MARKAB: A Toolset to Analyze EGNOS SBAS Signal in Space for Civil Aviation

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Abstract. The aim of this paper is to describe a toolset named MARKAB, recently developed to analyse the EGNOS Signal in Space. This toolset is intended to analyse the performance that can be obtained using the augmentation navigation system in civil aviation user community. We demonstrate the utility of MARKAB by processing SBAS Signal in Space logged with an EGNOS/WAAS dual frequency receiver installed at our monitoring station. Latest results show that MARKAB establishes an important improvement in the analysis of Required Navigation Performance to the augmentation system, contributing with a new technique to assess the performance in term of Continuity of Service.

1 Introduction

The validation of a Satellite Based Augmentation System (SBAS) requires a careful analysis of performance that can be experienced by the user before the system can be declared operative. The European Geostationary Navigation Overlay Service (EGNOS) is the European SBAS equivalent to the U.S. Wide Area Augmentation System (WAAS). With three geostationary satellites and a network of ground reference stations, this system transmits differential corrections and integrity data to enhance the positioning signals sent out by satellite positioning systems (GPS, GLONASS), and make them suitable for safety-critical applications such as commercial aviation. At the beginning of June 2006 the EGNOS system is ready to broadcast a continuous signal, including the so-called "Message type 0/2" (MT0/2) allowing to offer a graceful transition from EGNOS System Test Bed (ESTB) to EGNOS for Global Navigation Satellite System user communities. The broadcasted signal use the MT0/2 and the Band 9 of the ionospheric grid with the aim of improving the performance in the Northern European latitudes. The addition of MTO/2 is a significant milestone in the development of the navigation system for users of non-safety of life services. In the frame of performance validation activities, the European Organisation for the Safety of Air Navigation (Eurocontrol) has established a standardized data collection environment to evaluate the performance that can be achieved during flight operations for which the navigation system is intended. Thanks to the daily data collection and evaluation a wide expertise has been built up on the tools that are currently being developed to understand how the augmentation system works and how its performance can be evaluated. To be able to tell whether the system is available and can be used during a given period it will therefore be necessary to analyse its performance and compare it to the requirements. The requirements are expressed by the International Civil Aviation Organization (ICAO) under the form of Standards and Recommended Practices [2] in terms of Required Navigation Performance (RNP). The performance objectives for aeronautical applications are usually characterised by four main parameters: Accuracy, Integrity, Availability and Continuity. Among the principal user community the requirements for civil aviation are very strict in terms of Integrity and Continuity and hence the EGNOS performance is driven by those needs. In this contest it is important to establish the performance of the system that would be experienced by a potential user, and to verify the stability of the performance in certain time period. This paper describes a toolset named MARKAB recently developed and tested in MATLAB The Mathworks Inc. environment to analyse the EGNOS Signal In Space (SIS). Our objective is to demonstrate the utility of our toolset processing the SIS logged in a series of static measurements over extended periods with an EGNOS/WAAS dual frequency receiver, installed at our monitoring station. Results show that MARKAB represents a significant improvement in the frame of performance evaluation contributing to define a new technique to assess the Continuity of Service (CoS). Particular attention will be paid on the currently achieved system performance and how the augmentation system is able to fulfil civil aviation mission requirements.

2 Background

Each of the four RNP parameters corresponds to the risk that a certain event occurs that has the potential to lead to an excessive position error. The Accuracy covers the risk that an excessive system error causes a position failure. Unfortunately, real life navigation systems will always suffer from rare failures that cause its performance to degrade beyond the alert limit, which would make the system effectively unusable. However, when the user is made aware of failure, he can revert to backup navigation systems to still enable him to stay within the alert limit. In other words, failure detection can be exploited to mitigate the risk of position failures. The risk associated with latent system failures is covered by the Integrity requirement. The necessary level of integrity for each operation is established with respect to specific alert limits. When the integrity estimates exceed these limits, the pilot is to be alerted within the prescribed time period. Although reversion to a backup system mitigates the risk of using an erroneous system, such a reversion is itself without risk. This is particularly true in landing, the most demanding phase of flight. An unscheduled loss of the ability to determine and display a valid position, due to the detection of a failure condition, is specified by the Continuity requirement. For this concept, the Continuity of Service (CoS) relates to the capability of the navigation system to provide navigation Accuracy and Integrity during a given period for an intended operation. Finally, Availability covers the risk of a lack of guidance at the initiation of an intended operation. The RNP concept assumes that some kind of failure detection mechanism is used to notify the user in case of dangerous malfunctions. Signal availability is the percentage of time that navigational signals transmitted from external sources are available for use. Availability is a function of both the physical characteristics of the transmitter facilities [4]. The SBAS system provides the user with integrity information to compute the protection levels (Horizontal and Vertical Protection levels, HPL and VPL), which represent an upper bound on the position error. For each operational mode, the system is declared as unavailable when the protection level is greater than the Alert Limit (AL) defined in [2]. If the system is available and the position error is not bounded by the protection level, thence the event is considerer as a HPL and VPL failure, since the protection level is always supposed to be an upper bound on the position error (PE). In such a case, the event is declared as Hazardously Misleading Information (HMI), if the position error exceeds the AL or as Misleading Information (MI) if the AL isn't exceeded.

3 Markab

There are several approaches to the validation of satellite navigation systems. These include analysis, modelling and evaluation of collected data. In general, data must be collected and evaluated in order to demonstrate that the implemented system is compliant with the requirements [2]. After this, it is possible define the operational rules and procedures for aircraft to use the system for particular applications. Even if some studies have already been initiated on the operational side still various issues have to be resolved and will have to be adapted as more is learned about the actual operations that EGNOS can be used to support. The objective of MARKAB is to provide an efficient and fast statistical evidence about the performance of EGNOS in the airborne environment of commercial airlines and to determine to what extent it could be safely approved for operational use. It doesn't want substitute other tools developed during the Operational Validation phase, but simply it wants to be a toolset component that allow us to analyse and compare the performance of the augmentation system in a simple way and giving the possibility of easy access to the graphical presentation of the results. As mentioned above, a standardized data collection environment has been established to evaluate the performance by means a prototype tool named PEGASUS. It aims to be a step forward the development of a standard processing and analysing tool to be used for the EGNOS validation. MARKAB consists of several software components called modules. Each module is designed for a specific task like data concatenation, position solution analysis and processing. The toolset is composed of two main standalone components of the PEGASUS:

- **Convertor module**. It converts the binary raw data file producing several ASCII readable files which contain GNSS and SBAS related data.
- **GNSS_Solution module**. Its aim is to deliver a position solution compliant with the MOPS [3] for GNSS receivers used in avionics (GPS, SBAS).

These modules are completely integrated with those of MARKAB. This particular design of the MARKAB architecture allows the access to all the data, even at intermediate stages of data evaluation, and its display and visualisation. A complete data processing sequence can be summarized in Fig. 1.

The core of MARKAB is the developed module named Gen_report. Its aim is to manage, analyse and combine easily data from different input files or processed with

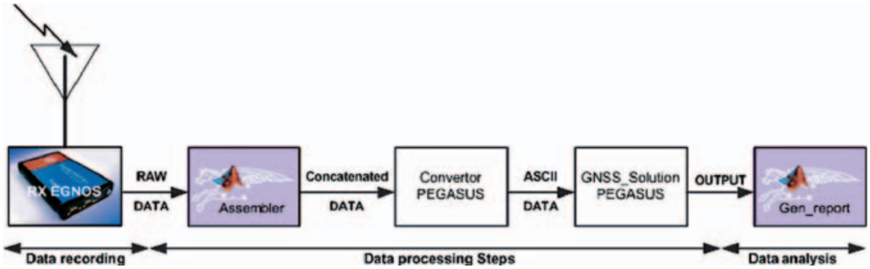


Fig. 1. MARKAB structure.

different modules. This module is composed of several MATLAB functions that implement the First Glance Algorithm [5], in addition to our algorithms to compute new parameters and indexes to evaluate the performance of the augmentation system. The RNP parameters definitions used are those defined in [3]. Gen_report reads from a directory, defined by the user, a series of files, (e.g. *.pos; *.smt; *.rng) generated by the standalone PEGASUS modules. These file are related to days belonging to the time period that the user is interested to analyse. The input data, results and parameters are stored in a dedicated directory on the computer file system, providing an easy access to the results, either by visualising the results by means of plots, or by producing a standard daily report containing the results.

4 Continuity of Service

The key process to verify the EGNOS system performance in terms of Continuity is the relationship between the CoS and the continuity characteristics of the broadcasted corrections [10]. The EGNOS system performance requirements, and in particular the CoS, are specified in the position domain. To assess CoS it is necessary verify that the system is able to provide navigation Accuracy and Integrity during any required time interval for an intended operation; such requirements are indicated in Table 1.

In the position domain, all parameters as HPL and VPL are time discrete series of values or samples with a time period of 1 sec. In according to [5], all valid samples for a given operation are computed by filtering all samples in order to take only those that are valid. With valid samples are identified all samples that have a navigation mode different from "*no position solution available*". At this point, it is important remark that are defined available samples all valid samples that have the corresponding navigation mode set on "*SBAS Precision Approach position solution*".

Table 1. CoS requirements.

Phase of flight	Departure	En-route	Terminal	Initial approach	APV
CoS	150 sec	300 sec	150 sec	150 sec	15 sec

For a given operation, available samples are computed considering all available samples for which the corresponding Protection Levels (*HPL* and *VPL*) are less or equal to the related Alert Limit threshold (*HAL* and *VAL*). For Precision Approach with Vertical guidance procedures (APV) the Alert Limits [4] are reported in Table 2.

We observe that considering all available samples and assigning the value 1 to the samples that are available for a given operation and the value 0 to the remaining samples, we obtain for each operation a time discrete binary series of the same length represented by the total number of all available samples. Therefore, each series represents the instants in which the augmentation system is available (samples of value 1) and when it is unavailable (samples of value 0). We define they as Total Availability for a given operation. Until today the PEGASUS tool analyzes the Continuity criteria counting, for a given operation, only all transition events from unavailable to available. This events are defined as Continuity events [5]. For greater clarity, we define Discontinuity states all instants in which the series is zero (Fig. 2). From the Total Availability, we can assess the CoS during any required time interval for an intended operation [2] performing that for each time interval there aren't discontinuity states.

In this way, for a given operation, to assess the concept of CoS we can filter the binary time discrete series of Total Availability by a Discrete Time Sliding Window Filter (DTSWF), (Fig. 3).

Considering a step size of one second (one sample), for each time sliding Window Size (*WS*), corresponding to the required time interval, it assigns at the current sample belonging to the lower limit of the current sliding window (current output sample) the value 1 if in the related window there aren't discontinuity states otherwise

Table 2. Alert limits in APV.

Facility performance	Horizontal alert limit	Vertical alert limit
APV-I	40 m	50 m
APV-II	40 m	20 m

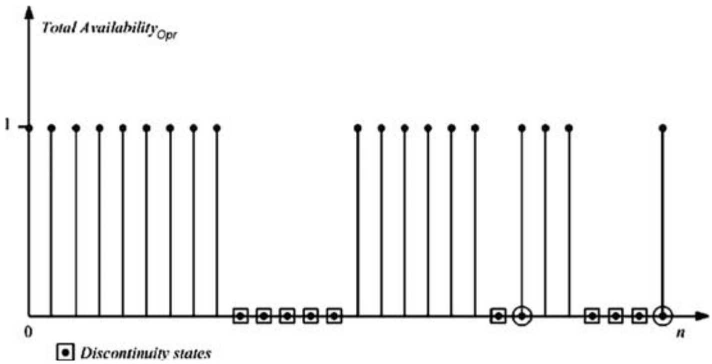


Fig. 2. Total availability for a given operation.

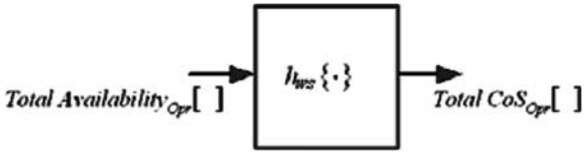


Fig. 3. DTSWF.

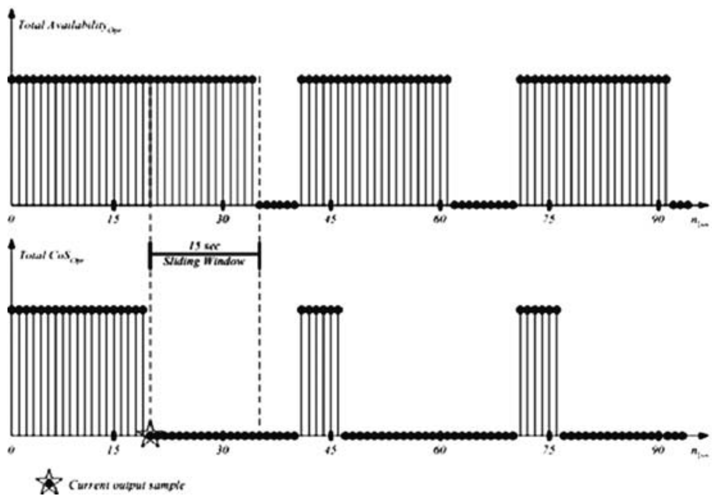


Fig. 4. CoS filtering in APV procedures.

it assigns the value 0 if in the related sliding window there is at least a discontinuity state (Fig. 4).

Thus we have another binary time discrete series, that we declare Total CoS for a given operation, in which any sample that has the value 1 represents the instant from which the navigation system will be available for the required time interval. Then indicating with $N_{available}$ the total number of available samples (duration of the discrete series), we can define the probability that the augmentation system will be continuous in any required time interval for a given operation as follow:

$$CoS_{WS\_Opr} = \frac{\sum_{N_{available}} Total\ CoS_{Opr}}{(N_{available} - WS - 1)} \quad (1)$$

5 Signal in Space Processing

In this section we show the most features of MARKAB processing the SIS logged in a series of static trials performed during May 2006. A series of results will be presented to assess the performance of our toolset and particular attention will be paid to the achieved system performance and how far the EGNOS system is able to fulfil civil aviation mission requirements.

5.1 Monitoring Station

Our monitoring station is located in a site of Sorrento country provided by our Department. The antenna is located on the roof of a building with good sky visibility. Its precise position has been determined by means GPS phase measurements in the WGS84 coordinate reference system:

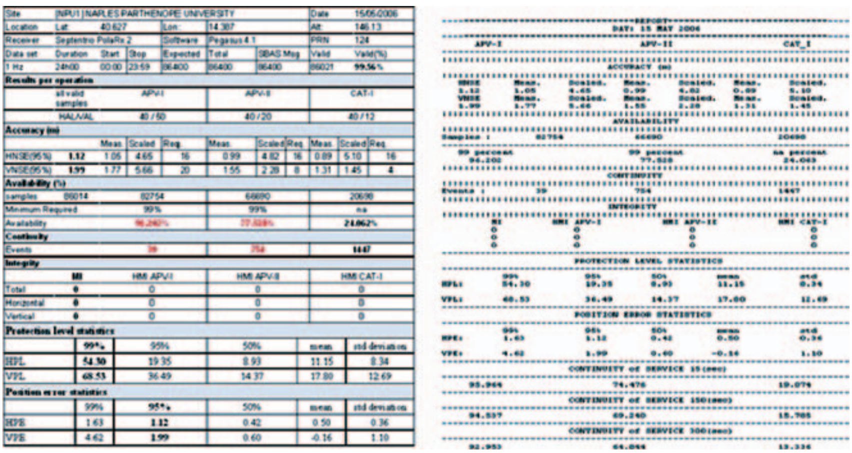
- Latitude: 40.62678163 North
- Longitude: 14.38733587 East
- Altitude: 146.132 m (above WGS84 ellipsoid)

The equipment of monitoring station is composed of following elements:

- Septentrio PolaNT dual frequency GPS antenna
- Septentrio-PolaRx2.4 GPS/SBAS receiver
- Logging PC connected to the receiver

5.2 MARKAB Performance

The main objectives of MARKAB are the automation of data processing within any time period (e.g. one day or more days, generally one month), to keep traceability of the process and to find data and results storage solution allowing the combination and the easy access to all data. To assess MARKAB accuracy performance in Fig. 5 is reported a comparison between a daily report generated by PEGASUS and the one by MARKAB. It is evident that the statistical parameters computed with MARKAB are the same with ones computed by PEGASUS. This result encourages us to show data in a series of plots to summarize the performance during any time period. Then we show a series of original plots to analyse the latest EGNOS performance.



Site	[NPU1] NAPLES PARTHENOPE UNIVERSITY								Date	15/05/2006
Location	Lat:	40.627		Lon:	14.387				Alt:	146.13
Receiver	Septentrio PolaRx 2			Software	Pegasus 4.1				PRN	124
Data set	Duration	Start	Stop	Expected	Total		SBAS Msg		Valid	Valid(%)
1 Hz	24h00	00:00	23:59	86400	86400		86400		86021	**99.56%**
Results per operation										
	all valid samples	APV-I			APV-II				CAT-I	
	HAL/VAL	40 / 50			40 / 20				40 / 12	
Accuracy (m)										
		Meas.	Scaled	Req.	Meas.	Scaled	Req.	Meas.	Scaled	Req.
HNSE(95%)	**1.12**	1.05	4.65	16	0.99	4.82	16	0.89	5.10	16
VNSE(95%)	**1.99**	1.77	5.66	20	1.55	2.28	8	1.31	1.45	4
Availability (%)										
samples	86014	82754			66690				20698	
Minimum Required		99%			99%				na	
Availability		[illegible]			[illegible]				**24.062%**	
Continuity										
Events		39			754				**1447**	
Integrity										
	MI	HMI APV-I			HMI APV-II				HMI CAT-I	
Total	0	0			0				0	
Horizontal	0	0			0				0	
Vertical	0	0			0				0	
Protection level statistics										
	99%	95%			50%			mean	std deviation	
HPL	**54.30**	19.35			8.93			11.15	8.34	
VPL	**68.53**	36.49			14.37			17.80	12.69	
Position error statistics										
	99%	**95%**			50%			mean	std deviation	
HPE	1.63	**1.12**			0.42			0.50	0.36	
VPE	4.62	**1.99**			0.60			-0.16	1.10	

```
REPORT
DAY: 15 MAY 2006
APV-I                         APV-II                        CAT_I
ACCURACY (m)
HNSE    Meas.   Scaled.   Meas.   Scaled.   Meas.   Scaled.
1.12    1.05    4.65      0.99    4.82      0.89    5.10
VNSE    Meas.   Scaled.   Meas.   Scaled.   Meas.   Scaled.
1.99    1.77    5.66      1.55    2.28      1.31    1.45
AVAILABILITY
Samples :       82754            66690                  20698
99 percent                  99 percent                  na percent
94.202                      77.520                      24.063
CONTINUITY
Events :        39               754                    1447
INTEGRITY
MI          HMI APV-I          HMI APV-II          HMI CAT-I
0           0                  0                   0
0           0                  0                   0
0           0                  0                   0
PROTECTION LEVEL STATISTICS
        99%       95%       50%       mean      std
HPL:    54.30     19.35     8.93      11.15     8.34
VPL:    68.53     36.49     14.37     17.80     12.69
POSITION ERROR STATISTICS
        99%       95%       50%       mean      std
HPE:    1.63      1.12      0.42      0.50      0.36
VPE:    4.62      1.99      0.60      -0.16     1.10
CONTINUITY of SERVICE 15(sec)
95.964                 74.476                 19.074
CONTINUITY of SERVICE 150(sec)
94.537                 69.240                 15.705
CONTINUITY of SERVICE 300(sec)
92.953                 64.099                 13.336
```

Fig. 5. PEGASUS and MARKAB daily report.

5.3 Monthly Analysis

To have a summary representation of performance we present an analysis performed on raw data collected during May 2006. Briefly we report only the most important daily parameter plots.

5.3.1 Accuracy. Daily Accuracy is computed as a 95 percentile of the error distribution of all valid samples within the assessed period [5], (Fig. 6).

5.3.2 Integrity. Daily Integrity is evaluated computing the minimum observed safety index defined as the ratio of protection level to the related position error (Fig. 7). The dashed line represents the threshold to MI detection.

5.3.3 Availability. Daily Availability is computed as the ratio of the number of available samples for a given operation to the total number of valid samples [5] (Fig. 8).

5.3.4 Continuity of Service. Daily CoS is computed in according to the relation (1) defined above (Fig. 9).

5.4 Daily Analysis

Daily analysis is performed processing raw data collected on 15 May 2006.

5.4.1 Performance in APV Procedures. The main features of MARKAB are a new graphical representation of performance parameters. We show a summary plot of performance provided in APV procedures (Figs. 10 and 11). In the upper and lower plot respectively it is represented the Total Availability and the Total CoS discrete

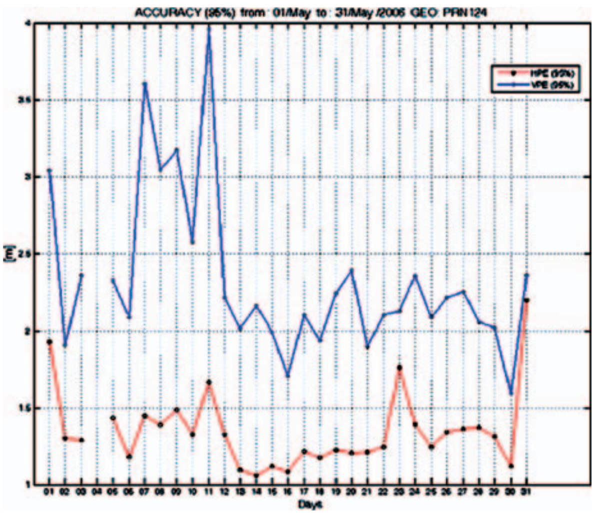


Fig. 6. Accuracy.

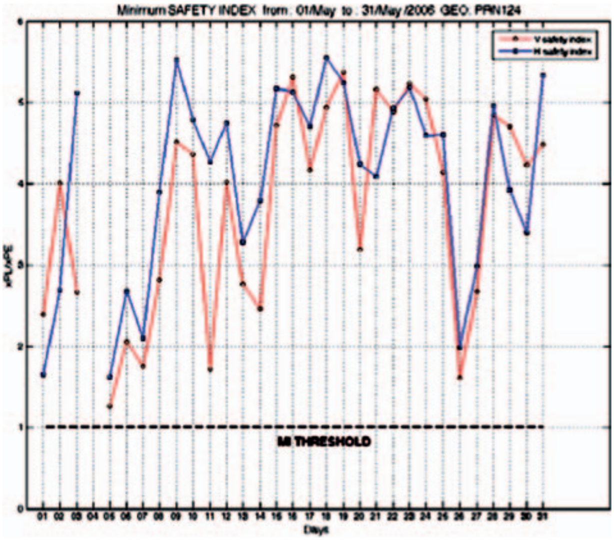


Fig. 7. Safety index.

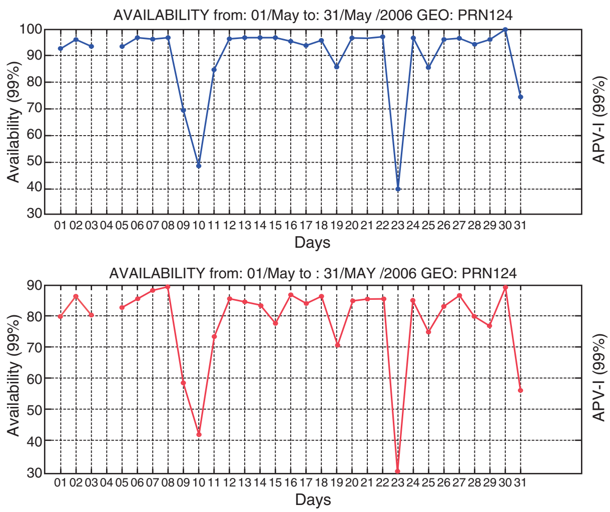


Fig. 8. Availability.

series for an interval of 15 sec, [4]. In the middle plot it is shown the continuity events position and duration referred to the upper plot (grey lines indicate only the transition events).

5.4.2 Integrity. Currently to assess performance in terms of Integrity the most used plot is the so called Stanford plot that summarizes the relations between the protection level (PL) and the position error (PE), Fig. 12.

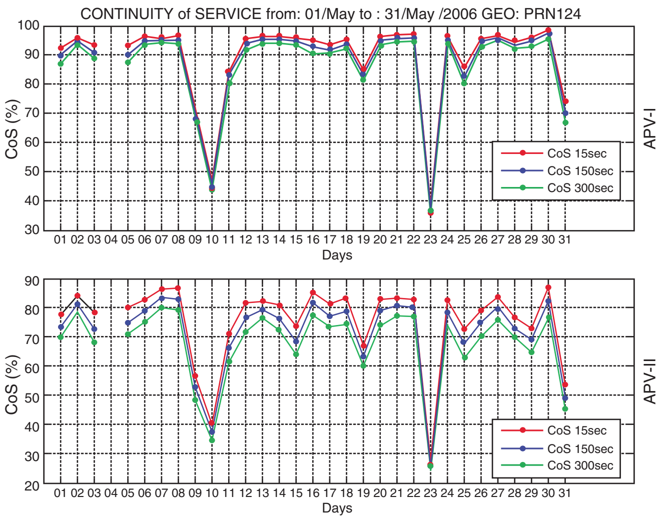


Fig. 9. Accuracy.

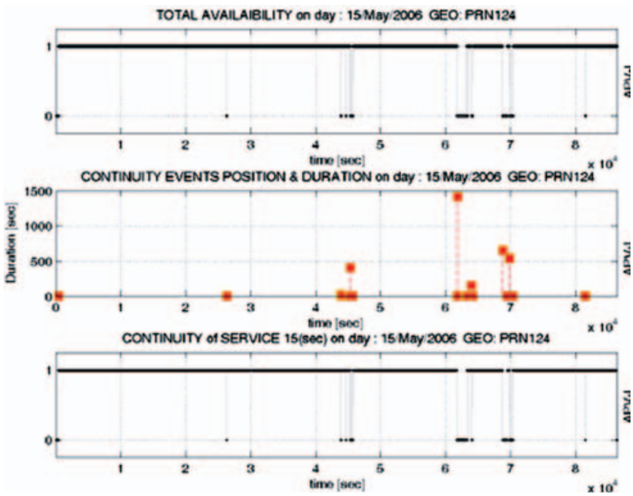


Fig. 10. APV-I performance.

To enhance the information provided with the Stanford plot we have performed a three-dimensional plot (Figs. 13 and 14) in which on x and y axises are represented the east/west and the north/south distances to a reference point of position solution.

On z axis we represents the protection level (horizontal or vertical). In this way we have a summarized representation of Integrity performance and position error. It is simple to notice that a conventional Stanford plot is the half-vertical plane containing the vertical line of the reference position and the corresponding position solution.

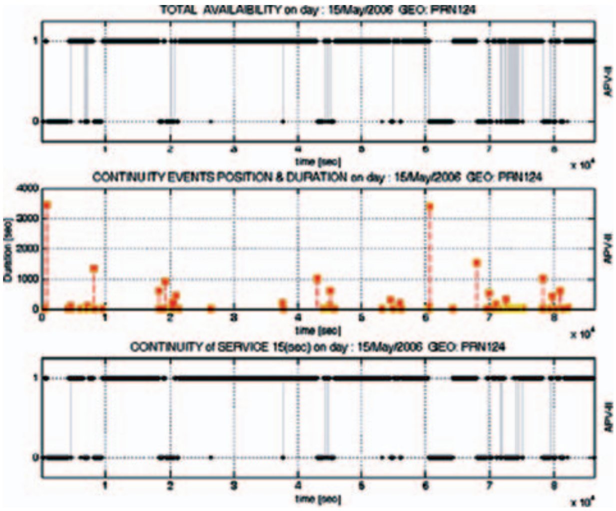


Fig. 11. APV-II performance.

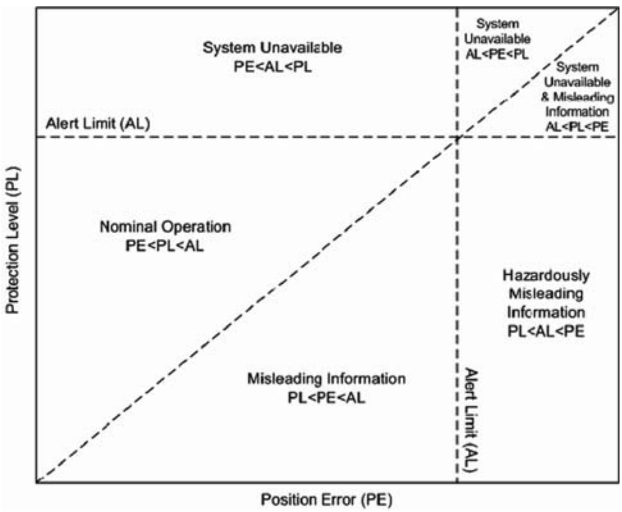


Fig. 12. Stanford plot.

5.4.5 Range Domain Analysis. The fast correction must be utilised in all navigation modes from En Route to Precision Approach. Fast corrections, provided as range correction values, are applied directly to the range measurements. Integrity indicators in the form of User Differential Range Error (UDRE) estimates are provided in the range domain.

This UDRE is an upper bound on the residual error of the pseudorange after the application of fast corrections; it is used to compute protection levels and

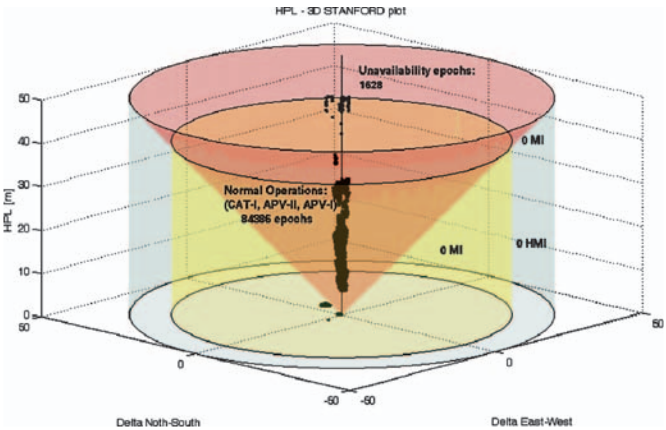


Fig. 13. Three-dimensional horizontal stanford plot.

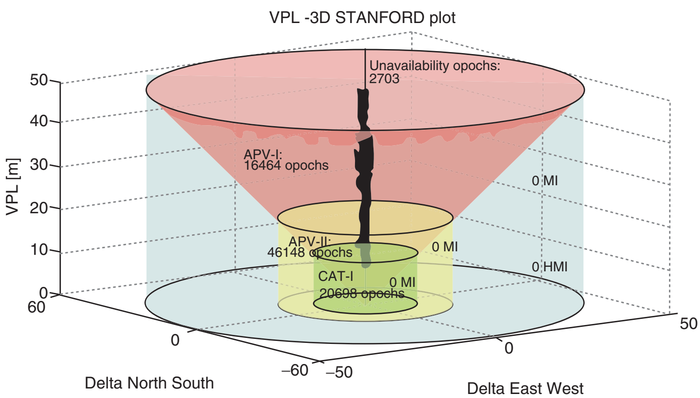


Fig. 14. Three-dimensional vertical stanford plot.

warning flags indicating that an individual satellite should not be used in the position solution.

To analyse these Integrity parameters we perform an innovative SKY plot on a Mercator projection in which for any Pierce point of the direct line-of-sight from the looked satellites to the our position through the ionosphere, we plot the parameter values by means the marker colours. In the Figs. 15 and 16 for all looked satellites, we show respectively the UDRE and the Ionospheric Vertical Delay (UIVD).

The contribution of receiver noise to the residual range error shall represent the accuracy performance of the airborne receiver, including receiver noise and multipath [1], [11]. The tracking accuracy of the receiver is evaluated as part of the accuracy requirements in [3]. The tracking accuracy for either a GPS or a SBAS satellite is depending on the current signal to noise ratio and the time since initialisation of the smoothing filtering. To asses the tracking accuracy we perform in the same way a SKY plot of the signal to noise ratio, Fig. 17.

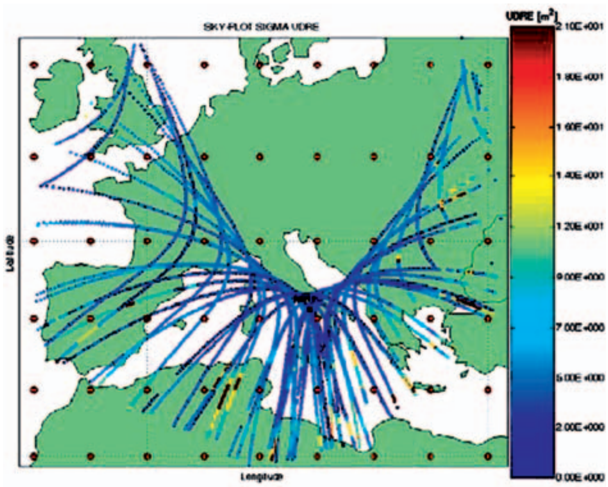


Fig. 15. UDRE SKY plot.

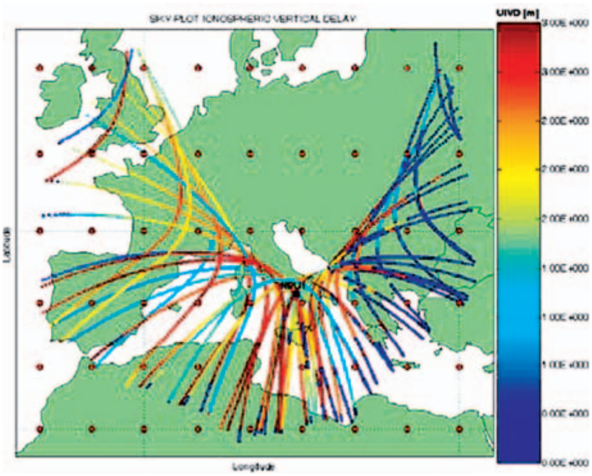


Fig. 16. UIVD SKY plot.

6 Conclusion

Our paper, placed in the frame of the EGNOS performance validation activities, has described a toolset named MARKAB recently developed to analyse the performance that can be experienced by a user, and to verify the stability of the performance for a fixed time interval. The objective of our toolset is to provide an efficient and fast statistical analysis about the performance in the airborne environment and to determine to what extent it could be safely approved for operational use. In order to

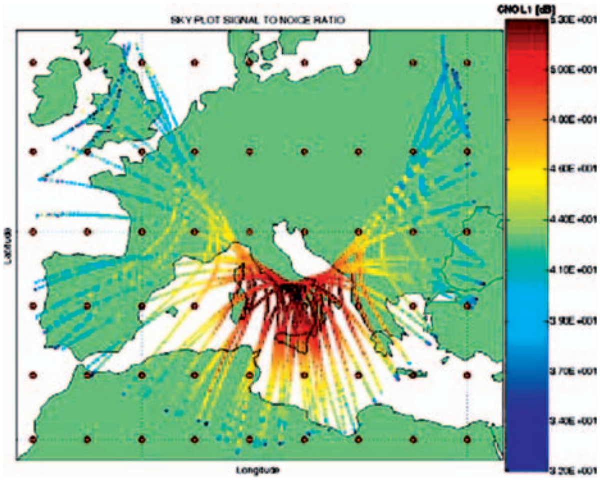


Fig. 17. Signal to noise ratio SKY plot.

gain experience with the European implementation of an SBAS system, confidence in the performance of that system has to be established. The architecture of MARKAB is designed in such a way as to provide easy and immediate access to the data, at all stages of data processing, and easy access to the graphical presentation of the results. Moreover, we have presented a new technique to assess the performance in terms of Continuity of Service which represents an important improvement in the context of performance evaluation. It allows us to define a new parameter to determine the probability that the augmentation system will be continuous in any required time interval for a given operation. The current performance of the augmentation system have been analysed in a series of static trials. These results raise a lot of hope to the validation of EGNOS system.

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