Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

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Demonstration of Satellite based Navigation for Civil Aviation

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Summary

Satellite positioning systems such as GPS (USA) and GLONASS (Russia) offer prospects for a world-wide available, high accuracy navigation system for application in civil aviation. Unfortunately, one of the shortcomings in both systems is that they lack integrity information, which is considered essential for any safety critical application, particularly for navigation in civil aviation. In order tot solve the lack of integrity of the current satellite positioning systems, Eurocontrol, ESA and the European Union, together called the European Tripartite Group (ETG), decided to start development of EGNOS. EGNOS stands for European Geostationary Navigation Overlay Service. It is a geostationary satellite based augmentation system for GPS and GLONASS.

In order to support the development of critical technology, the ESTB (EGNOS System Test Bed) has become available since February 2000 as a payload of the INMARSAT AOR-E satellite. It operates together with a growing number of ground based reference stations. After many static experiments with ESTB Eurocontrol considered it worthwhile to demonstrate the application of GPS/EGNOS as a navigation aid in a real-life aeronautical application: it was decided to demonstrate EGNOS capabilities in a curved approach procedure to the airport of Nice (France). Because NLR owns and operates a Cessna Citation research jet aircraft, which is equipped with a 'Research Flight Management System' (R-FMS), NLR was asked to integrate an EGNOS receiver with their R-FMS into the Citation and to perform the EGNOS based approach trials. In these trials, performed by NLR and Septentrio under contract of Eurocontrol, it was demonstrated that EGNOS/GPS, together with an aircraft's FMS supporting an EGNOS sensor is a very promising navigation aid for RNAV procedures and approach procedures up to CAT I navigation service level.

List of Abbreviations

AOC	Advanced Operational Capability
APV	Approach Procedure with Vertical guidance
ECAC	European Civil Aviation Conference
EEC	Eurocontrol Experimental Centre
EGNOS	European Geostationary Navigation Overlay Service
ESA	European Space Agency
ESTB	EGNOS System Test Bed
ETG	European Tripartite Group
FMS	Flight Management System
FTE	Flight technical Error
GEO	Geostationary Earth Orbit
GOV	GNSS Operational Validation
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HAL	Horizontal Alert Limit
HPL	Horizontal Protection Level
ICAO	International Civil Aviation Organisation
NLES	Navigation Land Earth Station
NSE	Navigation Sensor Error
PFD	Primary Flight Display
R-FMS	Research Flight Management System
RIMS	Ranging and Integrity Monitoring Station
RNAV	Area Navigation
SBAS	Space Based Augmentation System
TSE	Total System Error
VAL	Vertical Alert Limit
VPL	Vertical Protection Level
WAAS	Wide Area Augmentation System
WAD	Wide Area Differentials

Contents

(18 pages in total)

1 Introduction

Most of us are familiar with GPS and its basic principles. Receiving position and time from at least 4 satellites of the in total some 24 satellites of this system a receiver can combine this information to obtain its own co-ordinates (and time). With this straightforward approach, a very high positional accuracy in the order of 20 m can be achieved world-wide. This was even considered too accurate by the United Stated DoD (Department Of Defence), the owners of the system. Therefore, for strategic reasons the DoD purposely degraded the accuracy to approximately 100 m for several years for civil users, and switched off the so called 'selective availability' in May 2000. On the one hand very promising as a navigation aid for civil aviation, this satellite based positioning system cannot meet the navigation performance requirements for aeronautical applications (see: Table 1), which are characterised by four main parameters: accuracy, integrity, availability and continuity of service. The requirements of these parameters are highly dependent on the phases of flight. Neither GPS nor GLONASS can meet these service objectives without a system augmentation, although their performance in terms of accuracy alone could meet the requirements of en-route, terminal area navigation and non-precision approaches [3]. The EGNOS system development, which was started in the mid-nineties should solve the shortcomings, making satellite navigation feasible for civil aviation, first for the ECAC (European Civil Aviation Conference) area and in a later stage for Africa, Eastern Europe and Russia. EGNOS is one of the three Space-Based Augmentation System (SBAS). With EGNOS together with the United States WAAS system and the Japanese MSAS a worldwide SBAS system becomes available. The European Space Agency (ESA) is responsible for the design, development and technical validation of the EGNOS system. This technical validation is to be completed by early 2004. Eurocontrol is responsible for the co-ordination of the operational validation of EGNOS for civil aviation.

Table 1 ICAO Satellite Navigation Performance Requirements [8]

<table>
<tr><th>Typical Operation(s)</th><th>Accuracy lateral / Vertical (95%)</th><th>Alert limit lateral / vertical</th><th>Integrity</th><th>Time to alert</th><th>Continuity</th><th>Availibility</th></tr>
<tr><td>En-route, oceanic</td><td>2.0 NM / NA</td><td>4 NM / NA</td><td rowspan="4">10^{-7}/h</td><td>5 mn</td><td rowspan="4">10^{-4}/h to 10^{-8}/h</td><td>0.99 to 0.99999</td></tr>
<tr><td>En-route, domestic</td><td>0.4 NM / NA</td><td>2 NM / NA</td><td rowspan="2">15 s</td><td rowspan="2">0.999 to 0.99999</td></tr>
<tr><td>En-route, Terminal</td><td>0.4 NM / NA</td><td>1 NM / NA</td></tr>
<tr><td>Initial approach, NPA, Departure</td><td>220 m / NA</td><td>0.3 NM / NA</td><td rowspan="2">10 s</td><td rowspan="4">0.99 to 0.99999</td></tr>
<tr><td>APV-I</td><td>220 m / 20 m</td><td>0.3 NM / 50 m</td><td rowspan="3">$2x10^{-7}$ per approach</td><td rowspan="3">$1\text{-}8x10^{-6}$ in any 15 s</td></tr>
<tr><td>APV-II</td><td>16 m / 8 m</td><td>40 m / 20 m</td><td rowspan="2">6 s</td></tr>
<tr><td>CAT I</td><td>16 m / 4-6 m</td><td>40 m / 10-15 m</td></tr>
</table>

2 EGNOS

The EGNOS performance objectives with respect to civil aviation are to offer a primary means of navigation service for all phases of flight from en-route down to CAT 1 Precision Approach, providing the following services:

- WAD, the broadcasting of Wide Area Differential corrections. This will increase the positional accuracy up to the level required for precision approaches;
- GIC (GNSS Integrity Channel), providing integrity information to the users. Messages are broadcast providing status information concerning the GPS system. Important integrity information are the 'protection levels' HPL (Horizontal Protection Level) and VPL (Vertical Protection Level), indications of the remaining maximum position errors and timing requirements for satellite integrity warnings, which are defined by the Time-to-Alert;
- Ranging, the transmission of GPS-like signals from the EGNOS satellites, in this way increasing the number of available navigation satellites.

The principle of WAD corrections is a means to increase the positional accuracy. A network of ground based reference stations covering an area up to that of a continent, located each at a precisely known position gather ranging information from GPS and GLONASS. These reference stations calculate their GPS-based position and send the deviations from their actual position to a central processing facility. Information from all reference stations are combined and provided to all users, e.g. by a geostationary communication satellite. The users apply the differential corrections to augment their GPS-based positional accuracy. This principle has been demonstrated to work in many experiments, starting more than 10 years ago.

The EGNOS infrastructure (see also Figure 1) is composed of four segments: the ground segment, space segment, user segment, and the support facilities.
The ground segment consists of the reference stations, which are called RIMS (Ranging and Integrity Monitoring Stations). These RIMS are connected with the central processing facility, which are called Mission Control Centre (MCC). In the MCC the information of all RIMS are combined to messages containing integrity information, differential corrections for each monitored satellite and ionospheric and tropospheric delays. MCC sends these messages to the Navigation Land Earth Station (NLES) where they are to be uplinked to the Geostationary satellites called GEO (Geostationary Earth Orbit).
The EGNOS Space Segment is composed of three GEO satellites, i.e. INMARSAT AOR-E and IOR and ESA’s Artemis, providing coverage of the earth from South America to West-Russia longitudes. The GEO will broadcast the messages on the GPS L1 frequency to all users.
EGNOS shall be fully interoperable with WAAS (Wide Area Augmentation System), the United States SBAS implementation and the Japanese MSAS system to provide a world-wide SBAS signal in space coverage. The EGNOS User Segment consists of the EGNOS/GPS user equipment for civil aviation and other, e.g. land and maritime applications.

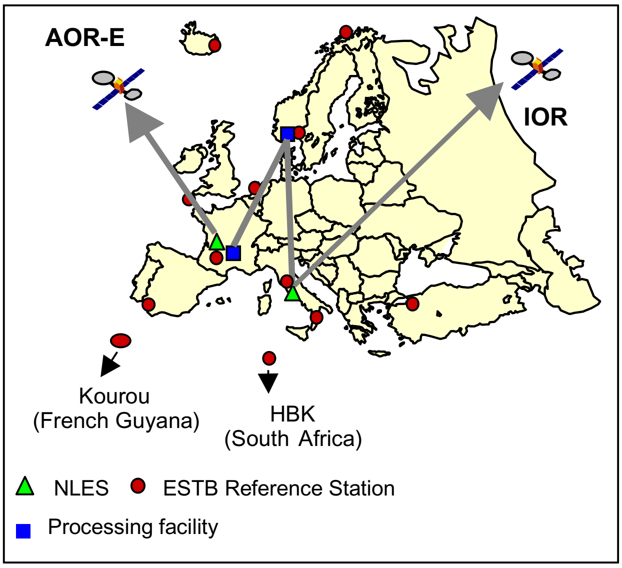

Figure 1 The EGNOS System Test Bed Architecture

In order to gain basic knowledge and to support the development of the EGNOS system and its user segment the EGNOS System Test Bed (ESTB) has been developed by ESA. ESTB is operational since February 2000 as a real-time, full-scale and fully compliant prototype of EGNOS. The differences with the real EGNOS are that the performance concerning integrity, availability, accuracy and continuity are not guaranteed, while also the RIMS infrastructure is limited to around 10 instead of the planned 40 RIMS. In the last 2½ years ESTB has proven an excellent research environment showing improving performance after successive upgrades. It also showed to be a very useful tool to demonstrate SBAS capabilities and performance to future users, in particular to civil aviation authorities, to encourage initial development of infrastructure and operational procedures for future EGNOS use in air traffic management.

From 2000 on ESTB was and will be used in various studies and demonstrations in different applications on land (road, rail and others, e.g. precision farming), maritime and aeronautical applications.

Apart from these research activities with ESTB, an industrial consortium led by Alcatel Space Industries is working under contract of ESA on the implementation, test and validation of the real, full scale EGNOS system. EGNOS is currently in its Implementation Phase, which will be concluded by the Factory Qualification Review. The subsequent Technical Validation Phase will be concluded by Operational Readiness Review (ORR), after which EGNOS will reach its Advanced Operational Capability (AOC), which is targeted for early 2004. AOC however does not include certification of EGNOS for aeronautical applications. It is up to the civil aviation community to decide under which conditions and for which operations EGNOS may be used for navigation purposes.

3 GNSS Operational Validation

As part of its commitment in the European Tripartite Agreement, Eurocontrol is held responsible for the co-ordination and execution of activities related to the operational validation of EGNOS for applications in civil aviation. Operational validation includes all activities that will demonstrate that EGNOS meets the requirements to support the flight operations for which it was intended. These operational validation activities are co-ordinated through a group known as the GNSS-1 Operational Validation (GOV) Working Group. The GOV Working Group is chaired by Eurocontrol Experimental Centre in Brétigny and consists primarily of European Air Traffic Service Providers as well as a few research organisations involved in satellite navigation related activities. NLR is one of the partners within the GOV Working Group.

The GOV group is performing various activities that will support the implementation of EGNOS services for civil aviation in European and African airspace. These activities deal with the development of tools for static and dynamic (airborne) data collection and evaluation, as well as performing 'early trials', focussing on gathering experience with EGNOS through ESTB and demonstrating EGNOS capabilities to authorities for application in civil aviation. In the tools category the development of PEGASUS should be mentioned. PEGASUS [9], which was developed by the Technical University of Braunschweig, is a software tool for validation of statically and dynamically acquired EGNOS data. Also, PREVAIL belongs to this category of activities. In the year 2000 within PREVAIL (Preparation for EGNOS Validation in Approach and Landing), various airborne instrumentation such as an EGNOS receiver and a Research Flight Management System (R-FMS) were adapted and integrated to provide EGNOS/GPS guided navigation for NLR's research aircraft, a Cessna Citation II.
Having those prototype tools available, the following logical step was to demonstrate the ESTB capabilities during an approach operation, which calculated the guidance along the desired flight path from GPS/EGNOS. Apart from studying the EGNOS capability, it is also important to show its benefits to the aeronautical community in order to give this nav aid an extra push to further acceptance and deployment.

Eurocontrol has defined the implementation of the Area Navigation (RNAV) concept as the crucial element in the future Navigation Strategy for the ECAC area [1]. RNAV is defined as 'a method of navigation, which permits aircraft operation on any desired flight path within the coverage of the station-referenced navigation aids or within the limits of the capability of self-contained aids, or a combination of these' [4]. The current view is that Europe in the coming 15 years will transition to a pure RNAV-based environment, with a possible exception of the precision approach phase of flight during which the aircraft may continue to receive guidance from fixed ground-based aids such as ILS and MLS. EGNOS will be the navigation sensor supporting all RNAV operations. Eurocontrol together with the French DGAC has designed a 3D RNAV approach procedure, which could show the benefits of EGNOS supporting this procedure. This demanding curved approach procedure, designed for the airport of Nice, was first tested in an aircraft simulator. This simulator was based on the Airbus family of aircraft and operated by a French flight test facility in Istres. These simulations demonstrated that flying the procedure based on GPS alone with a baro-altimeter to capture the ILS, which is then used for landing, was not possible since 2 NM is too short a distance for engaging the ILS mode to allow for aircraft stabilisation. On the other hand it showed that flying the approach based on EGNOS for the complete procedure up to touch down should be feasible [10]. So, now the time was right to test the EGNOS-based RNAV procedure in reality.

4 The ESTB-based Approach Procedures at Nice Airport

Nice Airport is France’s second busiest airport (Paris CdG is number one). The airport is not the easiest one to approach by plane, because the airspace surrounding Nice in the North and West is not available for approach procedures due to the offshoots of the Alps. An ILS is available and offers a straight-in flight path to runway 04L however leads over the idyllic village of Cap d’Antibes, introducing a high noise load. Therefore during visual flight conditions the ILS in general is not used. Instead, the flights are vectored-in by ATC following the so-called ‘Rivièra Approach’ procedure, which is difficult to execute and introduces a high workload for both pilot and air traffic controller. Not surprisingly, ATC Nice was very interested in an avionics supported RNAV procedure that enables avoiding the Cap d’Antibes.

Figure 2 DRAMO Experimental Approach Procedure at Nice airport

Two RNAV procedures were designed, one starting at the DRAMO holding, the other at the LERIN holding and both leading to runway 04L (see also Fig 2). The procedures were defined by 3D waypoints, defining a sequence of straight and curved segments. The most significant characteristics of the procedures are that they are fully 3D with two fixed radius turns in the horizontal plane combined with a continuous descent in the vertical plane. Also the manoeuvres have a short final segment so that the aircraft is lined-up with the runway only short to threshold. Finally the descent angle (3.5°) can be characterised as steep in order to reduce the environmental noise level.

5 Technical Implementation

Conditions for implementation would be two-fold. Firstly, the availability of an indication that the positional accuracy is reliable to be used by the aircraft's receiver by checking the integrity parameter. Secondly, the provision of an FMS and appropriate displays to provide adequate situational awareness for the pilot. Data acquisition during the trials should enable an analysis of the performance of both the EGNOS system and aircraft in terms of Navigation Sensor Error (NSE), Flight Technical Error (FTE) and Total System Error (TSE) in the lateral as well as the vertical plane (see Fig 5, 6, 7 and 8).

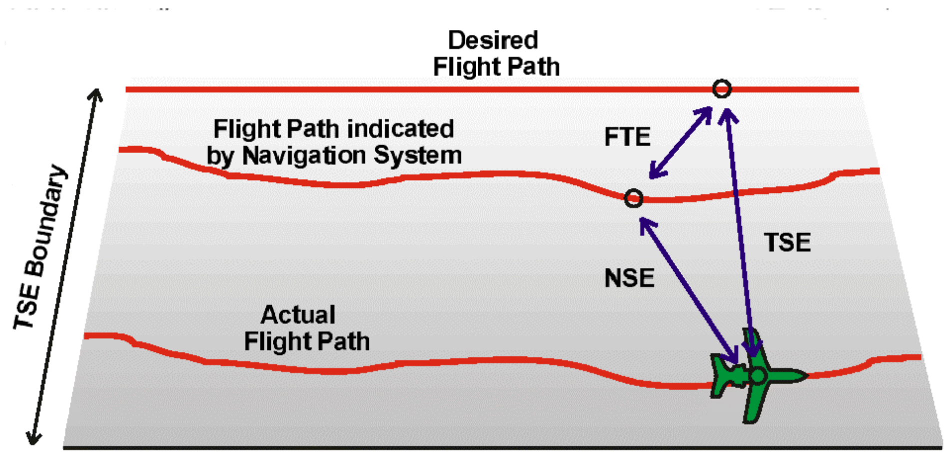

Figure 3 Definition of NSE, FTE and TSE parameters [1]

Figure 4 shows the platform as it was integrated into the Cessna Citation research aircraft for this experiment. Using an antenna splitter the EGNOS/GPS antenna on top of the fuselage was connected with three receivers. The Trimble MS750 GPS receiver together an identical ground based system located near the runway provided for the position 'truth' system. It was demonstrated before that in post-processing this combination can determine the airborne antenna position at cm accuracy, by determining the phase of the GPS carrier wave. The PolaRx-1 prototype EGNOS/GPS receiver developed by Septentrio was used to provide the R-FMS with the necessary position and integrity updates at a 10 Hz rate. Finally the Novatel Millenium EGNOS/GPS receiver was integrated in order to distinguish between receiver-related errors and problems and Signal In Space related problems in case they show up. The same set of receivers was also installed near the runway: the Trimble MS750, as is outlined, being part of the truth system, the other receivers to enable investigation of the influence of dynamics on the error budgets. Also multi-path and shadowing of the signal by the orientation of the aircraft, when occurring, should be easier to identify. The information from the PolaRx-1 receiver was fed into the R-FMS by serial line. This R-FMS on the one hand drove the removable experimental flight deck of the experimental pilot and the observer, featuring a high-resolution LCD showing a Primary Flight Display (PFD) and an experimental NAV display for pilot-in-the-loop guidance (see: Fig 5). On the other hand the R-FMS interfaced with the Cessna Citation's Honeywell SPZ-500 Flight Computer (via its MLS-receiver input) to enable auto-pilot guidance. The auto-pilot guided approaches were necessarily straight-in ILS look-alike approaches, because the Citation auto-pilot does not support curved approaches. Therefore curved approaches were performed using NLR's R-FMS, while for the straight-in EGNOS-based approaches the SPZ-500 auto-pilot or with the man-in-the-loop the Citation's FMS (a Universal Avionics UNS 1B) was used.

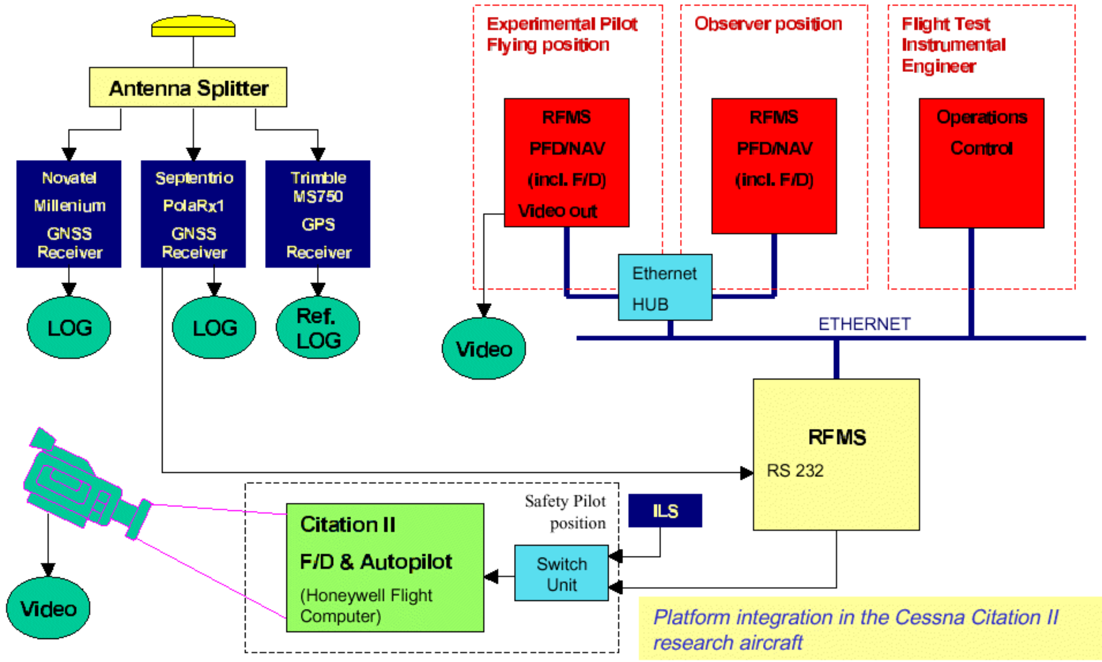

Figure 4 Platform integration in the Cessna Citation research aircraft [2]

An important aspect was the human-machine interfacing aspect of the PFD of the R-FMS for the pilot-in-the-loop situation. Two options were open: the Flight Director (F/D, see Fig 5) and the tunnel-in-the-sky. The F/D has been specifically designed to intercept and track a 3D trajectory, consisting of straight and curved segments (in the horizontal plane) and climb, level and descent segments in the vertical plane. The F/D design has been based on the so-called "quickened display" concept that significantly enhances pilots performance by compensating for the aircraft dynamical behaviour. The pilot's primary task is evidently to keep the F/D bars centred in the small black square at the centre of the PFD. The F/D design incorporates logic to anticipate the next leg type (e.g. turn direction, descent) of the approach procedure. Before this project NLR has made experiments with both guidance options. It showed out that in the tunnel-in-the-sky option provided for a higher situational awareness of the pilot, while the F/D was easier to fly and had a better performance in terms of keeping the aircraft on the required track, i.e. a smaller FTE. It was decided to use the F/D for the curved approaches, because of its track following performance.

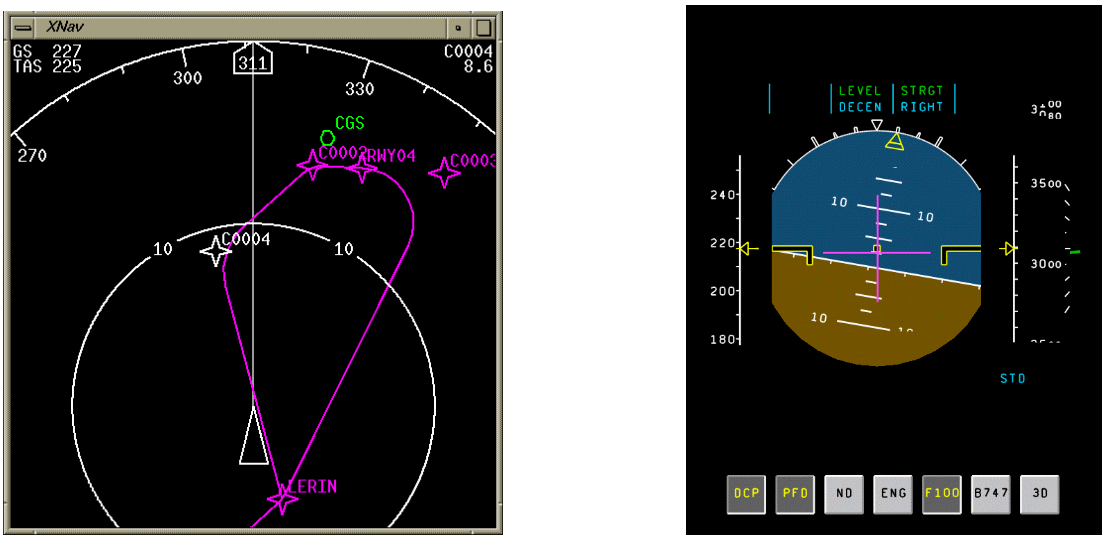

Figure 5 NAV and PFD display including F/D of the Research-FMS used for ESTB guided curved approaches

6 The Flight Trials

In total 12 approaches based on EGNOS positioning were performed:

- 3 RFMS-F/D guided curved approaches from DRAMO
- 3 RFMS-F/D guided curved approaches from LERIN
- 3 UNS-F/D guided ILS look-alike approaches
- 3 auto-pilot guided ILS look-alike approaches

The reason for also performing straight-in approaches was that it enabled various interesting comparisons, such as the NSE, FTE and TSE values of ILS-based approaches vs. EGNOS-based approaches and also the influence of curves on NSE, TSE and FTE as compared with straight-in conditions. Finally, the errors under man-in-the-loop conditions could be compared with auto-pilot conditions, but this comparison obviously is already well investigated (auto-pilot performs with smaller errors).

Although the trials were not free from problems (which can be considered as common practise in research) the trials in general were successful, resulting in very interesting data. With the help of good visual conditions and acceptable wind direction and the co-operative attitude of involved air traffic controllers under busy traffic conditions all intended approaches could be realised. Not unimportant, the pilots were happy with the guidance system, their experience in general was quite positive:
"The flight director guidance from the R-FMS used for the curved approaches was very smooth and provided for accurate tracking. The Septentrio receiver in general gave stable output of integrity values and no jumps in position were experienced. Basically it was easy to fly the curved approaches using the guidance from the ESTB."

7 Analysis and Results

Happiness of the pilots with the system is nice and important, but obviously even more important is performance of the system in terms of accuracy, integrity, availability and continuity relative to the ICAO requirements for satellite navigation for the various navigation service levels as defined in Table 1. To assess the EGNOS accuracy (NSE), position solutions from the PolaRx-1 EGNOS receiver were compared with positions according to the position truth system (see: Fig 3). Correctness of the truth track is very important and therefore this solution was cross-checked using data from another nearby GPS reference station in Nice and was found correct. The NSE then was determined as the difference between truth position and the EGNOS based position. The FTE was defined as the aircraft position according to the PolaRx-1 EGNOS receiver and the intended position, i.e. the position along the selected track as defined in the R-FMS database. This FTE is known in real-time and used for guidance on the PFD and NAV display. Finally, the TSE may be determined as the difference between the aircraft position according to the truth system and the intended position along the selected track.

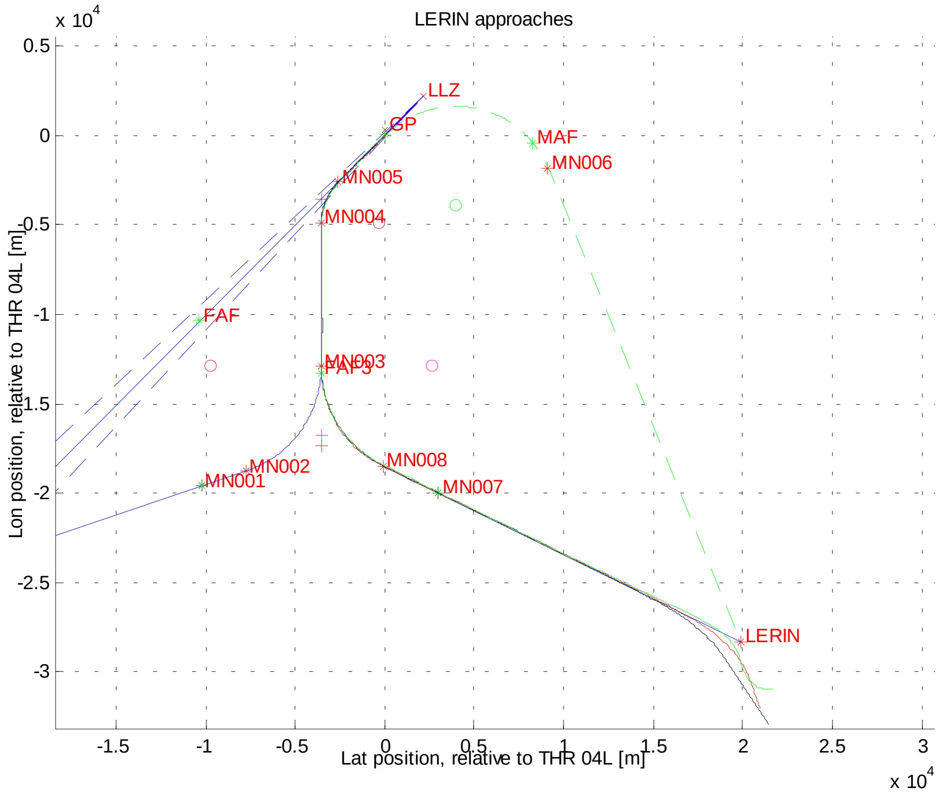

Figure 6 *Flight tracks of the LERIN (3 approaches) and (part of) DRAMO (3 approaches) curved approaches as obtained by the Trimble Truth system. 'o' represents the centre of a fixed radius turn, '+' represent fly-by way points*

For assessment of the availability and integrity performance the Horizontal Protection Level (HPL) and the Vertical Protection Level (VPL) shall be used relative to the Horizontal Alert Limit (HAL) resp. Vertical Alert Limit (VAL) as defined by ICAO (see: Table 1). Availability is defined as a valid GPS/EGNOS signal in space being available, while HPL < HAL and VPL < VAL for the identified navigation service level. An integrity violation is defined as horizontal NSE > HPL or vertical NSE > VPL [11]. Integrity requirements are extremely stringent, violations should never occur.

Discussing and showing all analysis results in this article would take too much space, therefore for details [2] should be referenced. This report will be made available at the Eurocontrol web site. Some high lights are given below. The EGNOS NSE (see Fig. 7) was characterised by a spread of a few meter, combined with a bias of a few meter. The nature of this bias in position error was investigated by ESA and repaired as published in [7]. The resulting EGNOS accuracy now (but after the Nice trials!) is in the order of 1 meter!

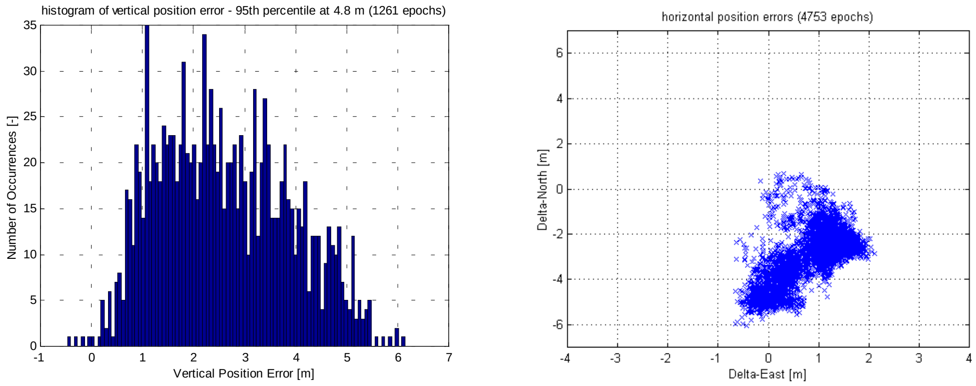

Figure 7 Vertical and horizontal NSE as measured during the DRAMO approaches

The FTE of the EGNOS guided Citation in general was larger than the NSE, in the order of a few wingspans. For curved approaches the lateral FTE was larger than for straight-in approaches, which is obvious because it is physically impossible for a inert aircraft to accurately fly a sequence of straight and fixed radius turn segments. This would require instantaneous changes of the aircraft bank angle. Further, the auto-pilot driven approaches had somewhat smaller FTE's than the approaches with man-in-the-loop.

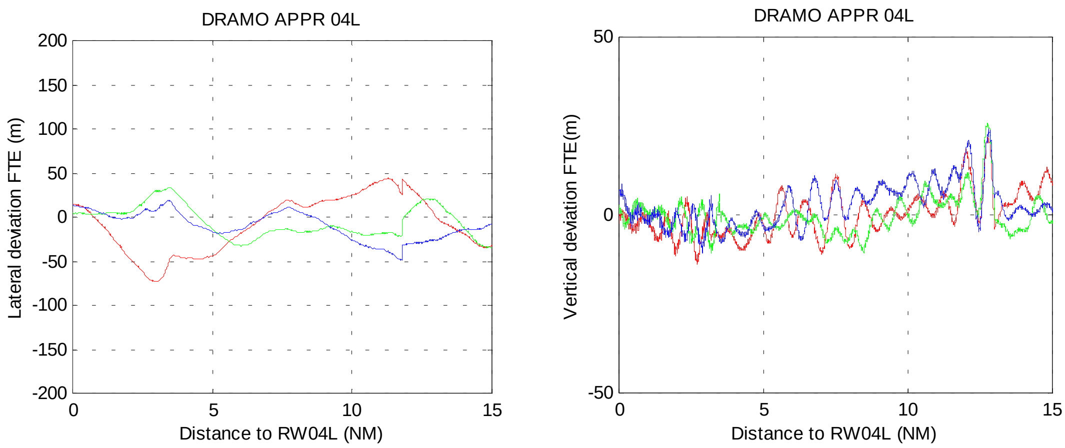

Figure 8 The lateral and vertical FTE in metres for the DRAMO approaches (- is left/below desired position, + is right/above desired position. FAF located at 13.3 NM

Concerning guidance availability, the PolaRx-1 prototype receiver now and then stopped outputting position updates because of aircraft shaking caused by selecting the flaps. Apart from this problem availability for all navigation service levels were close to ICAO requirements except for CAT 1 in the vertical plane. However after the trials ESTB has improved considerably and it is expected that the real EGNOS system will perform even better than ESTB, because of its denser RIMS network.

During the Nice trials not a single integrity violation was observed.

The flight trial data acquired at Nice airport was also a fruitful source for other related studies. ESTEC used the data to perform an NSE spectral analysis in the very low frequency part of the spectrum for identification (if any) with the eigen-frequencies of approach and landing mode of an aircraft [13]. Using the realised flight paths Eurocontrol worked out a noise impact study, to give an estimation of the noise benefit due to the use of an SBAS navigation system at Nice airport [12].

8 Conclusion and Future Work

The Nice approach trials demonstrate that EGNOS is a very promising navigation aid to support RNAV operations, possibly up to Cat 1 navigation service level.

However, in order to come to final introduction and operational use there is still a long way to go in many fields of research and development.
In the field of avionics one might think of development of the next generation Flight Management Systems supporting GPS/EGNOS as a navigation sensor and curved RNAV operations.
Concerning ESTB related research, there is much activity going on during the second half of 2002. For instance ASECNA together with ESA are preparing ESTB guided straight-in approaches outside the ECAC area (Senegal) using portable RIMS, while EEC together with Skyguide are preparing ESTB-based missed approach procedure flight trials at the airport of Sion (Switzerland).
Concerning the real EGNOS development, in 2003 the EGNOS-AIV flight trials under contract of ESA will complete the EGNOS system validation. NLR is also involved in preparation and realisation of those flight trials, so there is an interesting time to come.

9 WWW Links

http://www.esa.int/navigation
http://www.eurocontrol.fr/projects/sbas
http://www.nlr.nl/public/hosted-sites/satnav

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