The Satellite Navigation System EGNOS and Safety of Life Service Performance in Sofia

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***Key Words**: Satellite Based Augmentation System; safety parameters.*

***Abstract.** In this work EGNOS and some system performance results are presented. The recent system basic parameters performance for Southeast Europe is tested using real data measured by the EGNOS monitoring station placed by Eurocontrol in the Technical University of Sofia. All results are presented in plots showing the achieved performances which are briefly commented in the context of basic KPI of the system.*

I. Introduction

The European Geostationary Navigation Overlay Service (EGNOS) is a wide area Satellite Based Augmentation System (SBAS) which broadcasts „augmented" GPS data over a whole continent. It uses a combination of specialized satellites and ground-based stations to send correction signals to GPS receivers, as well as providing integrity information for each satellite's signal. The most demanding requirement for SBAS is to provide a service which offers precision approach capability, i.e. electronic position information to aircraft approaching runway.

Three SBAS implementations are currently operational: the Wide Area Augmentation System (WAAS) from USA, the EGNOS from EU, and the MTSAT Satellite Augmentation System (MSAS) from Japan. A fourth SBAS implementation, the GPS-Aided and GEO-Augmented Navigation System (GAGAN) from India, is in a later stage of development. A fifth SBAS implementation, the Russian Wide Area Augmentation System (SDCM) is currently in an early stage of development.

EGNOS is a joint project of the European Space Agency, the European Commission and Eurocontrol, the European Organisation for the Safety of Air Navigation. It is Europe's first activity in the field of the Global Navigation Satellite Systems (GNSS) and is a precursor to Galileo, the full global satellite navigation system under development in Europe.

EGNOS operations are now managed by the European Commission through a contract with an operator based in France, the European Satellite Services Provider. The EGNOS Open Service has been available since 1 October 2009. The EGNOS positioning data are freely available in Europe through satellite signals to anyone equipped with an EGNOS-enabled GPS receiver. The EGNOS Safety of Life service has been officially declared available for aviation on 02 March 2011. Space-based navigation signals have become usable for the safety-critical task of guiding aircraft during landing approaches in the central area on the European Civil Aviation Conference (ECAC) region.

In this work EGNOS architecture, basic parameters and Key Performance Indicators (KPI) for aircraft navigation are presented. The performance of the system safety parameters is examined over static tests using real the EGNOS data (from 19th of September to 18th of October 2011). They are measured by the Eurocontrol EGNOS monitoring station placed in the Technical University of Sofia, Bulgaria. It must be noted that Sofia is situated in Southeast Europe, i.e. in the border area on the EGNOS coverage region.

A time series analysis method called Singular Spectrum Analysis (SSA) [6] is applied to extract indicative of the EGNOS performance statistic trends. This method is partially suited to short, noisy time series, as these investigated in this work.

To analyse protection level conservatism an Inflation Indicator (II) is introduced and estimated.

II. EGNOS Architecture

The EGNOS system comprises (*figure 1*):

- A ground segment in charge of elaborating the EGNOS signal and managing the system.
- A space segment in charge of diffusing the EGNOS signal.
- The user segment located on the mobile, wishing to benefit from the EGNOS service.

The functions of the ground segment (EGNOS Wide Area Network) are as follows:

➢ Collecting data from the GPS satellites and transmitting it towards a processing facility. This function is performed by 35 Remote Integrity and Monitoring Stations (RIMS). It is planned to deploy 41 RIMS.

➢ Processing of GPS data, elaboration of data to be diffused and formatting of the EGNOS signal. This function is performed by 4 Master Control Centres (MCC). The MCC are composed of two parts:

- The Central Process Facility (CPF) in charge of calculation, validation and distribution of messages to be transmitted;
- The Central Control Facility (CCF). It receives all the data from the various elements of EGNOS and the network and is in charge of managing all the interfaces between these elements and of configuring EGNOS according to the status of these elements. It prepares the data which will be archived in order to study EGNOS performances off-line.
- 6 Navigation Land Earth Stations (NLES) transmit data towards geostationary satellites.

Two support facilities: Application Specific Qualification Facility (ASQF) and Performance Assessment Check out Facility (PACF) complete the ground segment architecture.

The EGNOS space segment is composed of three geosta-

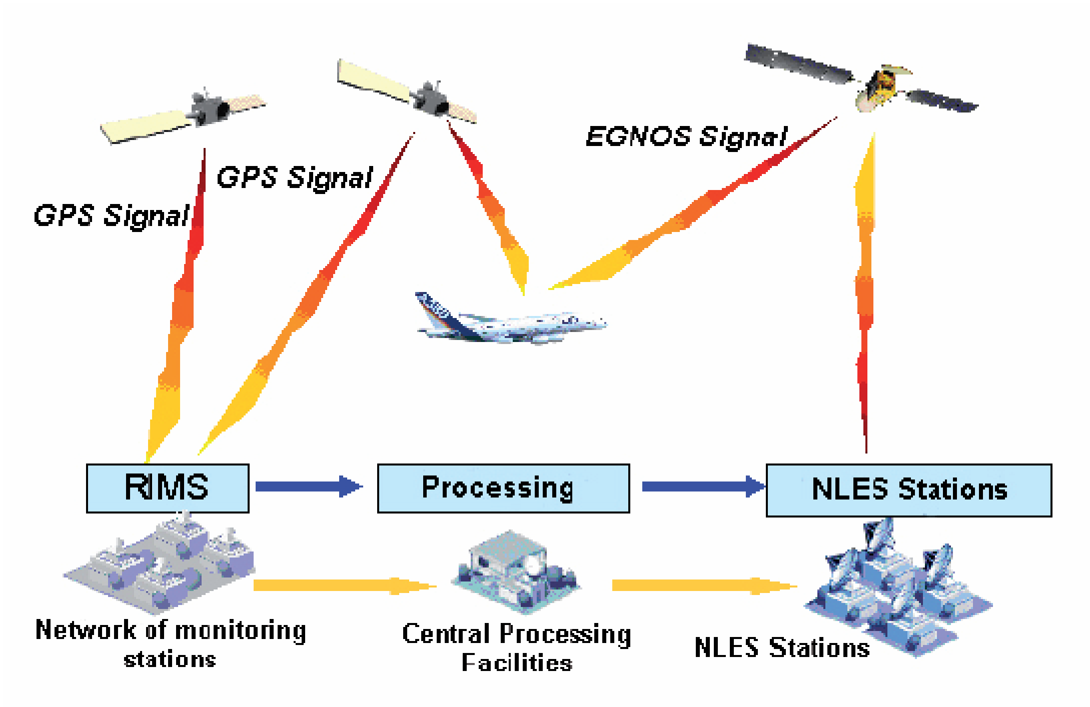

Figure 1. EGNOS architecture

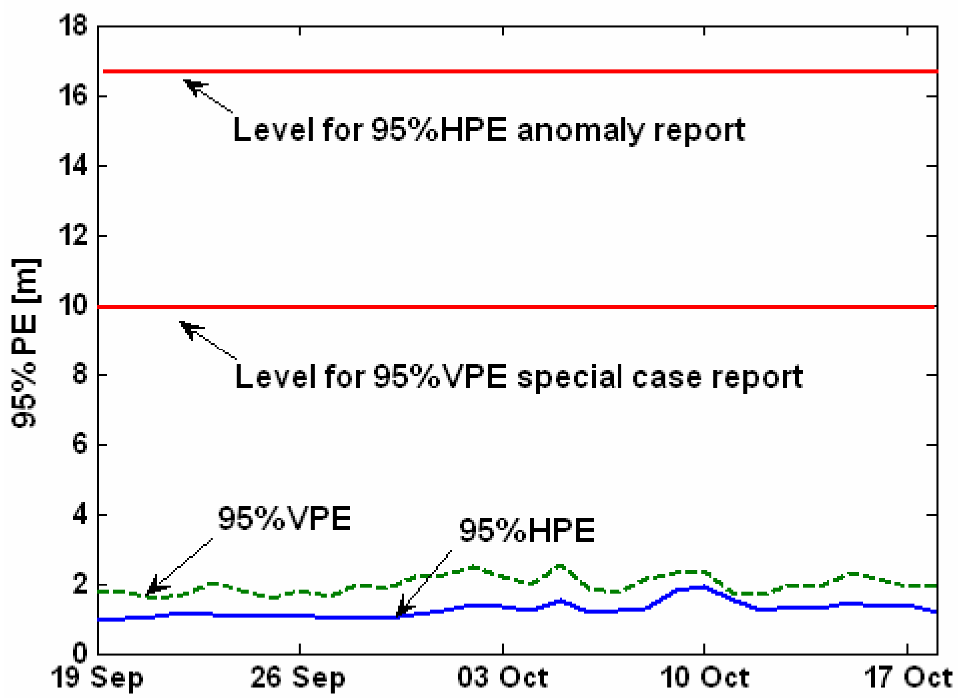

Figure 2. 95% percentile HPE and VPE for APV-I

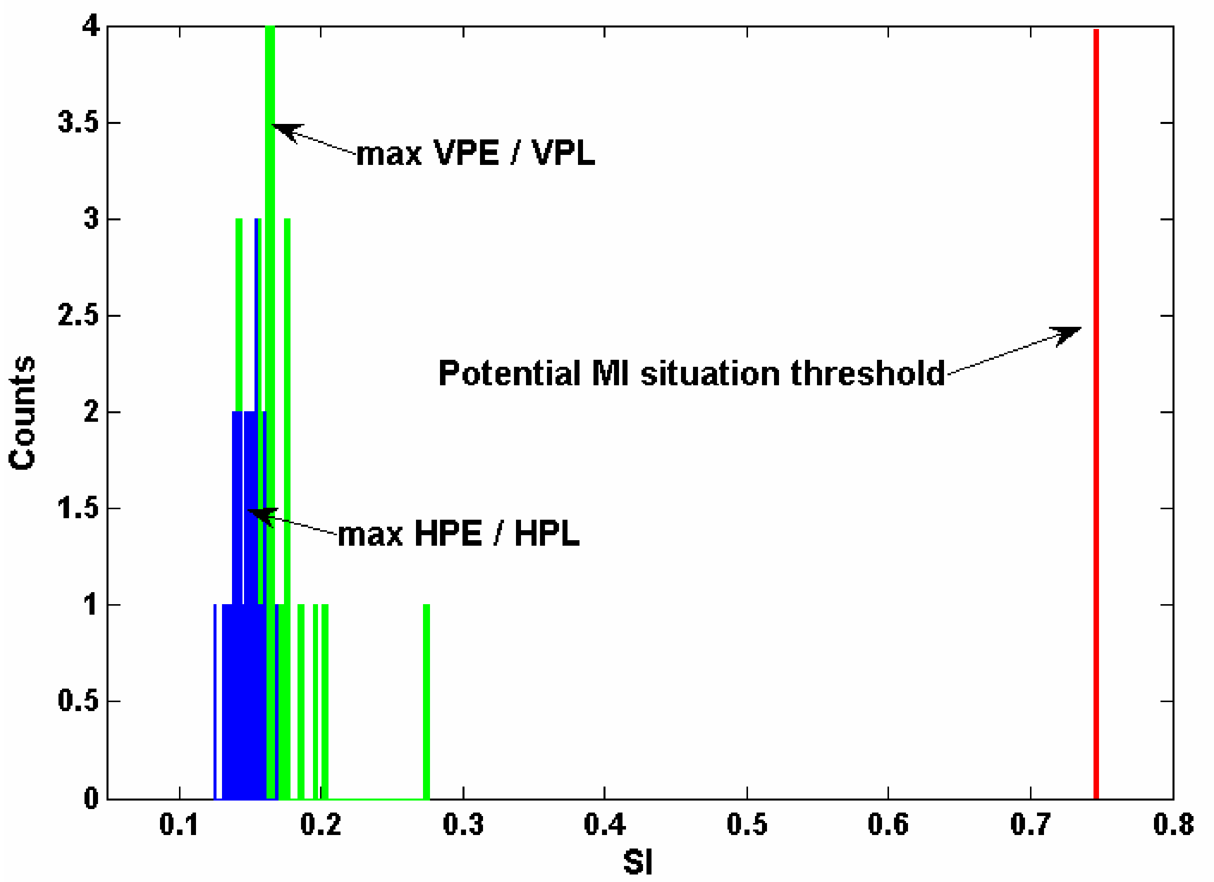

Figure 3. Position domain horizontal (maxHPE/HPL) and vertical (maxVPE/VPL) Safety Index histograms for APV-I

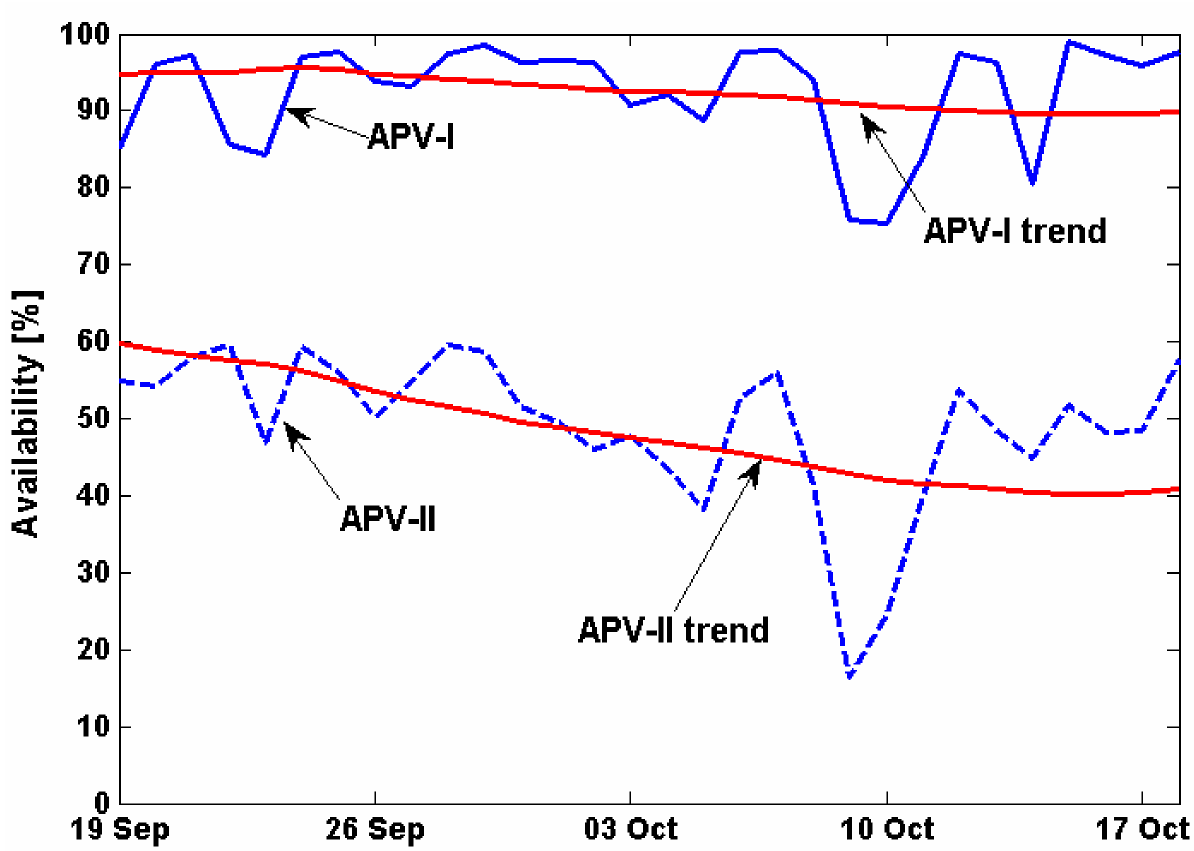

Figure 4. APV-I, APV-II availabilities and their trends

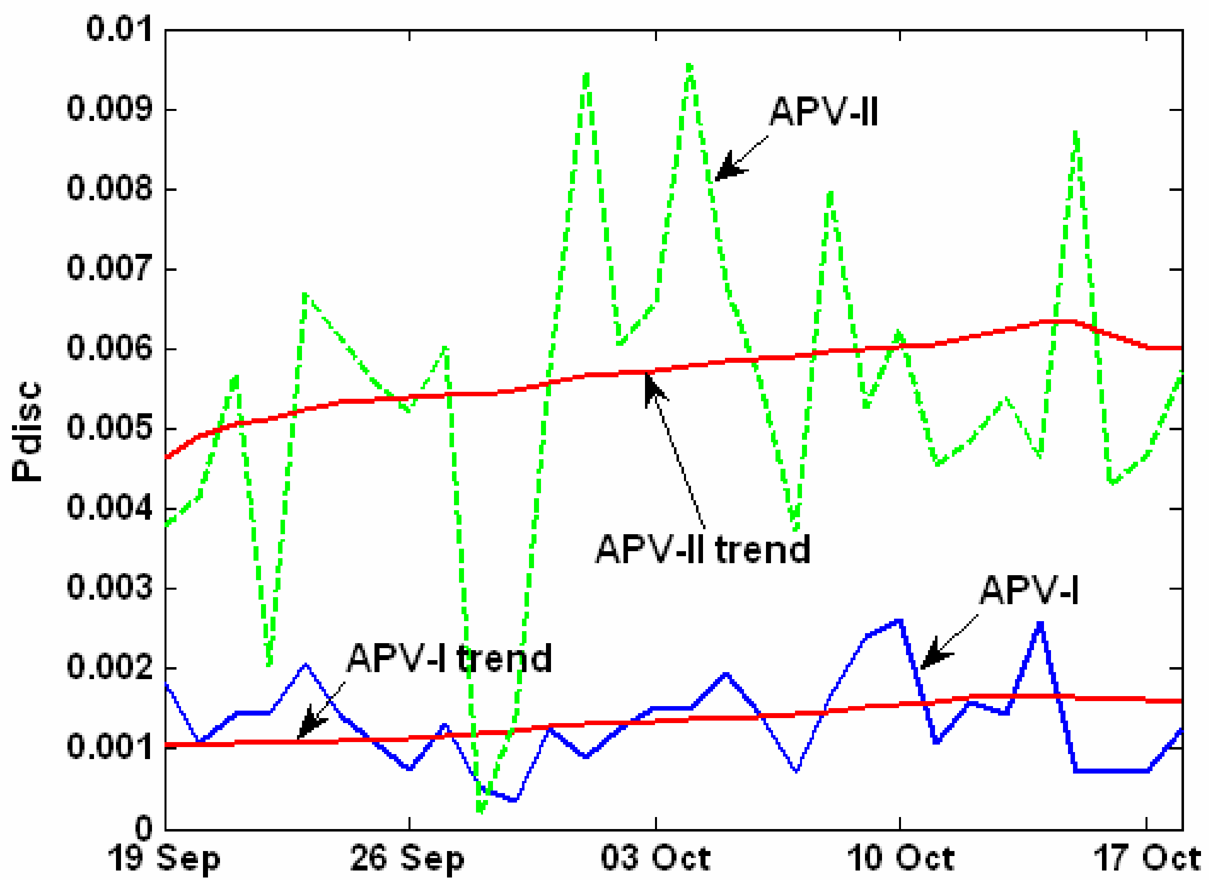

Figure 5. APV-I and APV-II probabilities of discontinuity and their trends

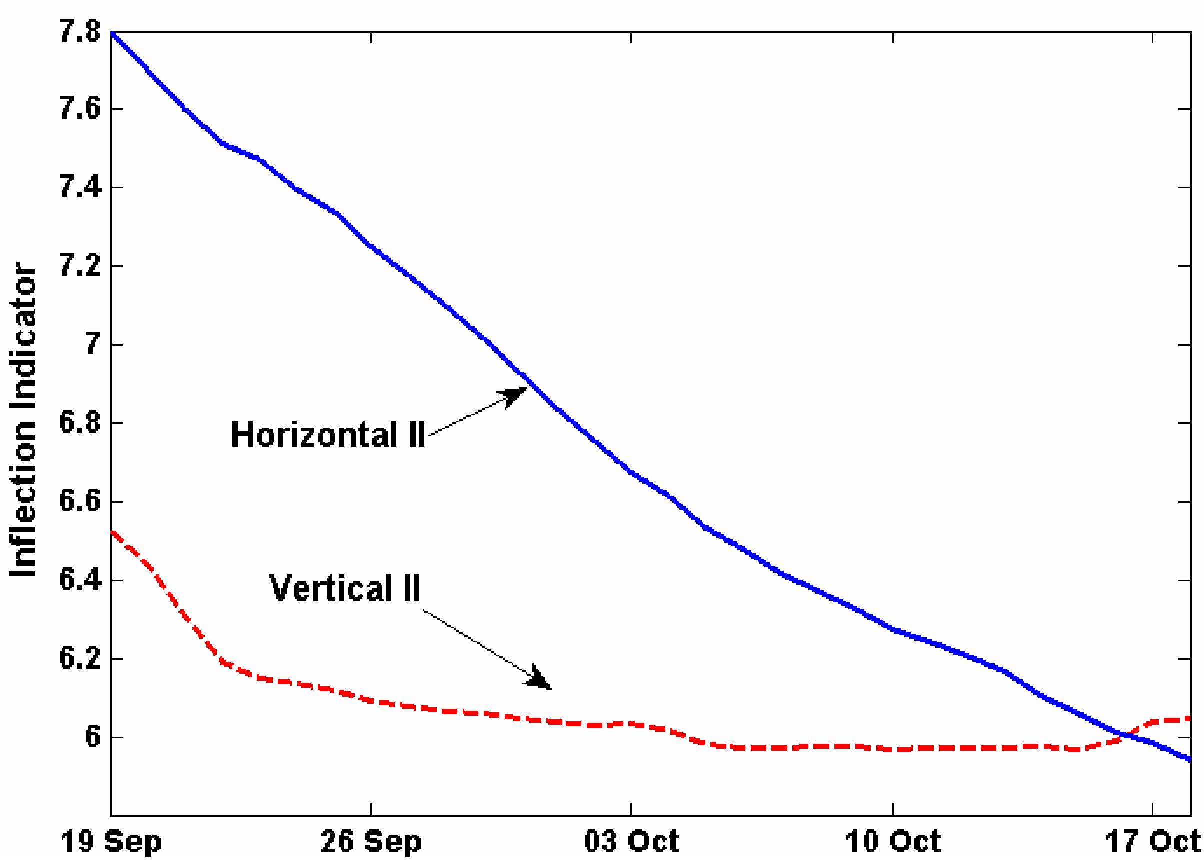

Figure 6. Trends of the Horizontal and Vertical Inflection Indicator

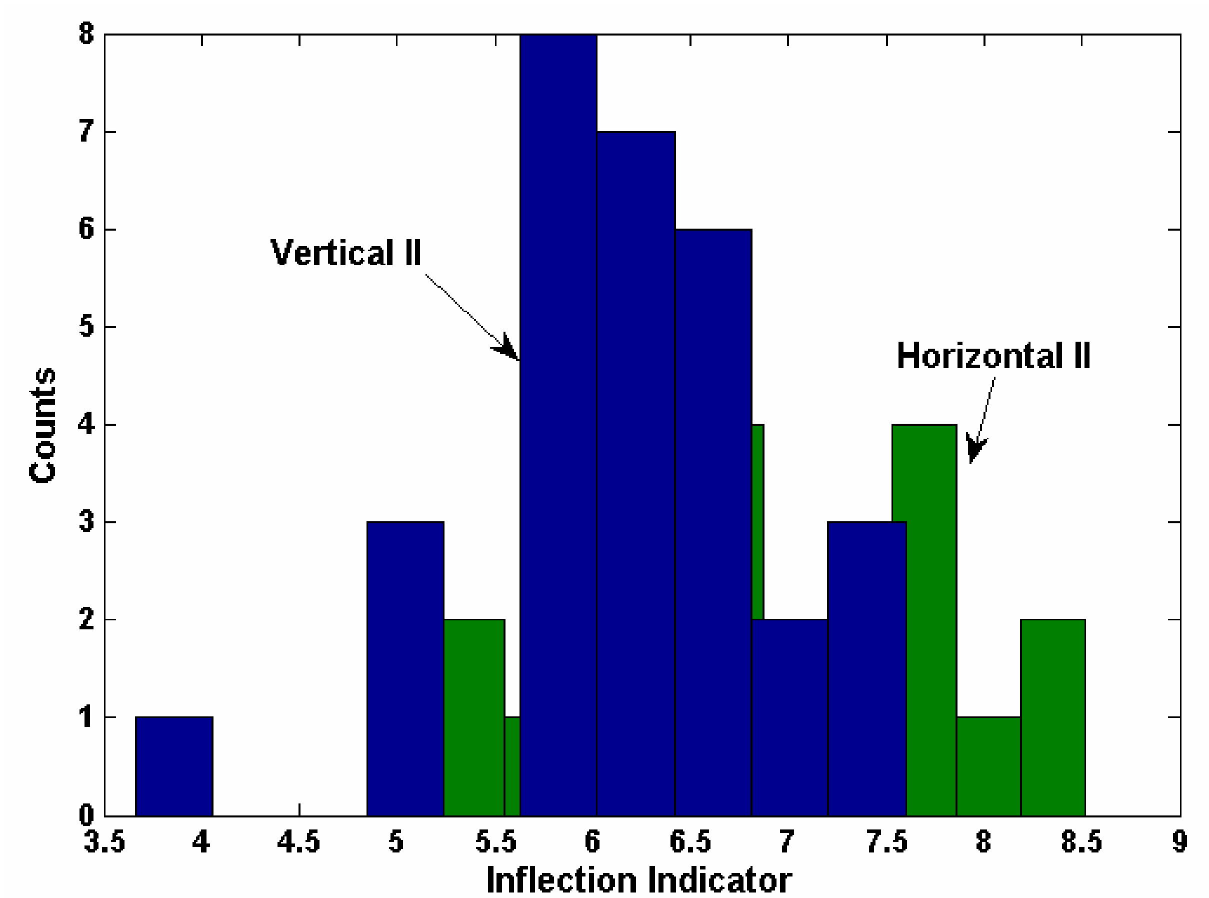

Figure 7. Histograms of the Horizontal and Vertical Inflection Indicator

tionary satellites. There are: Artemis (PRN 124), Inmarsat AOR-E (PRN 120) and Inmarsat AOR-W (PRN 126).

User segment is a set of EGNOS receivers developed for various types of users.

Nowadays EGNOS uses the same frequency (L1 1575.42 MHz) and ranging codes as GPS, but has a different data message format. Different message types have been defined to broadcast integrity data and Wide Area Differential (WAD) corrections. The message schedule follows a 6-second duty cycle. This is structured both to prioritise the 6-second integrity time-to-alarm and to minimise the time for EGNOS initialisation.

Integrity is provided at two levels: coarse use/don't use for all satellites in view of the service volume (including the GEOs); and two parameters - σ^2_{UDRE} and σ^2_{UIDE} - that are statistical estimates of the satellite and atmospheric errors remaining after applying the WAD corrections. These are used to compute a certified error bound for the position solution in an integrity assessment. The σ^2_{UDRE} term characterises statistically the residual User Differential Range Errors (UDRE) after having applied the fast and slow clock and ephemeris corrections. The σ^2_{UIDE} term is applied to the range vector where it characterises statistically the residual User Ionospheric Differential Errors (UIDE). Tropospheric errors may be mitigated using a simple model related to the receiver's position and the day number in the year.

EGNOS receivers compute a certified error bound for the position solution based on data broadcast by the GEO satellites, the user/satellite geometry, and the probability of integrity non-detection.

III. Some EGNOS Performance Results

The EGNOS basic parameters must guarantee that the user is informed on his position with sufficient accuracy and is alerted when the system exceeds tolerance limits. The Horizontal and Vertical Protection Levels (PL are computed to protect users from potential degradation of the system, expressed in terms of Horizontal and Vertical Position Error (PE) above a certain user level, called Alert Limit (AL). Several possibilities for the relation between PE, AL and PL exist. However, two cases are very important from a safety perspective [4]:

- PL<PE<AL: System is available but not safe, not leading to a hazardous situation, called Misleading Information (MI).
- PL<AL<PE: System is available but not safe and leading to a hazardous situation, called Hazardous Misleading Information (HMI).

Both cases are considered as an EGNOS out of tolerance condition, and are assumed as non-integrity events. If PL exceeds the AL the system is declared unavailable since in this case the probability of system non-integrity (misleading information) is high.

To process and analyze the EGNOS performance results for every day of the GPS system time, Eurocontrol has developed PEGASUS software tool [1,2]. The results presented in the next two sections are obtained using data collected during a month, from 19th of September to 18th of October 2011, at the Eurocontrol EGNOS monitoring station placed in the Technical University of Sofia (Antenna position: latitude - 42.65282663 deg; longitude - 23.354327455 deg; height - 658.899 m). The static tests were carried out with Septentrio PolaRx 2 receiver. These tests concern Approach with Vertical Guidance services (APV-I and APV-II). It must be noted:

- For APV-I service the horizontal AL equals to 40 m and the vertical AL equals to 50 m. For APV-II service the horizontal AL equals to 40 m and the vertical AL equals to 20 m.
- Sofia is situated in border area on the ECAC region.
- The presented results are obtained using Inmarsat AOR-E (PRN 120) signals.

There are four basic requirements, which the ICAO (International Civil Aviation Organization) compliant EGNOS safety of life service should satisfy. These are on accuracy, integrity, availability and continuity of the system and they are particularly stringent for landing precision approaches. Some general requirements (KPI) and results for APV services are presented below.

Accuracy. EGNOS position error is the difference between the estimated position and the actual position. For a large set of independent samples, at least 95 percents of the samples should be within the accuracy requirements. The 95 percent accuracy requirement is defined to ensure pilot acceptance, since it represents the errors that will typically be experienced. The accuracy requirement is to be met for the worst-case geometry under which the system is declared to be available. For the provision of EGNOS Safety of Life (SoL) service down to APV-I the system accuracy in the position domain (with a 95% confidence level) shall be less than 16 m in the horizontal and 20 m in the vertical domain.

Figure 2 presents the 95% daily horizontal and vertical Position Errors (PE) for APV-I service. The established results confirm that *the system could provide better accuracy performance than required* for this precision approach. All 95% horizontal PE values are less than 1.9 m. All 95% vertical PE values are in the vicinity of 2 m. Max 95% vertical PE equals to 2.4 m.

The integrity is a measure of the trust which can be placed in the correctness of the information supplied by the total system. Integrity includes the ability of the system to alert the user when the system should not be used for the intended operation (or phase of flight). 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.

According to the integrity requirements of ICAO [4], the allowable probabilitties of non-integrity event (probabilities of HMI) per landing approach, are 10^{-9} and 10^{-7} for the horizontal and vertical components respectively. The position domain Safety Index (SI) is defined as the ratio between the true navigation system error and the corresponding protection level $SI = PE / PL$. There is potential MI situation if SI is bigger than 0.75. There is real MI every time when the instantaneous SI exceeds 1.

Figure 3 shows histograms of the daily maximum horizontal and vertical SI values. *All SI values are less than 0.28 and are far from potential MI situation threshold of 0.75.* It must be noted that since 2007 there are no non-integrity events.

The **availability** of a navigation system is the ability of the system to provide the required function and performance at the initiation of the intended operation. The availability is an indication of the ability of the system to provide usable service within the specified coverage area. The signal availability is the percentage of time that navigational signals transmitted from external sources are available for use. The availability is a function of both the physical characteristics of the environment and the technical capabilities of the transmitter facilities. The local availability of EGNOS for APV-1 shall be better than 99 % over the nominal operational lifetime of the service.

Figure 4 illustrates the estimated APV-I, APV-II availabilities and their trends. The APV-I availability trend lies in the vicinity of 93%. As mentioned above Sofia is situated in South-east Europe, i.e. in the border area on the EGNOS coverage region and *the system mainly does not provide the expected service (more than 99% availability).* The APV-II availability trend lies in the vicinity of 50%. The main reason for cases of extremely low availability is that there are time periods when the number of visible satellites is less than the number of used satellites.

The **continuity** of a system is the ability of the total system (comprising all elements necessary to maintain aircraft position within the defined airspace) to perform its function without interruption during the intended operation. More specifically, the continuity is the probability that the specified system performance will be maintained for the duration of a phase of operation, presuming that the system was available at the beginning of that phase of operation, and predicted to exist throughout the operation. The continuity event (anomaly) is observed every time when at epoch $PL < AL$ and at epoch $PL \geq AL$.

For APV services the duration of a phase of operation is 15 s and the algorithm used for the computation of the continuity risk is based on the 15 seconds sliding window computation technique. The current requirement indicates a continuity risk limit of less than 1.10-4 per 15 s in the core part of ECAC and 5*10-4 per 15 s in most of ECAC.

Figure 5 presents the estimated probabilities of discontinuity P(disc.) and their trends for APV-I and APV-II services. The established *results are mostly not consistent with current limit of the service discontinuity, namely 5*10-4 per 15 s.*

IV. Inflection Indicator as Metric for Protection Level Conservatism

To analyze the PL conservatism an Inflation Indicator is introduced and estimated in this work.

The SBAS PL is defined as bounds on the PE with a probability derived from the integrity requirements. It translates what is known about the pseudorange error into a reliable limit on the positioning errors and thus is one of the major components of the SBAS integrity mechanism.

As the EGNOS differential correction errors are approximately Gaussian [4,7], the current protection level equations are based on the Gaussian statistics: all errors are characterized by a zero-mean Gaussian distribution which is an upper bound of the true distribution in a certain sense. The EGNOS vertical PL is defined as a bound on the vertical PE with a probability derived from the integrity requirements [5] as follows:

(1) $$VPL = K\sigma_v = K \sqrt{\sum_{i=1}^{N} s_{U,i}^2 \sigma_i^2},$$

where is a bound of the standard deviation (std) σ_p for the vertical component of the position domain, is the number of satellites which contribute to the position solution, $s_{U,i}^2$ are geometrical parameters, σ_i are bounds of std's of the corrected range measurement errors and is a factor, corresponding to the expected probability for a unit variance zero-mean Gaussian process. It must be noted that a similar methodology is developed to assess horizontal protection level.

In order to guarantee integrity, the PL must be sufficiently large so as to cover PE. When departures from the zero-mean Gaussian model are significant, the broadcast confidence terms must be inflated in order to provide protection for all user geometries. This leads to a loss of availability even for users who do not observe the satellite with the problematic errors. That is why the PL cannot be unduly conservative. As such, a careful evaluation of the low, but conservative PL is a challenging task [9]. In [7] a total inflation factor $\Theta = PL/(K \times \sigma_p)$ that provides a convenient metric to enable analysis of the different overbounding strategies is defined. By analogy with an Inflation Indicator (II) is introduced as: $II = PL_{mean}/(K \times PE_{std})$, where dthe aily protection level mean and the position error std are estimated. The scaling parameters correspond to the allowable probabilities of the horizontal and vertical hazardously misleading information (10^{-9} and 0.5×10^{-7} respectively, per landing approach).

Figure 6 presents trends of the horizontal and vertical Inflection Indicator. As it is expected the results show: the horizontal PL is as rule more conservative than the vertical PL.

Figure 7 shows histograms of the horizontal and vertical Inflection Indicator. The flatness of the horizontal II probability distribution is bigger as result of the PL assessment methodology. It must be noted that *an inflation of the PL values often 'cost' availability*. As a mean of the system availability improvement the USA GNSS Evolutionary Architectural Study (GEAS) recommends *a shift of the integrity responsibility towards the user receive*r [9]. The main goal is to increase the availability for different precision approaches without sacrifice the integrity.

V. Concluding Remarks

The availability of EGNOS to aviation announced on 2 March 2011 by the European Commission, means that aircraft will soon be able to use satellite technologies to establish their vertical positioning during approaches. Nowadays the EGNOS coverage area is the ECAC region but a geographical service extension toward Africa and Mediterranean being implemented.

The established results support the claim: nowadays EGNOS performance is stable with high quality of the accuracy and integrity.

To compute xPL, EGNOS transmits integrity information (external to user receiver) on the signal in space. The confidence values of this information are inflated to protect the worst-satellites-geometry user as opposed to the typical user. This imperfect matching has led to an inflation of the xPL values. The expected service for APV (more than 99% availability and continuity risk limit of less than 10^{-4} per 15 s) not only in the core part of ECAC should be achieved in future by improving the EGNOS coverage. Beside this, as a mean of the SBAS availability improvement the GEAS recommends a shift of the integrity responsibility towards the user receiver.

Acknowledgements

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