Approaching Nice with the EGNOS System Test Bed

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BIOGRAPHY

Santiago Soley graduated with a MSc in Telecommunication Engineering from the *Universitat Politecnica de Catalunya* in 1998. He started to work on Satellite Navigation in 1997 with Indra-Espacio S.A. In 1999 he joined the ESA GalileoSat Team to work on the Definition Phase of Galileo. Since October 2000 he has been working as a consultant for EUROCONTROL at their Experimental Centre in the GNSS Programme Office, giving technical support in various activities related to GNSS-1 Operational Validation.

Rick Farnworth graduated with a BSc in Electronic Engineering from the University of Wales in 1988 and was awarded a PhD in 1992 for his work on LORAN-C coverage prediction modelling. He then joined the United Kingdom CAA's National Air Traffic Services to work on R&D projects relating to the application of satellite navigation systems in civil aviation. Since February 1996 he has been working for EUROCONTROL at their experimental centre in the GNSS Programme Office where he is project leader for all SBAS-related activities in EUROCONTROL.

Edward Breeuwer obtained his MSc in Electrical Engineering from Delft University of Technology in 1992 and was awarded a PhD from the same university in 1998 for his work on integrated navigation systems. From October 1997 to November 2001 he worked as a consultant for EUROCONTROL at their Experimental Centre in the GNSS Programme Office. In January 2002 he joined ESA where he is working as a system engineer in the Galileo Team based at the ESA Technical Centre (ESTEC) in the Netherlands.

ABSTRACT

The EGNOS System currently under development by the European Space Agency (ESA) is expected to reach its operational capability by 2004. As a part of its commitment to the European Tripartite Agreement between the Commission of the European Union, the European Space Agency and Eurocontrol, Eurocontrol is responsible for the co-ordination and execution of various activities related to the operational validation of EGNOS.

EGNOS is designed, among other things, to meet the requirements of both Precision Approach and RNAV Approach with Vertical Guidance, also known as LNAV/VNAV or APV. Work has started recently in the ICAO Obstacle Clearance Panel (OCP) to develop design criteria for approach procedures using SBAS.

Eurocontrol, in co-operation with ESA and the French DGAC, performed a simulation in a transport flight simulator at a flight test centre (CEV) in Istres, south of France, to study EGNOS-based approaches on a specific approach procedure to the airport of Nice, France. The procedure was designed using recent ICAO OCP working material and assumes State-of-the-art capabilities of the on-board Flight Management System (FMS). Nice airport is a very interesting example of a location where the introduction of SBAS Systems may bring operational benefits.

Following the simulation, as a part of the GOV (GNSS-1 Operational Validation) Working Group Activities, Eurocontrol has flight-tested the procedure in real-life using a dedicated EGNOS receiver inside an experimental aircraft for both data collection and aircraft guidance.

This paper describes the set-up of the receiver and the FMS inside the aircraft for the curved and ILS-like approach procedure to Nice and provides a quick view of their influence on the control characteristics of the experimental aircraft. The results also include an assesment of the performance of the ESTB (EGNOS System Test Bed) during the approaches. First experiences of the pilots flying the procedure are also presented.

1. INTRODUCTION

EGNOS, the European Satellite-Based Augmentation System (SBAS) to GPS, is currently under development and is expected to be in operation in 2004. EUROCONTROL, as a part of its commitment to the European Tripartite Agreement with the Commission of the European Union and ESA, is responsible for the co-ordination of the operational validation of EGNOS for Civil Aviation.

Operational validation includes all activities that will demonstrate that EGNOS is ready to be implemented to support the flight operations for which it is intended. The operational validation activities are co-ordinated through a group known as the 'GNSS - 1 Operational Validation (GOV) Working Group, chaired by EUROCONTROL and

primarily composed of European Air Traffic Service Providers intending to offer navigation services based on EGNOS.
The GOV group is performing various activities that will support the implementation of EGNOS services for Civil

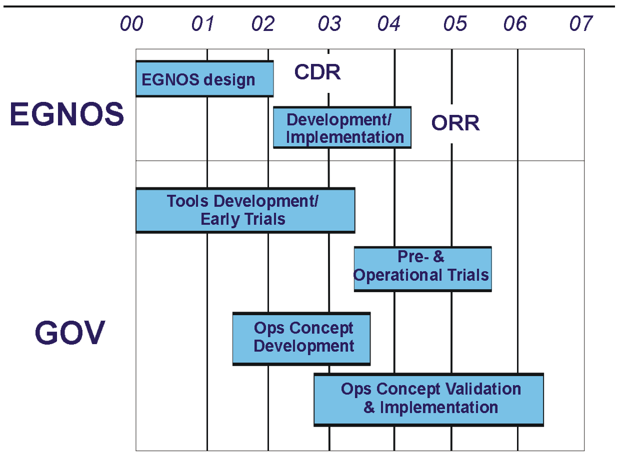

Figure 1 EGNOS and GOV schedule

Aviation in European airspace [17]. One important activity within the GOV is to establish the type of operations that will be supported by EGNOS and based on this to develop an operational concept for the use of EGNOS by Civil Aviation in Europe.

Experimental work plays a crucial role within the work carried out by the GOV. The current 'Early Trials' activities focus primarily on gathering experience with EGNOS using the EGNOS System Test Bed (ESTB). It includes the development of prototype tools for static and onboard data collection and evaluation.

Combining both technical and operational activities, EUROCONTROL in co-operation with ESA and the French DGAC, has flight tested a specific approach procedure to the airport of Nice which could be considered as a curved Approach with Vertical guidance (APV).

2. EGNOS AS A SENSOR FOR RNAV

The Concept of Operations for SBAS is likely to vary in different parts of the world depending on the navigation strategy for these regions. The primary basis in European airspace for the management and introduction of aircraft operations and the associated navigation aids required is the EUROCONTROL Navigation Strategy for ECAC. The main driver for the Nav Strategy is the associated Area Navigation (RNAV) implementation strategy included in it. It is within the latter that EGNOS will play its role.

Area Navigation (RNAV): 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.[7]

The current planning is that Europe in the coming 15 years will transition to a pure RNAV-based environment, where only in the precision approach phase of flight the aircraft may continue to receive guidance related to the location of fixed aids such as ILS or MLS. EGNOS will, in principle, be a navigation sensor supporting all RNAV operations.

EGNOS for Approach

The accurate vertical guidance provided by EGNOS will provide some real benefits for the approach, missed approach and departure phases of flight. RNAV procedure design criteria that exist today in these phases of flight are only 2-D (therefore also known as Lateral NAV or LNAV). In November 2001 the ICAO Obstacle Clearance Panel (OCP) published the first criteria for procedures giving credit to vertical guidance into the aircraft navigation system from the Baro-altimeter. The FAA Order 8260.48 [7] with WAAS approach design criteria illustrates this concept of operations. This approach minimises the complexity of the procedures design while accommodating aircraft with various types of onboard equipment.

It is believed that both, the improved horizontal and vertical guidance from SBAS could make a substantial improvement. Firstly, the approach area width may be reduced and, secondly, the approach minima may be reduced even in the case of obstacles, since there will be no longer a need for certain operational restrictions, such as the application of temperature corrections for Baro-VNAV. Furthermore, the availability of the near Cat-I performance of EGNOS over a wide area encourages the consideration of approaches outside the runway centreline, so called curved approaches, for which renewed interest exists given the increasing environmental concerns around airports.

An Experimental EGNOS Approach procedure to Nice

To evaluate the potential use of EGNOS for approaches where part of the Final Approach Segment (FAS) is not aligned with the runway centre line (also known as curved approaches) a simulation was performed of a specific approach procedure to Nice airport illustrated in Figure 2. The simulation was performed in a commercial transport aircraft simulator with a cockpit lay-out based on the Airbus family that was operated by the French flight test facility (Centre d'Essais en Vol - CEV) in Istres.

The approach to Nice is a very interesting example where the introduction of curved RNAV approach procedures could bring environmental benefits. The current choices in Nice are between a visual approach along the peninsula of Cap d'Antibes followed by a sharp unguided turn towards Runway04L. Due to the difficulty of flying this approach the minima are high.

minima: specified altitude below which descent must not be made without the required visual reference [7]

Under low-visibility conditions the alternative is an ILS Cat-I approach straight over the peninsula raising many complaints from local inhabitants. SBAS could introduce a navigation capability that will make the curved approach more easily flyable by providing guidance all along the procedure. Furthermore it would avoid the need to fly over the peninsula even in more demanding meteorological conditions.

For the purpose of the simulation a procedure that modern aircraft are able to fly was designed by Yves Coutier of the French DGAC. Due to the unavailability of specific SBAS design criteria, working material of the ICAO OCP for Baro-VNAV was used in conjunction with ILS design criteria for the Final Approach Segment (FAS) and material developed in the early 90's for MLS-based curved approaches. This method was considered acceptable due to the absence of obstacles on the approach path. The experimental Nice procedure is illustrated in Figure 2. Important design aspects are related to the capability of the aircraft Flight Management System (FMS). The curves from waypoints MN002 to MN003 and from MN004 to MN005 are fixed-radius turns that only state-

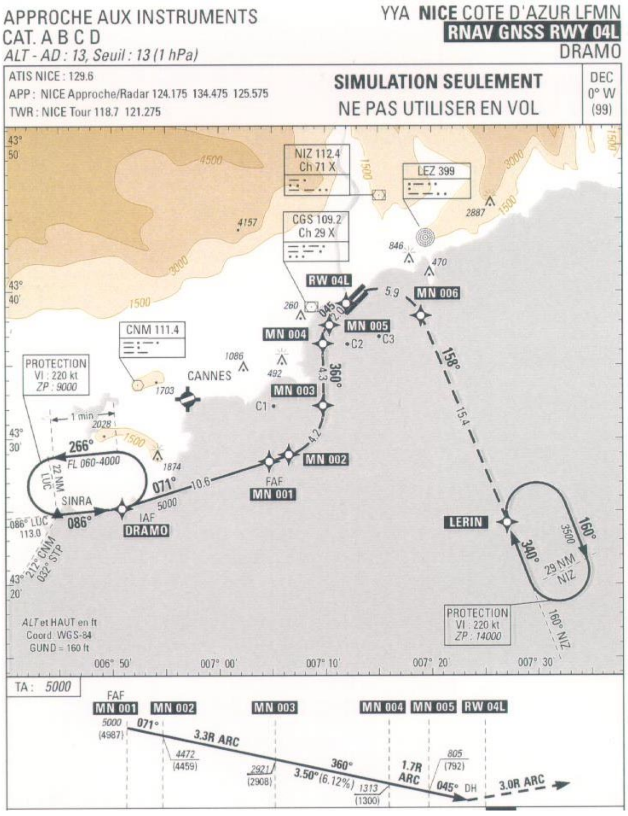

Figure 2 Approach chart from waypoint DRAMO, a possible RNAV approach to Runway 04L at Nice airport in France based on SBAS. The procedure was designed for the purpose of the SBAS approach simulation by the Aix-en-Provence Office of the French DGAC using ICAO OCP working material and is not intended for actual implementation.

of-the-art FMSs are able to fly. In particular the second turn is sensitive to tailwind, which could cause difficulties when lining up for the approach. The FAS includes the final turn and a reduced runway-aligned segment of 2 nautical miles (NM). This is only possible if the aircraft is flying the final turn in a stabilised approach configuration, which requires vertical guidance all along the approach path from a high integrity navigation aid such as EGNOS

To simulate the influence of SBAS, an EGNOS error simulator operated at ESA Technical Centre (ESTEC) was used to generate a set of data representative of the Signal-In-Space (SIS) performance of both GPS alone and of EGNOS. Although well representative of the SIS the simulator was not able at that stage to take aircraft dynamics into account. Another limitation during the simulations was the fact that the Flight Simulator at Istres had a Flight Control Unit without the capability to fly fixed-radius turns. The guidance laws in the simulator's FMS therefore were modified to allow an approximation of this capability.

Two main scenarios were studied for comparison:

- GPS alone with Baro-altimeter to capture the ILS, which is then used for landing
- EGNOS for the complete procedure

When performing the simulation, it quickly appeared that the first scenario was not possible since 2NM is too short a distance for engaging the ILS mode to allow for aircraft stabilisation. Only a navigation aid providing continuous guidance along the approach would allow the Nice procedure to be flown.

Flying the procedure using the second scenario under various wind conditions achieved satisfactory performance. In fact, it was found that the influence of the EGNOS error was not noticeable during the approach.

The main conclusion was therefore that the introduction of such procedure would be possible given the navigation accuracy achievable with EGNOS. Conditions for implementation would be, firstly, guarantees for the position accuracy through its integrity and, secondly, the capability of the aircraft in association with its FMS plus sufficient situational awareness for the pilot through appropriate displays.

3. FLYING THE EGNOS APPROACH PROCEDURE

Following the approach simulations at Istres, EUROCONTROL decided to flight-test the procedure in real-life using a dedicated EGNOS receiver onboard an aircraft for both data collection and guidance. For this purpose EUROCONTROL contracted the National Aerospace Laboratory (NLR) from the Netherlands to carry out the curved approaches as well as a series of ILS look-alike straight in approaches.

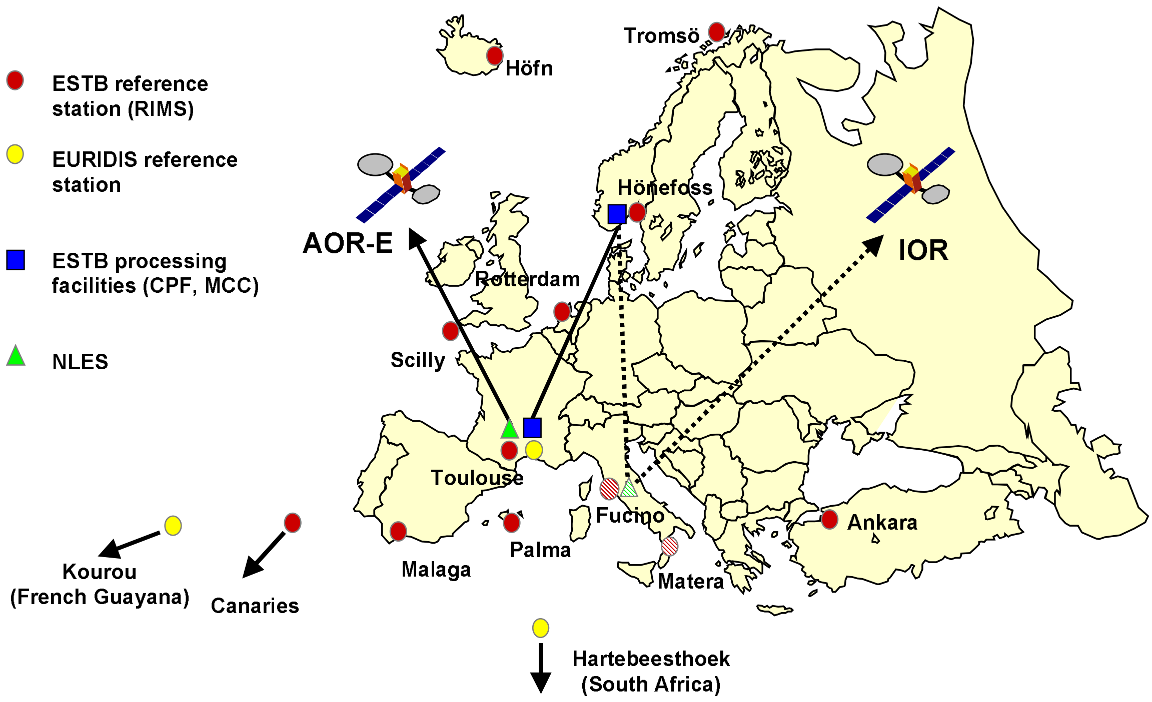

Figure 3 EGNOS System Test Bed Architecture

NLR's Cessna Citation II aircraft, integrates a Research Flight Management System (RFMS) that is fully programmable and able to accept data from various on-board systems. It includes a flight director feature, which when fed with EGNOS position data can provide curved approach guidance. A total of 12 approaches at Nice airport were performed comprising:

- 3 Flight Director (F/D) guided straigth in approaches
- 3 auto-pilot guided straight-in approaches
- 6 RFMS-F/D guided pre-defined curved approaches

EGNOS Today: The EGNOS Sytem Test Bed

Since February 2000 the EGNOS System Test Bed (ESTB) has been broadcasting over Europe. The ESTB is a complete EGNOS prototype and has recently been upgraded to be in line with RTCA MOPS Do-229A.[4]

The new ESTB configuration, called Version 1.1, has ten reference stations with Central Processing Facilities in Honefoss, Norway and Toulouse, France (see Figure 3). The ESTB signal is currently continuously available from the AOR-E Inmarsat-III satellite and for specific tests from IOR as well.

The NLR Cessna Citation II: Prepared for Flying EGNOS

NLR conducted the approaches using their Cessna Citation II research aircraft. In the framework of the FAST programme (Future Aircraft Systems Test-Bed), NLR has prepared the Citation aircraft for the integration and testing of ATM systems and concepts. One important component of FAST is the Citation Removable Experimental Flight Deck, featuring high-resolution LCD displays including:

- Primary Flight Display
- Experimental Navigation Display
- 4D Flight-Director(F/D) Guidance
- 3D Auto-flight Guidance which enables coupling of experimental guidance instrumentation to the aircraft's auto-pilot

Septentrio PolaRx-1: A new EGNOS receiver in Europe

Septentrio, a new European company developing GNSS receivers, provided a special version of their PolarRx-1 receiver able to provide, in real-time, ESTB-positioning and integrity data to the aircraft flight management system.

The PolaRx-1 is a 24-channel receiver that supports dual frequency GPS, GLONASS, EGNOS and WAAS satellite systems.

During the flights the PolaRx-1 was working on L1 single frequency, computing ESTB-enhanced position if both long-term and fast corrections were available from the AOR-E GEO satellite for at least 4 satellites in view. Otherwise the GPS stand-alone position was computed. The ESTB Ionospheric model was applied if data was available from the ESTB for at least 4 satellites in view. Otherwise the GPS model broadcast in the ephemeris message was applied. Integrity was computed in meters for the Horizontal and Vertical Protection Levels (HPL, VPL) as defined in the MOPS Do229A [4], based on the variances of the fast corrections, ionospheric model, receiver measurements (modelled for a beta Class-3) and tropospheric model.

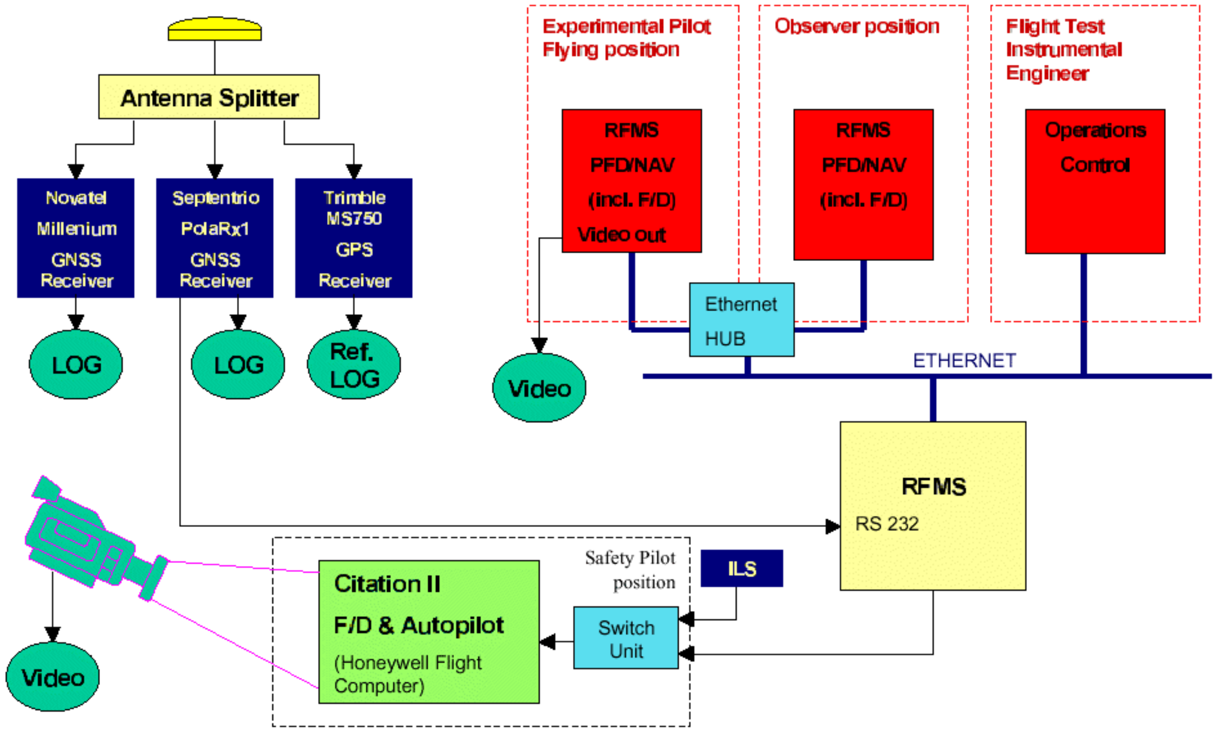

Figure 4 Platform integration in the Cessna Citation II research aircraft

Trimble RTK: A Truth Reference

To asses the accuracy of the ESTB position in flight, a dual-frequency Trimble MS750 GPS-RTK rover and ground system were used as a truth reference.

On board the aircraft the Trimble receiver was connected to the same antenna as the Septentrio receiver guiding the approach. The ground reference receiver was placed at a surveyed location on the Nice airport close to Runway04L.

Even though the Trimble MS750 system can provide a real-time reference position, offers a better accuracy when using post-processing. Therefore, to obtain accuracy within the 1cm level, data collected on ground and in the aircraft during the flight trials were post-processed afterward.

Novatel Millenium OEM-3: A second solution

A second truth reference system was based on a set of Novatel Millenium OEM-3 receivers. One receiver was integrated inside the Cessna Citation II using the same antenna as Trimble and Septentrio, while the other receiver collected data on a surveyed point on the airfield next to the runway.

The second reference point was surveyed with kind support from the French REGAL GPS permanent network.
The two sets of carrier phase data, aircraft and ground, were processed using Commercial Software based on phase processing techniques (GeoGenius from Spectra Precision Terrasat) to generate a second truth reference. This second truth reference allows further analysis and comparison for the validation of the results.

Flying Curved Approaches

The EGNOS capability to provide aircraft guidance was investigated in two different ways at the airport of Nice : Firstly, by applying the ESTB position and integrity data to support flying curved approach procedures, and secondly by providing ILS look-alike ESTB guidance to fly straight-in approaches.

As illustrated in Figure 4, Septentrio provided a special version of their PolaRx-1 firmware able to provide in real-time with a required update rate of 10Hz, ESTB-positioning and integrity data to the Cessna Citation 's RFMS. The curved procedure was coded in the RFMS and the resulting guidance information was presented on the research flight guidance display from the Removable Experimental Flight Deck. Also integrity information of the ESTB was provided to the pilot by indicating when the GNSS-1 HPL (Horizontal Protection Level) is exceeding a predefined HAL (Horizontal Alert Limit) or when VPL (Vertical Protection Level) is exceeding the predefined VAL (Vertical Alert Limit).

With this configuration a total of six curved approaches were flown, three from each waypoint: DRAMO (see Figure 2) and LERIN (see Figure 9).

Flying Straight in ILS-like

The ILS Cat-I is today the standard approach procedure to the airport of Nice under low-visibility conditions. This procedure is approaching the Runway04L straight over the peninsula of Antibes.

For flying the ILS-like approaches with GNSS-1 guidance, the RFMS was modified in order to interface with the aircraft Flight Computer. ESTB position information was fed into the route planner of the RFMS, which translated this data into ILS localiser and glide-slope deviations. By means of a switch unit (see Figure 4) this data could be selected in place of the ordinary ILS guidance to interface with the Citation's Flight Computer, which in turn generates the Flight Director or auto-pilot guidance. With this configuration, two series of three F/D guided approaches and auto-pilot guided approaches were flown.

4. DATA ANALYSIS AND RESULTS

On the 26th and 27th of September 2001, four flights with approaches to runway 04L of Nice airport were performed. During these flights data were collected on the ground and on the aircraft to be analysed and post-processed afterwards.

Data Collected Ground/Aircraft		
Receiver	Data	Data Rate
Septentrio PolarRx1	ESTB time, position and integrity	10Hz
Novatel Millenium	ESTB time, position	1Hz
Timble MS750	GPS position	1Hz

Table 1 Data collected on the ground and on the aircraft

Pegasus*Plus: An ESTB Data Processing Tool

The GOV Working Group is working towards an harmonised method of data processing and analysis for SBAS measurements. For this purpose EUROCONTROL is developing the necessary tools.

PEGASUS*PLUS is a software prototype able to process data collected in-flight and on the ground with the European Satellite Test-Bed (ESTB). The PEGASUS*PLUS environment integrates five major software components (see Figure 5).

- The CONVERTOR translates receiver-native GNSS data into a generic format
- The PLAUSIBILITY CHECK Program checks the output of the Convertor and uses user-defined plausibility rules to detect any anomalies in the data set
- The WINGPSALL program uses the output of the CONVERTOR to determine a GNSS navigation solution and the horizontal/vertical protection levels in accordance with the MOPS Do229A [4]
- The ALGORITHMS use the output of the CONVERTOR and the WinGPSALL to analyse the satellite constellation, to determine predictive integrity monitoring qualifiers and to perform integrity monitoring using Receiver Autonomous Integrity Monitoring (RAIM) or Aircraft Autonomous Integrity Monitoring (AAIM) algorithms.

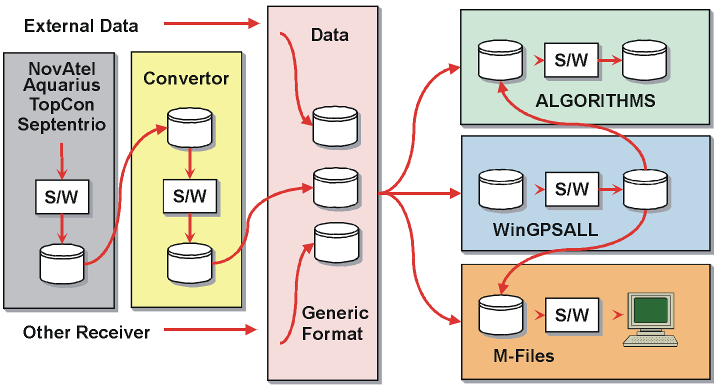

Figure 5 PEGASUS Architecture

- The M-FILE RUNNER gives the possibility to the user to run a set of Matlab tools able to display results in different formats

The PEGASUS*PLUS environment facilitates the scheduling of tasks. Furthermore, developments are underway to include a database layer for more efficient storage and retrieval of data. Additional functionalities include a truth reference processor for use with flight trial data.

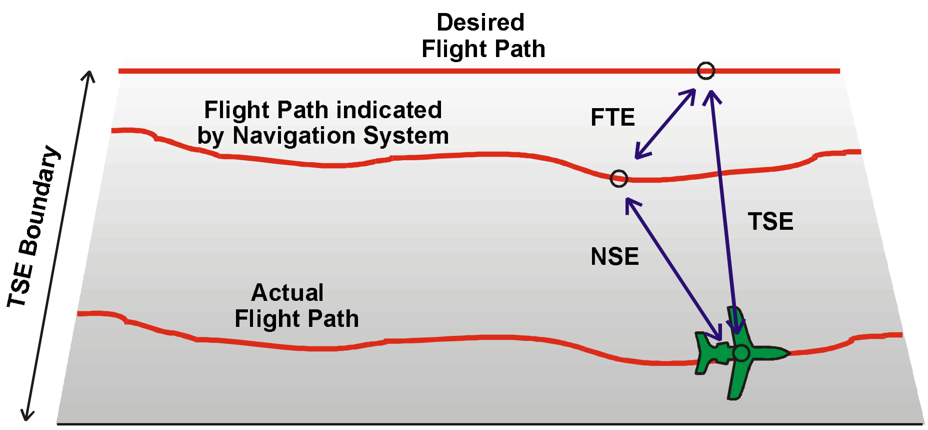

Figure 6 The Navigation System Error (NSE) is the difference between the actual position of an aircraft and its computed position. The difference between the required flight path and the displayed position of the aircraft is called Flight Technical Error (FTE) and contains aircraft dynamics, turbulence effects, man-machine-interface problems, pilot errors, etc. The vector sum of the NSE and the FTE is the Total System Error (TSE)

Data Analysis

The objective of the data processing and analysis was to determine the performance of the ESTB and the guidance derived during both manually and auto-pilot flown approaches.

The ESTB NSE (Navigation System Error) performance was assessed, together with the FTE (Flight Technical Error) for both the F/D guidance with the man-in-the-loop and for the auto-pilot guidance in case of the straight-in ILS look-alike approaches (see Figure 6). For the curved approach procedures comparison with the auto-pilot FTE was not feasible, because the Cessna Citation II auto-pilot cannot compute deviations in case of a curved approach track.

The Navigation System Error and Integrity

The flight test data from the aircraft was processed using PEGASUS*PLUS to determine a GNSS navigation solution and the horizontal/vertical protection levels in accordance with the MOPS Do229A. Using the position solution from the off-line carrier-phase solution from the Trimble RTK the NSE was determined in both, the horizontal and vertical domain.

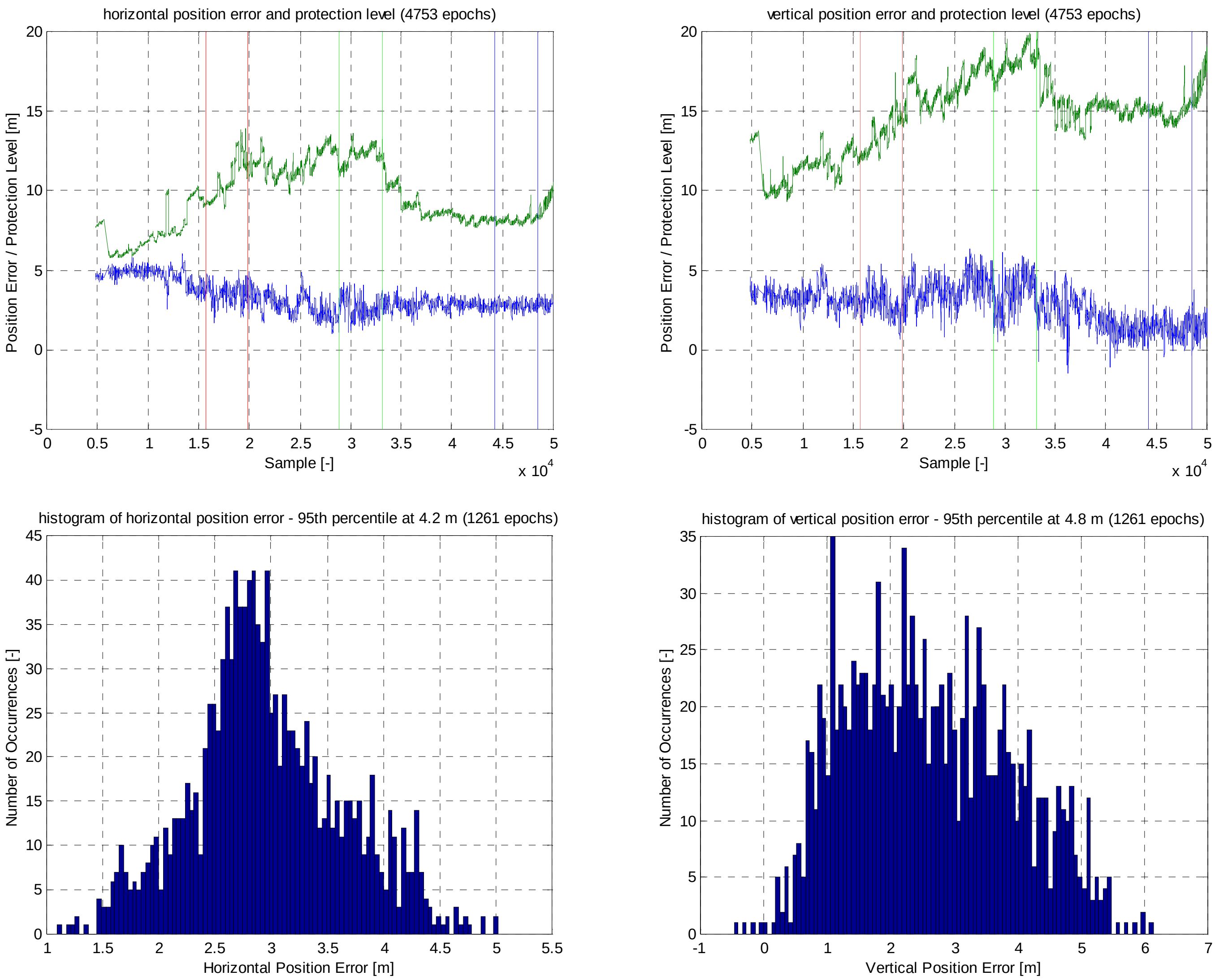

Figure 7 A series of three curved approaches were flown starting at waypoint DRAMO (see Figure 2). The first plot on the top left shows the Horizontal Position Error and Horizontal Protection Level for the total flight. In the same plot, the three approach segments from the Initial Approach Fix (IAF) to the Threshold of the Runway (THR RW04L) are identified with different colours for each approach. The plot on the top right presents the same results for the vertical component of the error. The two graphs show how the Position Error is always overbounded by the Protection Level with sufficient margin for both horizontal and vertical error components,. During the whole series of three approaches, no outage on the GNSS navigation solution was observed. Data corresponding just to the three approaches (from the IAF to the THR RW04L) was used to generate the corresponding Horizontal and Vertical Position Error distribution plots presented on the bottom half of the picture, with 95%values of 4.2m for the Horizontal component and 4.8 for the vertical.

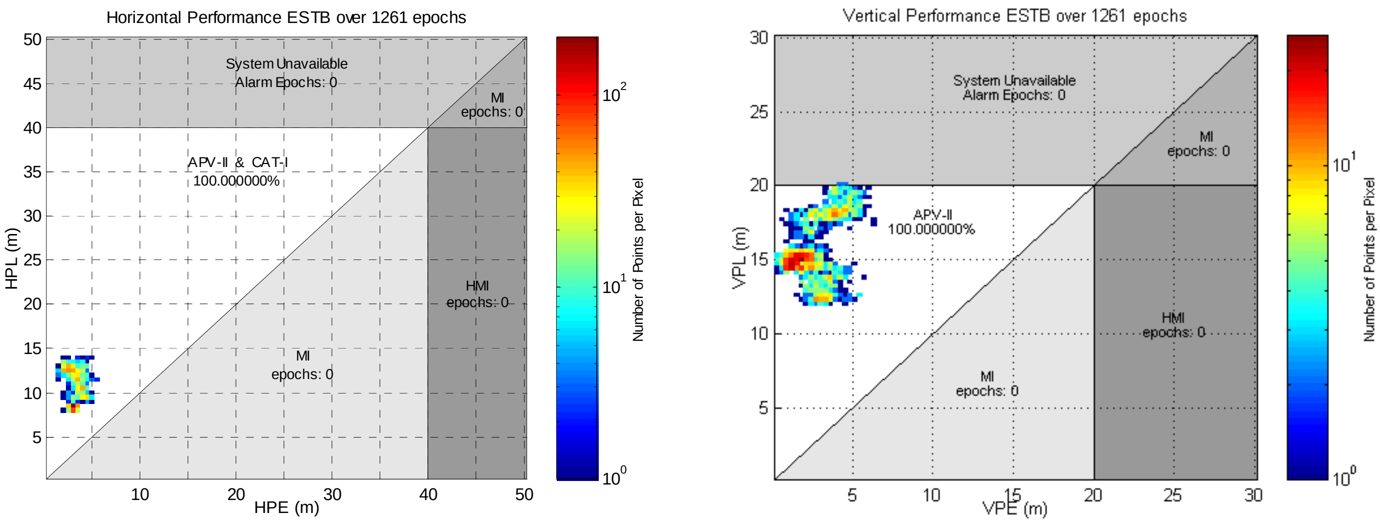

Figure 8. Known as the Stanford Plot, shows the absolute value of the Position Error versus the Protection Level for the Horizontal (left) and Vertical (right) components, where the colour coding indicates the number of measurement samples. For the evaluation of integrity the alert limits and accuracy requirements of the APV-II approach phase have been used (see Table 3). It is important to realise that in situations where the computed protection level exceeds the corresponding alert limit an alert is raised and the approach cannot proceed. If the approach has already begun, this condition is a continuity failure and a missed approach must be conducted. Otherwise the system is declared available for that epoch. As can be seen in the plots, during the three approaches from waypoint DRAMO the system achieved an availability of 100% for APV-II.

Figure 7 and Figure 8 present the ESTB system performances and integrity in the horizontal and vertical domain during the series of three approaches from waypoint DRAMO (see Figure 2).

	Horizontal NSE		Vertical NSE	
App	Mean	Std Dev	Mean	Std Dev
1	3.6 m	0.5 m	2.8 m	0.8 m
2	2.5 m	0.5 m	4.1 m	0.9 m
3	2.8 m	0.3 m	1.2 m	0.6 m

Table 2 DRAMO approaches, 27th Sept.2001 - NSE

In Table 2, the mean values and Standard deviations corresponding to the three approaches are summarised. Position accuracy between 2.5m and 3.6m were obtained in lateral, 2.8m to 4.1m in the vertical.

Requirements for APV-II	
Lateral Accuracy (95%)	16 m
Horizontal Alert Limit (HAL)	40 m
Vertical Accuracy (95%)	8 m
Vertical Alert Limit (VAL)	20 m

Table 3 Requirements for APV-II

Taking into account the performances required for APV-II operations (Table 3), it can be concluded that the accuracy achieved by the ESTB was sufficient, during the series of three DRAMO curved approaches, for precision approach operations.

Another series of three curved approaches were flown on the 27th of September but starting from waypoint LERIN. Like the DRAMO approach, this procedure (illustrated in Figure 9) was designed for the purpose of the simulations and trials by the Aix-en-Provence Office of the French DGAC using ICAO OCP working material and is not intended for actual implementation. The ESTB NSE and integrity performance was assessed obtaining similar results to those already presented for the DRAMO approach.

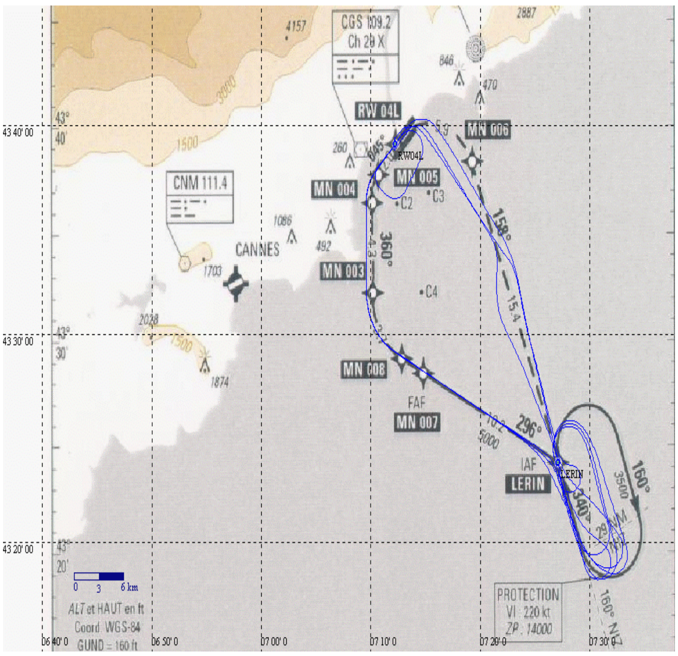

Figure 9 Approach chart from waypoint LERIN, a possible RNAV approach to Runway 04L at Nice airport. The ground tracks from the series of three approaches performed on the 27th Sept 2001 are shown.

The Flight Technical Error
The FTE (Flight Technical Error) is the difference between the required flight path and the position displayed to the pilot (see Figure 6). In order to assess the FTE, it was necessary to define a method for extracting the desired flight path for the whole approach just from the waypoints defined in the approach chart. It was assumed that the curved approaches could be coded in the Cessna RFMS as a flight path composed by straight and curved segments between each consecutive waypoint on the chart (see Figure 10).

Taking into account that assumption, the RFMS from the Cessna Citation, was able to know in real-time the GNSS position solution from the Septentrio receiver, and the desired position extracted from the coded approach chart. The FTE, calculated from the comparison of these two positions was presented on the Primary Flight Display (PFD).

Figure 10 illustrates how the lateral and vertical guidance was calculated in the RFMS during the approach for the straight and the turn segments.

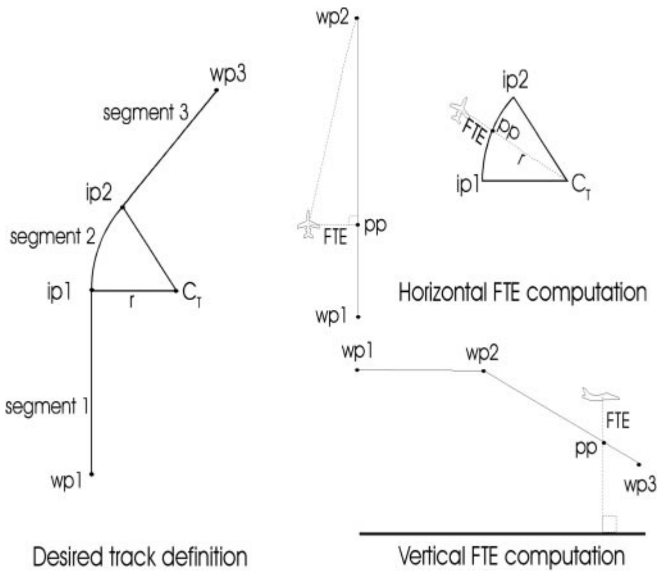

Figure 10 Desired track definition in the RFMS and FTE calculation for the horizontal and vertical component. The Horizontal FTE calculation is obtained by taking the difference between the computed position and its projection point on the desired track. Vertical FTE is determined by taking the difference between the computed altitude and the projection point on the desired track.

The results presented in this paper focus on the FTE and TSE in the horizontal plane. Results for the vertical dimension are not yet available.

Figure 11 presents the results obtained for the FTE during the series of three approaches from waypoint DRAMO.
Mean values and standard deviations were also computed (see Table 4)

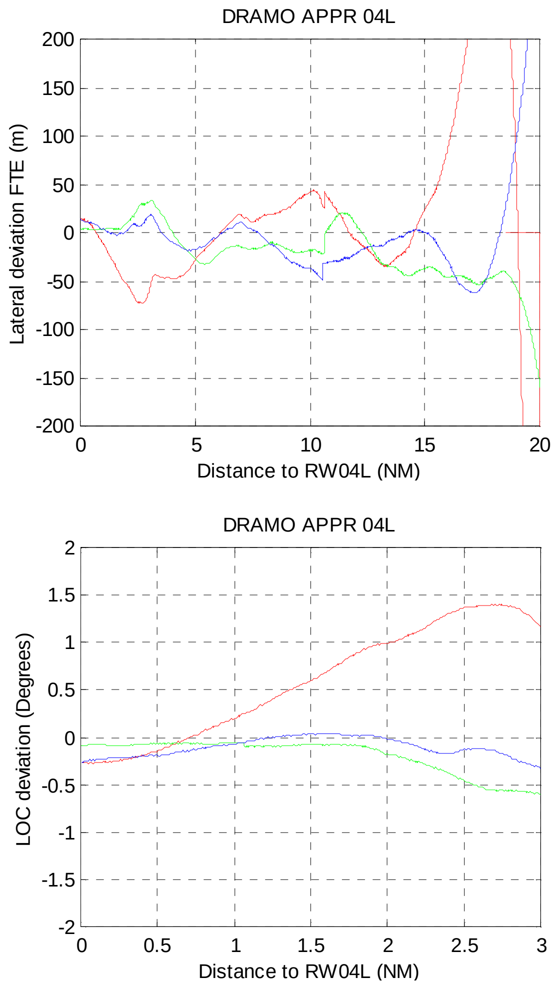

Figure 11 Lateral Flight Technical Error (FTE). The first plot above shows the FTE, in meters, for the series of three approaches from waypoint DRAMO: red for the first approach, green for the second and blue for the last one. Below, the FTE is presented in degrees for the last straight segment of 3NM from the THR RW04L as a localizer deviation. The localizer deviation is defined as the angular distance between the aircraft and the ideal localizer path for the ILS/VOR Cat I standard approach.

	Horizontal FTE		Horizontal TSE	
App	Mean	Std Dev	Mean	Std Dev
1	6.7 m	33.7 m	5.8 m	34.2 m
2	2.9 m	17.7 m	2.8 m	17.9 m
3	9.5 m	16.9 m	8.7 m	17.1 m

Table 4 DRAMO approaches, 27th Sept.2001 – FTE and TSE mean values and standard deviations

The Total System Error
The Total System Error (TSE) is the difference between the actual path and the desired path. It is the vector sum of the NSE and FTE as presented in the Figure 6. After computing the NSE and the FTE, the TSE was then assessed for the whole series of approaches. Figure 12 presents the TSE results corresponding to the three approaches from waypoint DRAMO, while the mean and standard deviation values are summarised in Table 4.

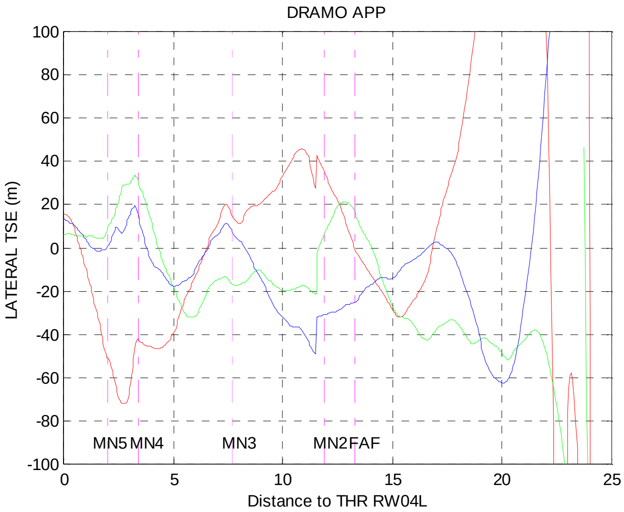

Figure 12 TSE calculated for the series of three approaches from waypoint DRAMO.

Moreover, it was interesting to compare the effect of the NSE in the total error component for the straight in approaches with the F/D or the auto-pilot guidance.

Figure 13 and 14 summarizes the TSE results obtained for both series of approaches. It can be noticed a more stable error tendence for the auto-pilot guided ones, as it was expected. The NSE and FTE calculated values were in line with the ones presented for the curved approaches (see Table 2 and 4).

The main conclusion from the error analysis is that the TSE is driven mainly by the FTE and not the NSE.

The Pilot Experience: "It was easy to fly"
After the flights, the pilots provided a report on their experiences. Their experience in general was quite positive;
«The flight director guidance from the RFMS used for the curved approaches was very smooth and provided for accurate tracking.
The Septentrio receiver in general gave stable output of HPL and VPL values and no jumps in position were experienced. Basically it was easy to fly the curved approaches using the guidance from the ESTB»

«The curved approach from LERIN was flown using the flight director with input from the ESTB. The intermediate approach track of 296 was easy to intercept and maintain. The level altitude was also easy to maintain with the guidance and the interception of the GNSS glide slope was smooth and clear. Turning to the right at MN008, with speed 180Kts, was easy, and the bank angle was well controllable with the speed reduced to 160Kts
At MN003 the flaps were selected. Afterwards, during the straight descent between this waypoint and the next MN004, the speed was reduced to 140Kts. The final right turn at MN004 aligning the RW04L was smooth and easy to control even with a slight tail wind (180/7), with bank angles between 10 and 20 degrees »

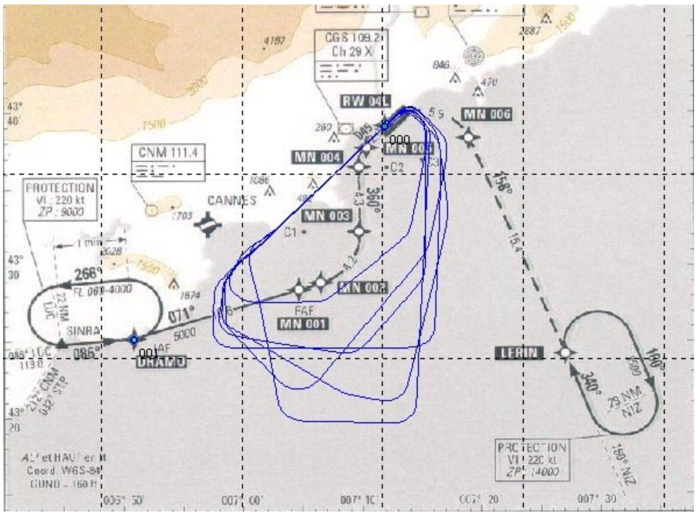

Figure 13 Ground tracks for the total of three Flight-Director guided straight in approaches. The approach profile coincides with the ILS 04L Cat-I approach to the Nice airport.

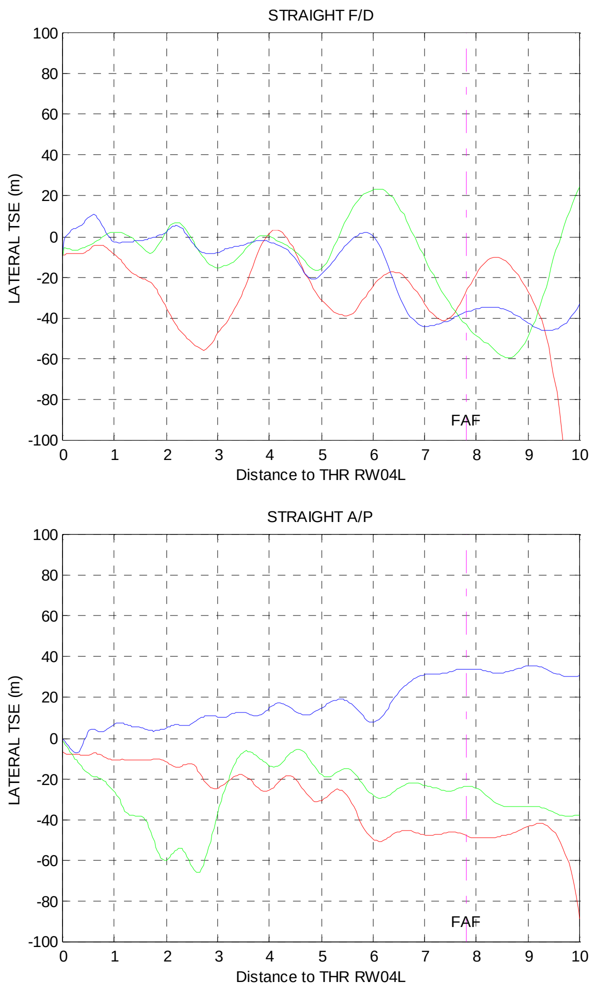

Figure 14 The plot on the top presents the TSE for the three F/D guided approaches (with the man-in-the-loop). Below the same results are presented for the auto-pilot guided ones.

For the DRAMO approaches the same smooth behaviour was observed by the pilots.

«We flew the first three straight-in approaches manually and the last three on the Auto-Pilot. During all the six approaches, localiser interception was a little bit too slow with very small bank angles. Also, a number of times a slight oscillation in the bank angle was observed while tracking the Localiser/Glide-Slope on the autopilot. But in general we were very impressed with the guidance from the ESTB system.»

5. CONCLUSIONS AND FUTURE WORK

The flight simulations in Istres in the south of France, and the approach trials to Nice have confirmed that EGNOS is a promising navigation aid to support RNAV approach operations and more particularly curved approaches. The trials that were reported on in this paper were primarily focussed on obtaining first experiences and on demonstrating potential capabilities.

Further work will need to have a greater focus on operational implementation. To this aim the GNSS-1 Operational Validation Working Group is currently developing an operational concept document describing how EGNOS will be used in Europe in the future. Furthermore support is provided to the work going on in the ICAO Obstacle Clearance Panel. Further trials planned in the near future will support this work and in addition will focus on the development of EGNOS-based approach operations in the Member States.

Follow the developments on the GOV website:
http://www.eurocontrol.fr/projects/sbas

For information on EGNOS and the ESTB check the ESA web-site:
http://www.esa.int/navigation

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- The Centre d'Essais en Vol in Istres (France) performed the simulations of the Nice approach
- NLR in the Netherlands performed the flight trials with their Cessna Citation II research aircraft
- Septentrio in Belgium provided a special version of their PolaRx-1 firmware and excellent technical support during the flight trials
- The Technical University of Braunschweig in Germany supported Septentrio

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