are 99% for each flight operation type. Note that the EGNOS was not yet in a full operational status.

4.3 EGNOS non-Permanent Monitors Stations

For system development and test purposes, one test monitor station was installed in the military area of the Lisbon Airport. All available equipment could be installed and used in this test site. Normally up to two NovAtel L1/L2 600-LB antennas are used.

As the GTEV and local partners are responsible for the EGNOS operational evaluation in all Portuguese area, after the operationally of the EGNOS system, the realisation of static monitoring campaigns is planned for several locations in Portugal, including Madeira and Azores Islands. These static campaigns will occur in limited time periods, typically one week. For these static evaluations a NovAtel Millenium OEM3 receiver and one NovAtel 600-LB antenna will be used. As usual, the data will be collected in a computer, using the NovAtel SLOG program.

5 EGNOS Flight Trials

Additionally, GTEV in collaboration with the PoAF flight squadron 504 is also responsible for the realization of some flight trials in the frame of the EGNOS operational evaluation and using several instrumented aircrafts. The EGNOS data are collected with the available EGNOS experimental receivers, installed in the instrumented aircrafts, using its internal memory or with airborne computers.

To evaluate the EGNOS position accuracy, the aircraft truth reference trajectory could be determined using three available methods.

- NovAtel RT-20 L1 real time differential GPS system. This system consists basically in one NovAtel RT-20 onboard receiver, one antenna and one radio modem. On the ground, one of up to three NovAtel reference stations were used, consisting basically in one NovAtel RT-20 receiver and one radio modem.
- Trimble Total Control differential GPS software. The aircraft truth reference trajectory could be evaluated using the differential GPS Trimble Total Control software with dual-frequency carrier phase reference data collected in several GPS reference stations, like those installed in the Technical University of Lisbon.
- Precise Point Positioning (PPP) software [10]. In a near future, when the EGNOS system becomes operational, for some flights the aircraft's truth reference trajectory would be evaluated using the PPP software from the TU Delft. This method will be applied by the EDCN TU Delft partners and will allow a one meter accuracy determination of the aircraft's truth reference trajectory, for a complete flight regardless of the existence of ground GPS reference stations.

5.1 Dassault Falcon 20

Until recently, a PoAF Dassault Falcon 20, normally used in verification and calibration of navigation aids, was used on the evaluation of ESTB. In addition to the extensive instrumentation system of this aircraft, two NovAtel L1/L2 512 and L1 514 antennas were installed, allowing the usage of the various available EGNOS experimental receivers in this aircraft (figure 8). This aircraft is presently in a non-operational status.

Fig. 8. PoAF Dassault Falcon 20

As normally this instrumented aircraft was used to evaluate conventional navigation systems in Portugal, it made possible the evaluation of the ESTB system and also its comparison with other conventional navigation systems.

5.2 Dassault Falcon 50

Since the beginning of 2005, all aircrafts from the PoAF Dassault Falcon 50 (figure 9) fleet could be instrumented and used in the evaluation of the EGNOS system. These aircrafts are normally assigned to VIP transportation with a usual flight plan not just limited to the Portuguese airspace but potentially larger than the EGNOS coverage region. The EGNOS data are collected in these aircrafts with the Septentrio PolaRx-2 receiver, using the second Flight Management System (FMS) L1 GPS antenna with an antenna splitter. Note that this is possible since the PEGASUS software only uses the L1 GPS data.

Fig. 9. PoAF Dassault Falcon 50

After some delays, in 2006 one of the PoAF DASSAULT FALCON 50 aircraft instrumented with a dedicated NOVATEL L1/L2 512 antenna became available. The EGNOS data are also collected with the SEPTENTRIO POLARX-2 receiver using its internal memory. Additionally other aircraft data, like navigation and aircraft dynamic data, are recorded in a airborne computer, allowing the comparison of the EGNOS navigation solution with other conventional navigation systems.

These aircrafts may also be used in flight trials to test operational rules and procedures for aircraft to use the EGNOS system as a navigation system, namely according the established in the ICAO Document 8071.

5.3 EGNOS Flight Trials Results

In this section the EGNOS performance during some flight trials is presented and analysed. The EGNOS navigation solution and performance was computed with EUROCONTROL PEGASUS software.

On 15 March 2004, a ESTB flight trial was performed with the instrumented PoAF DASSAULT FALCON 20 aircraft using a ILS CAT IIIB calibration flight, performed in the Lisbon area. The ESTB data have been collected with a SEPTENTRIO POLARX-2 receiver and a NOVATEL L1/L2 512 antenna. As mentioned before, this receiver log up to 12 L1/L2 GPS data and up to 3 geostationary satellite data, at 1Hz and using its internal memory. To evaluate ESTB position accuracy, the aircraft truth reference trajectory was determined using a NOVATEL RT-20 real time differential GPS system, consisting in one onboard receiver, the NOVATEL L1 514 antenna and one radio modem. On the ground, one NOVATEL RT-20 reference stations was used, located in the military area of the Lisbon Airport.

Figure 10, shows the aircraft flight path. Note that during this flight the ESTB data were broadcasted by the PRN131 geosatellite, with a relative small elevation (around 4º) implying the lost of some ESTB data, mainly due to aircraft manoeuvres.

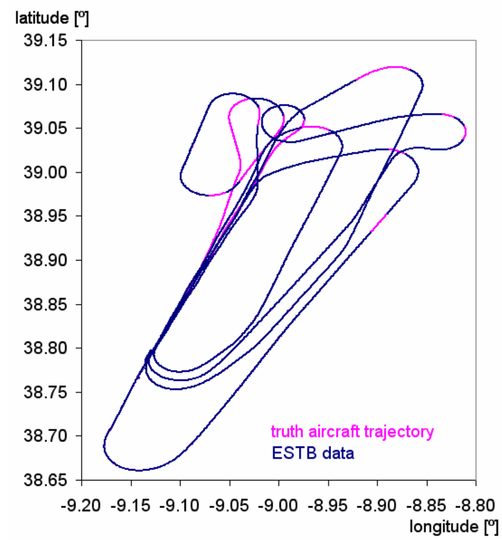

Fig. 10. Flight path (RT-20 truth aircraft trajectory – blue; ESTB navigation solution – pink)

Figure 11 and 12 shows the HPE/HPL and VPE/VPL versus time. In total, the ESTB navigation solution was generated for 5338 epochs. The corresponding 95th percentiles are 1.5 m for HPE, 2.4 m for VPE, 7.2 m for HPL and 10.0 m for VPL. The computed availability was 100% for all evaluated flight operation modes (CAT-I, APV-II and APV-I). No integrity events have occurred.

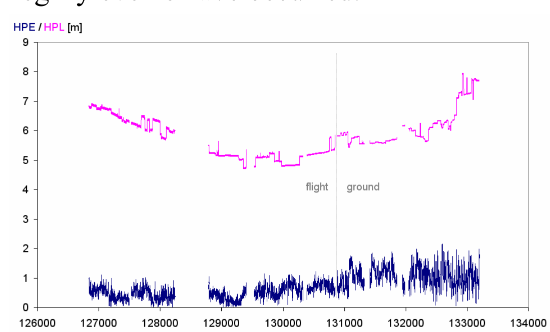

Fig. 11. HPE (blue) and HPL (pink) versus time

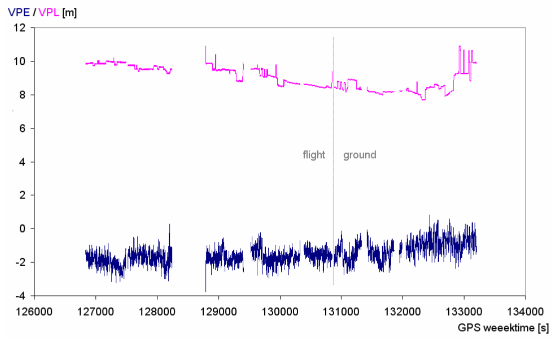

Fig. 12. VPE (blue) and VPL (pink) versus time

In 19 May 2005, EGNOS data have been collected in an instrumented PoAF DASSAULT FALCON 50 aircraft during a flight from London to Lisbon. The graph in figure 13 shows the aircraft flight path and the service availability. The data have been collected with the SEPTENTRIO POLARX-2 receiver and the EGNOS navigation solution was computed with data broadcasted by the PRN124 geosatellite.

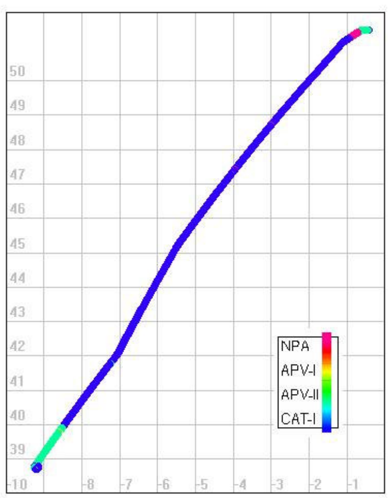

Fig. 13. Flight path and service availability

Figure 14 shows the computed protection levels. The presented results show that the overall EGNOS performance was degraded near London, because at that time they are close to the EGNOS boundary coverage region, therefore the number of used satellites is small.

The evaluation was made for 8960 epochs and the computed system availability was 83.3% (CAT-I), 99.0% (APV-II) and 99.0% (APV-I). The Protection Levels 95th percentiles are 19.9 m (HPL) and 17.2 m (VPL).

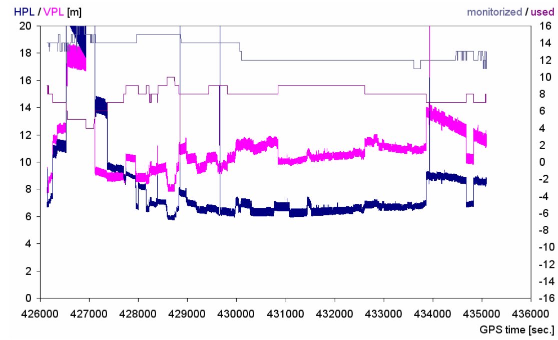

Fig. 14. HPL (blue), VPL (pink), NSV versus time

In 8 December 2005, EGNOS data have been collected in an instrumented PoAF DASSAULT FALCON 50 aircraft during a flight from Lisbon to Koln and return. EGNOS data have been collected with the SEPTENTRIO POLARX-2 receiver and the EGNOS navigation solution was computed with data broadcasted by the PRN124 geosatellite. The data collection was interromped in Koln. Figure 15 shows the flight path and the service availability.

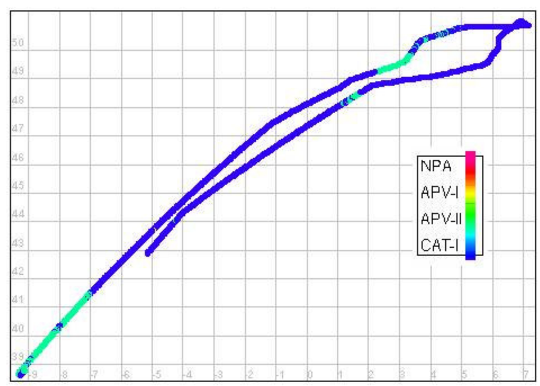

Fig. 15. Flight path and service availability

The computed system availability in the ongoing flight, 6605 epochs, was respectively 97.5% (CAT-I), 99.9% (APV-II) and 99.9% (APV-I). The 95th percentiles are 8.7 m (HPL) and 13.6 m (VPL). For the return flight, 10025 epochs, we obtained 74.8% (CAT-I), 99.9% (APV-II) and 99.9% (APV-I). Again, the 95th percentiles are 9.15 m (HPL) and 9.78 m (VPL). These very good results show the real potential of the EGNOS system, for aeronautical applications. Note that the worst results have been obtained in Portugal, mainly due to bad geometry.

Figure 16 shows the flight path and the service availability, computed with data collected on 12 December 2005 with the Septentrio PolaRx-2 receiver in a Dassault Falcon 50 flight from Algiers to Lisbon. The EGNOS Navigation solution was computed with data broadcasted by PRN126 geosatellite.

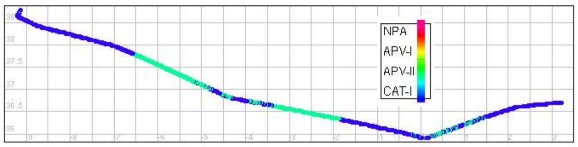

Fig. 16. Flight path and service availability

The computed service availability figures have been 65.3% (CAT-I), 100% (APV-II) and 100% (APV-I). They are also very good results and obtained in the boundary of the EGNOS coverage area. Figure 17 shows the Navigation Errors and Protection Levels in Lisbon area. The aircraft truth reference was computed with the Trimble Total Control software, using L1/L2 reference data collected in the Lisbon Airport, for a maximum distance of 50 km.

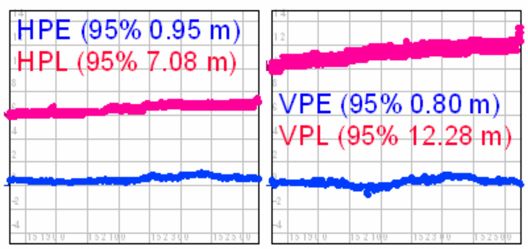

Fig. 17. Navigation Errors (bleu) and Protection Levels (pink) in Lisbon area

Again the presented results are very good and meet all ICAO SARPs requirements for CAT-I flight operation, witch is even better than the EGNOS requirements.

6 Conclusion

The work presented in this paper shows the Portuguese contribution to the operational validation of the EGNOS system. More than just the authors', this paper illustrates the work of a large set of people and organizations, namely thru the joint effort involved inside the EDCN and in coordination with ESA.

Even if the results from the EGNOS static evaluation performed in Lisbon presently don't meet the defined requirements, when the EGNOS system becomes operational there will be an increase in its performance. Results from the flight trials are much promising and show that the overall EGNOS performance is better when the receiver is airborne. For instance the required APV-II 99% availability was obtained in all presented flight trials. Further work will focus on the influence of aircraft manoeuvres and on testing operational rules and procedures for aircraft to use the EGNOS system as a navigation system, namely according the established in the ICAO Document 8071.

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