Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

NLR-TP-2001-197

PREVAIL
A platform for EGNOS validation flight trials

A.N. van den Berg, H.P.J. Veerman, E. Breeuwer and R. Farnworth

DOCUMENT CONTROL SHEET

	ORIGINATOR'S REF.		SECURITY CLASS.
	NLR-TP-2001-197		Unclassified

ORGINATOR
National Aerospace Laboratory NLR, Amsterdam, The Netherlands

TITLE
PREVAIL
A platform for EGNOS validation flight trials

PRESENTED AT:
the GNSS 2001 Conference, Sevilla, Spain, 8 –11 May 2001

AUTHORS	DATE	pp	ref
A.N. van den Berg, H.P.J. Veerman, E. Breeuwer* and R. Farnworth * Eurocontrol Experimental Center (EEC)	June 2001	17	6

ABSTRACT
Prior to the operational implementation of EGNOS, the civil aviation community requires assurance with respect to the performance and safety of EGNOS-based operations. In the frame of the GNSS-1 Operational Validation (GOV) project, EUROCONTROL requested the development of a platform to be used for flight trials. In this context the Netherlands National Aerospace Laboratory NLR developed together with the Spanish company GMV a platform that can be used for two purposes: EGNOS navigation data collection for Navigation System Performance analysis and EGNOS based guidance for demonstration purposes and Total System Performance analysis.
The PREVAIL platform was installed on the NLR Cessna Citation II research aircraft for flight trials during the period between 25 September and 2 October 2000. During a number of flights (ferries between Schiphol and Brétigny-sur-Orge and trials around Brétigny-sur-Orge) EGNOS Satellite Test-Bed (ESTB) based navigation data was recorded with two different GNSS-1 receivers (Aquarius®, Millennium®) and at Brétigny-sur-Orge local DGPS RTK data was recorded to serve as a truth reference.
This paper presents not only some of the results of the (early) trials that were performed with the PREVAIL platform, but it also discusses the process of analysing the (large amounts of) obtained data.

Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

NLR-TP-2001-197

PREVAIL
A platform for EGNOS validation flight trials

A.N. van den Berg, H.P.J. Veerman, E. Breeuwer* and R. Farnworth*

* *Eurocontrol Experimental Center (EEC)*

This report is based on a presentation held at the GNSS 2001 Conference, Sevilla, Spain, 8 - 11 May 2001.

Division:	Air Transport
Issued:	June 2001
Classification of title:	Unclassified

Biography

Axel van den Berg graduated as a MSc. in Aerospace Engineering from Delft University of Technology in 1997. He joined the Space Systems Department of the Netherlands National Aerospace Laboratory NLR in 1998, where he is now involved in both EGNOS and GALILEO Safety and Validation activities.

Henk Veerman obtained his MSc. in Experimental Physics from the University of Amsterdam. In 1987 he joined the Instrumentation department of the Avionics division. There he was involved in flight trial activities, first for the certification of the Fokker 50, 70 and 100 aircraft, later for projects in which NLR’s research aircraft are involved.

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. Since October 1997 he has been working as a consultant for EUROCONTROL at their Experimental Centre in the GNSS Programme Office, where he is involved in various activities focusing on the implementation of satellite navigation in civil aviation.

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 Project Office where he is responsible for various R&D projects related to satellite navigation.

Abstract

Prior to the operational implementation of EGNOS, the civil aviation community requires assurance with respect to the performance and safety of EGNOS-based operations. In the frame of the GNSS-1 Operational Validation (GOV) project, EUROCONTROL requested the development of a platform to be used for flight trials. In this context the Netherlands National Aerospace Laboratory NLR developed together with the Spanish company GMV a platform that can be used for two purposes: EGNOS navigation data collection for Navigation System Performance analysis and EGNOS based guidance for demonstration purposes and Total System Performance analysis.

The PREVAIL platform was installed on the NLR Cessna Citation II research aircraft for flight trials during the period between 25 September and 2 October 2000. During a number of flights (ferries between Schiphol and Brétigny-sur-Orge and trials around Brétigny-sur-Orge) EGNOS Satellite Test-Bed (ESTB) based navigation data was recorded with two different GNSS-1 receivers (Aquarius®, Millennium®) and at Brétigny-sur-Orge local DGPS RTK data was recorded to serve as a truth reference.

This paper presents not only some of the results of the (early) trials that were performed with the PREVAIL platform, but it also discusses the process of analysing the (large amounts of) obtained data.

Abbreviations

ADS-B	Automated Dependent Surveillance Broadcasting
AL	Alert Limit
CDI	Course Deviation Indicator
EGNOS	European Global Navigation Overlay Service
EPF	Experimental Pilot Flying
EPNF	Experimental Pilot Not Flying
ESTB	EGNOS System Test Bed
FAST	Future Avionics Systems Test-bed
GMV	Gruppo Mechanica del Vuelo
GNSS	Global Navigation Satellite System
GOV	GNSS-1 Operational Validation
GPS	Global Positioning System
MOPS	Minimum Operational Performance Specifications
NLR	National Aerospace Laboratory
PFD	Primary Flight Display
PL	Protection Level
PREVAIL	Preparation for EGNOS Validation in Approach and Landing
RFMS	Research Flight Management System
RTCA	Radio Technical Commission for Aeronautics
RTK	Real Time Kinematics
SIS	Signal In Space
TTA	Time to Alarm
XPE	Horizontal or Vertical Position Error
XPL	Horizontal or Vertical Protection Level

Contents

(17 pages in total)

1 Introduction

The main objective of the PREVAIL project was to develop a platform that could be used for dynamic GNSS-1 (Operational) Validation purposes. With this platform, practical experience can be gained from the currently available experimental signals provided by the EGNOS Satellite Test-Bed (ESTB) [ref-1]. This experience should lead to a proper preparation for the actual validation activities once the *"real"* EGNOS system will start its broadcasting. Especially standardisation and the development and validation of tools required for the processing of the data are of the utmost importance.

This paper first describes the PREVAIL platform itself and the experimental set-up for the flight trials. Next the practical issues concerning the elaboration of the acquired measurement data are discussed. Finally the performance as measured during the PREVAIL campaign is presented and discussed.

2 Dynamic EGNOS test platform

The PREVAIL test platform was developed based on an already existing EGNOS data processing tool developed by GMV. This processing tool uses the raw data from the receiver (DSNP Aquarius 5001 SD) and computes the position solution, protection levels and Receiver Autonomous Integrity Monitoring (RAIM) status, according to Minimum Operational Performance Specifications (MOPS) change 1 or 3 [ref-2], [ref-3]. Both the raw data from the receiver as well as the output of the processing can be logged for post-processing and analysis purposes.

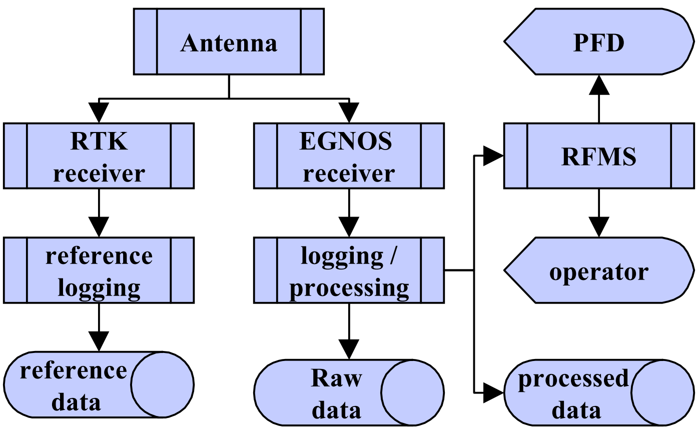

Figure 1: PREVAIL architecture

NLR's Cessna Citation research aircraft provides the airborne environment. In combination with the Future Avionics Systems Test-bed (FAST) this constitutes a very flexible platform for Flight Trials. The output of the processing tool is fed into NLR's Research FMS (RFMS), which is part of the FAST system, in order to provide guidance information to the Experimental Pilot Flying (EPF). Currently the guidance information is presented as a tunnel-in-the-sky (see figure 2). In the near future also coupling of the auto pilot and Course Deviation Indicator (CDI) will be implemented.

Figure 2: Primary Flight Display and controls for the Experimental Pilot Flying (PFD EPF)

The first pilot is in charge of safety, and navigates on the standard certified avionics, while the second pilot (or EPF) can take over control using the experimental instrumentation (FAST). The control and operation of the RFMS is performed by an operator and Experimental Pilot Not Flying (EPNF) seated behind the Pilots.

For the truth reference, a set of Trimble 750 RTK receivers has been used [ref-4]. The base station was installed near the airport, and a rover records the reference track data on board from the same antenna source as the EGNOS receiver. The resulting reference track is only available off-line after post-processing.

3 Flight trial set-up

The Prevail Flight Trials have been performed as a piggy back of an Autonomous Dependent Surveillance Broadcasting (ADS-B) Trial. This trial was held during the period of 25/09/2000 till 02/10/2000 around Bretigny Airport. A total number of 10 flights have been performed, including the ferries. However due to the fact that the full ESTB service was not available at all times, especially during the morning flights and some problems with the logging of the Aquarius receiver, only 5 flights resulted in usable data.

The equipment was installed as shown in figure 3, including one additional GNSS-1 receiver (Novatel Millennium®) that was provided by Eurocontrol in order to have an opportunity to analyse the data also by using the PEGASUS software [ref-5]. PEGASUS is an EGNOS processing tool that was primarily developed for static data analysis acquired with a Novatel Millennium® receiver. However, as this receiver was also required to provide a time base for the ADS-B trial, it was not available all of the time. In the mean time, PEGASUS has been adapted to process the Aquarius raw data.

In total, five different data streams have been logged:

- Reference base-station;
- Reference dynamic rover;
- Aquarius raw data;
- Prevail real-time solution;
- Millennium raw data.

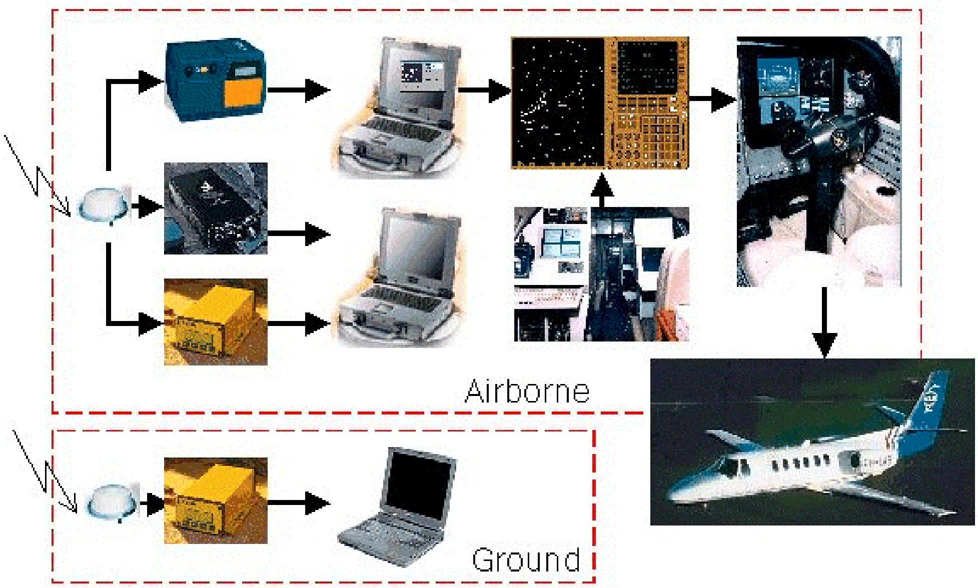

Figure 3: Flight Trial set-up

4 Data processing and analysis

Probably the most important part of validating a system by means of real data is the measurement itself. However, properly processing, archiving, analysing and presenting the results can be considered just as important. With the large amounts of data and the many conversion steps, small mistakes or inaccuracies in the processing could have serious effects on the final performance results.

For a dynamic data campaign the following issues can be addressed:

- **Synchronisation of data**

The independently acquired truth reference track needs to be compared correctly with the EGNOS position solution. The measurement sets have to be synchronised. Gaps (or outages) in one of the data sets will cause mismatching of the time-tags, but also the time-tags could be misleading. The time tags for the Aquarius receiver are based on transmission-time instead of reception-time, which is common for most types of receivers. A difference of about 0.075 seconds was identified, which coincides with the travel-time of the signals. This difference should certainly be accounted for, as in this short period of time an aircraft will have covered several meters.

- **Selection of valid data**

Usually the first minutes of a data-set contain initialisation effects, which should be disregarded. However, in the middle of the data-set one can experience more of these (unwanted) effects (e.g. due to loss of lock or Signal in Space failures). Once these unwanted effects are removed from the data, the performance might appear better than it actually is, but by leaving them in the data the opposite might be the case.

During the tests there was only an experimental Signal in Space (SIS) available from the ESTB, which is not as stable as the *"real"* EGNOS SIS should be. The same is the case for the user equipment. Therefore, it is sometimes necessary to filter the data, but this should be done, only by applying a set of agreed upon rules.

- **Validity of processing steps**

Processing of a specific data-set with different tools could lead to different results. This should be avoided by using only commonly agreed processing steps. Even in the most simple conversion steps inaccurate algorithms or parameters could have major impact on the final results. Standardisation of all steps in the process of performing and analysing a flight trial will improve the quality and the uniformity of the results from different campaigns.

- **Representation of results**

In order to enable the comparison of results from different campaigns one should also standardise the representation. The *"Stanford graph"* (figure 4 and 5) showing XPL against XPE is one of the most commonly used graphs, directly showing performance in terms of Accuracy, Availability and Integrity. However, the best first impression of the quality of the data and the performance over time during a flight trial is obtained by looking at the XPL and XPE versus time plots. Both frequency and duration of events can be identified from these plots, where this information is lost in the *"Stanford graphs"*.

PRN status plots in combination with the flown track give a better insight in the geometry-related effects on the performance. This could be useful to explain degraded performances that occurred during a flight.

In order to assess the performance in terms of accuracy statistics, the figures of the statistical distribution for XPE and XPL could provide better insights. It is important to recognise that zeros in the data (e.g. failures) will affect the statistics in a positive but undesirable way.

Only when unexplained effects require more detailed analysis one should investigate the EGNOS messages in more detail.

5 Analysis tool

The process of analysing the acquired data of a flight trial is an extensive activity. The following steps can be identified in the PREVAIL processing. This illustrates the number of tools that are required before the final results are obtained:

a) Acquired log files
- Raw reference data
- Raw EGNOS data
- PREVAIL real-time solution (binary)

b) Processing
- Reference processing => ref(time, lat, lon, alt)
- PEGASUS processing [ref-4]
  (1) Converter => 1Hz files
  (2) WinGPSall => EGNOS(time, lat, lon, alt, XPL, status parameters)
- PREVAIL bin2asc => EGNOS(time, lat, lon, alt, XPL, status parameters)

c) Apply reference track
  (1) Import of all data sets (a, b and c) into a common tool (Access via Excel)
  (2) Make data uniform (headers, format)
  (3) Synchronise to time labels
  (4) Compute and add XPE values to data logs

d) Analyse the data
  (1) Select “valid” data
  (2) Compute statistics
  (3) Generate plots (Matlab/Excel)

Most of these steps are still manual exercises. With growing amounts of data (both in size and number) this process becomes unworkable. Moreover, little errors are easily made and could affect the final performance figures considerably.

PEGASUS so far only covers a limited part of the processing. Especially the incorporation of the (dynamic) reference into the data is a crucial step that would benefit a lot from automation.

6 Performance results

Not all of the flight trails have resulted in successful data. The performance results in this analysis are presented for one relatively short and “uneventful” flight. This implies that there is not a high level of confidence in the statistical values, but it does provide an indication of the performances.

In the following, the results of the Flight Trial on the 29th of September 2000 are presented. The flight lasted half an hour and included two laps with a fly-by over the runway. Figure 4 shows the HPL/HPE (left) and the VPL/VPE (right) over a period of 2000 seconds. The height profile of the flight is included in blue. The figure also shows three different solutions. From top to bottom: first the PREVAIL real-time solution, then the PEGASUS off-line solution based on the Aquarius raw data, and below the PEGASUS solution based on the Millennium receiver output.

Figure 4: XPL (purple) and XPE (yellow) versus time for three different solutions from one single trial. (the XPL scale is 30 meters)

At first glance it appears that the performance with the Millennium receiver is better than with the Aquarius. One of the reasons is probably that the Millennium receiver has some internal smoothing, while for the Aquarius (and both PEGASUS processing's) this was turned off. The strongly degraded performance (during the fly-by) that is visible only for both Aquarius solutions suggests that the Aquarius receiver has lost track on the geostationary signal, while the Millennium continued without a problem.

The major conclusion that can be drawn from this figure 4 is that the quality of the tools/platforms for validating the performance should be thoroughly scrutinised. Another example of the differences in solution is shown in Figure 6.

Figure 5 represents the "Stanford graphs" for this flight. It is a plot of the XPL versus XPE of all the separate samples and does not provide any information on frequency and duration of events. This implies that the integrity breaches (below diagonal VPL=VPE) that show up in the Vertical graph have not necessarily lasted longer than the allowed Time to Alarm (TTA).

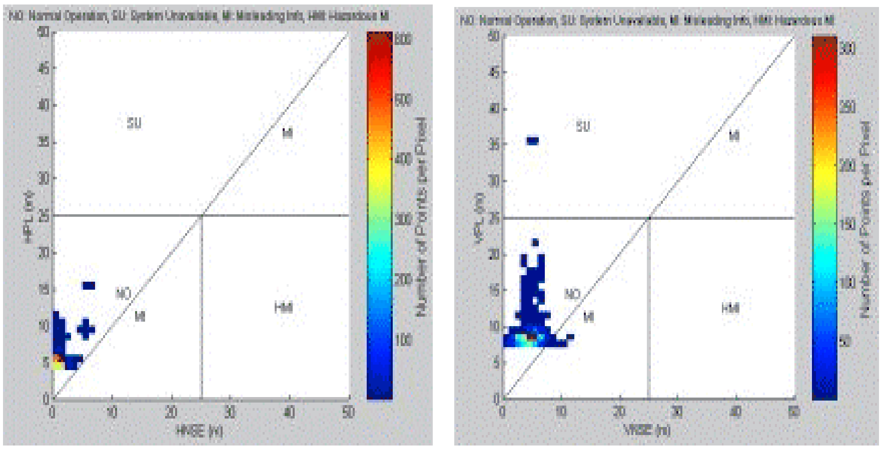

Figure 5: Horizontal (left) and Vertical (right) "Stanford graphs"

Accuracy

Accuracy can be presented in two different forms: the protected accuracy or Protection Level (PL) and the experienced accuracy or Position Error (PE). The first is what the pilot is aware of and thus drives the "practical" availability. The second is the actual accuracy performance of the system, as formulated in the requirements. In the following table the PREVAIL solution accuracy statistics are provided.

	HPL	HPE	VPL	VPE
average	5.1	1.3	8.3	4.3
sigma	0.3	1.0	0.5	1.0

Availability

Availability can be directly derived from the "Stanford graphs", given a specified Alert Limit (AL). However for a justified Availability result, a lot more data should be regarded. Gaps in the data that are caused by the truth reference data should not be taken into account. However all other out of scale events should!

During the half-hour flight the horizontal and vertical Protection Levels have not exceeded the Alert Limits (both set to 25 meters), except during a short interruption of the position solution. There were a few interruptions in quick succession, totalling 18 seconds of outage, with the total unstable period lasting a little more than 1 minute.

In combination with a 20 seconds period of RAIM alert, the total availability for this flight was 98% (38 seconds on a total of 1981 seconds).

Continuity

Continuity is rather difficult to assess as there has not been specified how long an outage is allowed to last. Currently all initiations of an outage regardless of the duration should be taken into account. This implies 5 times in half an hour. Translated into a probability of occurrence per 15 sec the trial endured a continuity of 0,04/15s.

Both the availability and the continuity results can not be considered representative for the ESTB performance. The amount of "valid" data is far too little for this.

Integrity Risk

Integrity Risk of the system can be expressed in two different ways: either with respect to the Protection Level or to the Alert Limit. In order to have operation independent results it is more useful to express Integrity Risk with respect to the Protection Levels.

Accounting for the allowable Time to Alarm (TTA), all of the short-term integrity failures should not be taken into account for the integrity computation. During the flight only in a few short (less than TTA) events, the Vertical Protection Level was exceeded by the Vertical Position Error. This implies that no integrity failures occurred during this flight.

Combination of flights

It is clear that the previous discussed performance is based on too little data to be significant. In order to reach a higher confidence in the performance figures one needs to combine the results of separate flight trials. It is very tempting to only take into account "successful" flight trials. At the present experimental stage this is realistic, and one of the major goals is to identify the sources of "unsuccessful" flight trials.

Figure 6 is an example of such an unsuccessful flight trial. Both HPL/HPE-time graphs show completely different results, but are based on the same data. It is hard to tell which one is the *"best"* (or most realistic) result. Probably the processing of one off the two was not correct.

PREVAIL indicates a slowly decreasing performance finally leading to extreme HPL values followed by a complete loss of the solution. The integrity is still guaranteed (HPL > HPE) during this first part of the trial, but availability is strongly affected.
The PEGASUS solution indicates the opposite. It starts with unexpected high values that do not show up in the PREVAIL solution. The solution is even lost for a few minutes, but when it comes back the performance looks nominal (with the exception of a lot of singular points) for a while. However, halfway through the flight there is a jump in the HPE resulting in a integrity violation, which lasts until eventually the complete solution is again lost.

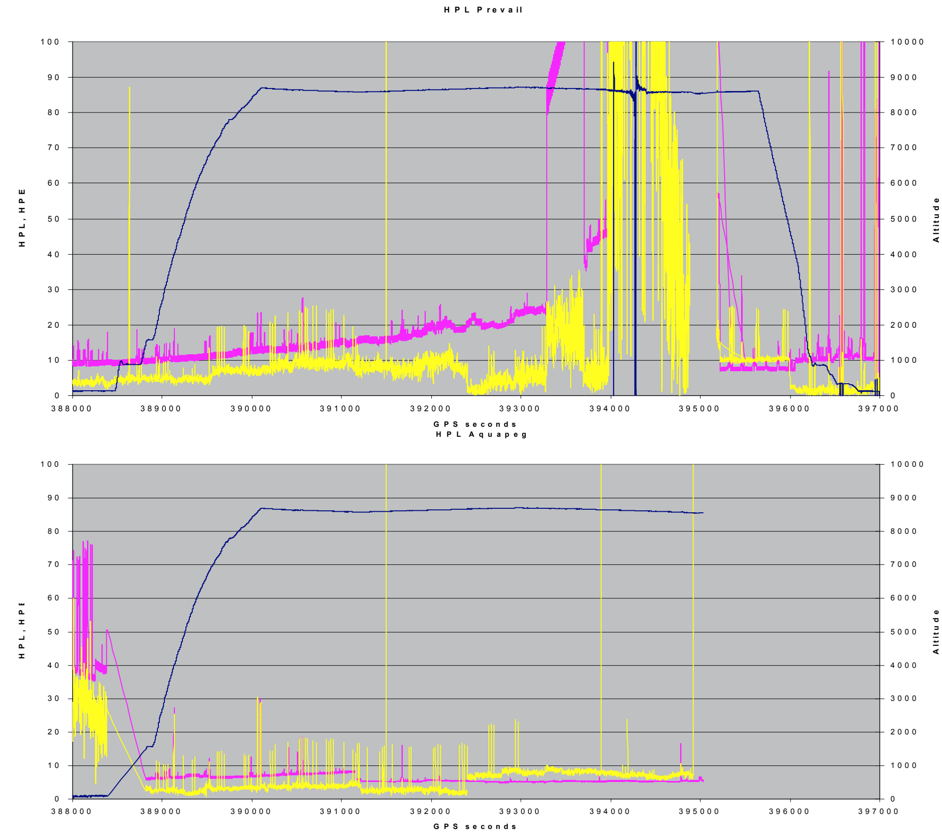

Figure 6: HPL(purple)/HPE(yellow) versus time for the realtime Prevail solution (top) and the off-line Pegasus solution (bottom) from one flight on 28/9/2000, (HPL scale is 100 meters)

Once the performance is more stable and the flight trial processing is fully standardised (*validated*) the different flight trials should result in similar performances. Some will be better than others, but for validation purposes none shall be discarded.

7 Conclusions

Although based on a limited amount of data, the achievable dynamic navigation performance with the ESTB in terms of accuracy and protection levels seems to be conform expectation. However, the performance in terms of availability and continuity is strongly affected by the experimental state of both the service (ESTB) and the user equipment (receivers).

Obviously the “real” validation can only be initiated as soon as the final operational EGNOS service becomes available. However, the current ESTB service is a good environment to prepare for the validation. At this stage the tools and processing steps themselves should be validated and specific behaviour of the performance can be analysed.
Analysing the EGNOS performance under flight conditions is an extensive activity. There are many steps of processing necessary before the performance becomes apparent. It is recommended to automate this process as much as possible. In order to increase the confidence in the performance figures resulting from (validation and certification) Flight Trials, it is important to standardise all of the processing steps and validate the tools to be used for the data processing and analysis.

8 Acknowledgements

The authors would like to acknowledge Harm van Gilst, Emilio González and Jose Maria Legido for their hard and good work during the holiday period in order to reach the short deadline for the flight trials. Furthermore we would like to thank the ADS-B team for their co-operative support and the opportunity to share their flight trial.

9 References

[ref-1] *N. Suard, H. Secretan,* ESTB SIS user interface description*, E-TN-ITF-E31-0008-ESA, June 2000.*

[ref-2] *RTCA/DO-229,* Minimum Operational Performance Standards for GPS/WAAS Airborne Equipment*, Change 1, 16/01/1996.*

[ref-3] *RTCA/DO-229a,* Minimum Operational Performance Standards for GPS/WAAS Airborne Equipment*, Change 3, june 1998.*

[ref-4] *J. Samson, H. de Haan,* Evaluatie van de Trimble MS750 GPS-ontvangers*, NLR-TR-2000-448, August 2000.*

[ref-5] *C. Butzmuehlen,* Pegasus ICD*, issue E, November 2000.*

[ref-6] *E. González and J.M. Legido,* GNSS User Platform User Manual*, GMV-PREVAIL-UM, version 1.1, 29/09/00.*