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EGNOS PERFORMANCE BEFORE AND AFTER APPLYING AN ERROR EXTRACTION METHODOLOGY

ABSTRACT

In this work the EGNOS performance before and after applying a novel methodology called Error Extraction is tested using real data. These data are collected at the EGNOS Monitoring Station placed in Sofia by Eurocontrol. The tests concern aircraft navigation, namely Approach with Vertical Guidance services. All results confirm that the designed new algorithms are very promising. They allow reduction of the error standard deviation and significant availability improvement without breaches of the integrity. The probability of system discontinuity decreases substantially.

Keywords:
SBAS, protection levels, accuracy, integrity, availability, continuity.

INTRODUCTION

The European Geostationary Navigation Overlay Service (EGNOS) is the first pan-European satellite navigation system. It augments the US GPS satellite navigation system and makes it suitable for safety critical applications. The availability of EGNOS to aviation is announced on 2 March 2011 by the European Commission. The system basic parameters (accuracy, integrity, availability and continuity) must guarantee that the user is informed on his position with sufficient accuracy and is alerted on time, when the system exceeds tolerance limits. The Horizontal and Vertical Protection Levels (HPL and VPL) are computed to protect users from potential degradation of the system, expressed in terms of Horizontal and Vertical Position Error (HPE and VPE) above certain user levels, called Horizontal and Vertical Alert Limit. To compute xPL, SBAS transmits integrity information (external to user receiver) on the signal in space. The confidence values of this information are inflated to protect the worst-case user as opposed to the typical user. This imperfect matching has led to an inflation of the xPL values.

In works [5, 6], a novel methodology called Error Extraction for EGNOS performance improvement is presented. It concerns receivers with high velocity accuracy and is simple to implement within the user receiver after the navigation solution computing. The main objective is to obtain system accuracy and availability improvement without integrity sacrifice. By realization of the EE algorithm, high quality estimation of zero mean position error can be obtained. It is useful for the position error reduction and forming of the xPL component that arises only from the noise. To do this, algorithm which holds constant rate of integrity is realized. To calculate the xPL component due to bias, its upper bound is formed on the basis of the given maximum possible range bias, number of used satellites and Dilution of Precision.

In this work the EGNOS performance (accuracy, integrity, availability and continuity) before and after applying EE based algorithms is examined over tests using real EGNOS data collected at the EGNOS Monitoring Station placed in Sofia by Eurocontrol. These tests concern aircraft navigation, namely Approach with Vertical Guidance services (APV-I, APV-II and CAT-I).

EE BASED ALGORITHMS FOR xPE AND xPL DECREASING

In satellite based navigation systems the position solution is separated into East, North and Vertical components. The measurement in each component is a sum of the true position $x(i)$ and error $\xi(i)$:

$$y(i) = x(i) + \xi(i) \ . \quad (1)$$

To remove $x(i)$ three consecutive measurements of the position $y(i)$ and velocity $v(i)$ are used as follows [6]:

$$\begin{aligned} \bar{u}(i) &= y(i) - 2y(i-1) + y(i-2) - \frac{1}{2}[v(i) - v(i-2)]T = \\ &= \xi(i) - 2\xi(i-1) + \xi(i-2) - \frac{1}{2}[\eta(i) - \eta(i-2)]T, \end{aligned} \quad (2)$$

where T is the sample period and $\eta(i)$ is the velocity measurement error. This error is assumed zero-mean white Gaussian noise [5]. Passing $\bar{u}(i)$ through filter with transfer function $F(z) = 1/(1-\rho z^{-1})^2$, where $0 < \rho \le 1$, the output with z-transform:

$$u(z) = \frac{(1-z^{-1})^2}{(1-\rho z^{-1})^2}\xi(z) + \frac{(1-z^{-2})}{2(1-\rho z^{-1})^2}T\eta(z) \tag{3}$$

is obtained. If the user receiver has high velocity accuracy (standard deviation less than 0.01m/sec) the centered error $u(i) \approx \bar{\xi}(i)$ can be extracted by setting $\rho \approx 1$ in (3).

The above presented methodology, called Error Extraction (EE), is used in this work for:

- More precise positioning:

$$P(i) = \begin{cases} \sqrt{[\tilde{y}_E^2(i) + \tilde{y}_N^2(i)]}, & \text{for horizontal position} \\ \tilde{y}_V(i), & \text{for vertical position} \end{cases}, \quad \tilde{y}(i) = x(i) + \xi(i) - u(i)\,. \tag{4}$$

- Calculation of the xPL component due to centered xPE (noise) [5]:

$$xPL_{noise}(n) = \frac{S(n)}{M}(P_{HMI}^{-1/M} - 1), \quad S(n) = \sum_{i=n-M+1}^{n-M/2} wE(i) + \sum_{i=n-M/2+1}^{n} (2-w)E(i)\,. \tag{5}$$

This algorithm uses reference window of M samples and holds constant rate of integrity risk probability P_{HMI}. Weight coefficient w is used to provide timely alert, when the system exceeds tolerance limits. $E(i)$ is the noise component of xPE estimates:

$$E(i) = \begin{cases} \sqrt{\beta[u_E^2(i) + u_N^2(i)]}, & \text{for noise component of HPE} \\ \beta|u_V(i)|, & \text{for noise component of VPE} \end{cases}, \tag{6}$$

and factor β represents the upper bound of the ratio between the input and output error standard deviation. This factor is evaluated analytically and is tabulated for various values of the filter parameter ρ.

To calculate the xPL component due to range biases, the upper bound xPL_{bias} is formed on the basis of the estimated maximum possible range bias $\mu_{\max}$, number of used satellites N and Dilution of Precision $xDOP$ as follows [5]:

$$xPL_{bias}(n) = \alpha\mu_{\max}\sqrt{N(n)} \cdot xDOP(n)\,, \tag{7}$$

where α is an inflation factor required to increase the unweighted bias bound to bound the weighted bound in the horizontal/vertical position. $xDOP$ is a dimensionless parameter which relates the contribution of relative satellite geometry to the errors in horizontal/vertical position determination. Finally, the new xPL is obtained as a sum of both xPL components:

$$xPL = xPL_{noise} + xPL_{bias} \, . \tag{8}$$

KEY PERFORMANCE INDICATORS

There are four basic requirements, which the International Civil Aviation Organization (ICAO) compliant EGNOS Safety of Life (SoL) service should satisfy [3, 4]. These are on accuracy, integrity, availability and continuity of the system and they are particularly stringent for landing precision approaches. The definitions of the system Key Performance Indicators (KPI) are as follow:

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 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.

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 probabilities of non-integrity event per landing approach, are 10^{-9} and 0.5×10^{-7} for the horizontal and vertical components respectively. 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 Misleading Information (MI) situation if SI is bigger than 0.75. There is real MI every time when the instantaneous SI exceeds 1.

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. Availability is an indication of the ability of the system to provide usable service within the specified coverage area. The local availability of EGNOS for Approach with Vertical Guidance service shall be better than 99% over the nominal operational lifetime of the service.

The **continuity** of a system is the ability of the total system to perform its function without interruption during the intended operation. More specifically, 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. Continuity event (anomaly) is observed every time when at epoch T_{i-1} $PL < AL$ and at epoch T_i $PL \geq AL$.

For Approach with Vertical Guidance service 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 (probability of discontinuity) limit of less than 1×10^{-4} per 15 s in the core part of ECAC and 5×10^{-4} per 15s in most of ECAC.

EXPERIMENTAL RESULTS

The results presented in this section are obtained using data collected during a month, from 11th of February to 10th of March 2012. This period covers the data collected immediately after EGNOS System Release 2.3.1+ deployment [1]. Among its improvements it has 3 new Reference Monitoring Stations and some operability and performance enhancements.

All experiments were carried out with Septentrio PolaRx 2 single frequency L1 receiver. For this type of receiver horizontal velocity error standard deviation is 1.5 mm/sec and vertical velocity error standard deviation is 2.8 mm/sec. The used EGNOS monitoring station is placed in Technical University of Sofia (Antenna position: latitude — 42.65282663 deg; longitude — 23.354327455 deg; height — 658.899 m). As the true position for the static test is known with high accuracy it enables the proper assessment of the real xPE. One should bear in mind the following:

— 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;
— for Cat-I service the horizontal AL equals to 40 m and the vertical AL equals to 12 m;
— Sofia is situated in border area on the European Civil Aviation Conference (ECAC) region;

— the presented results are obtained using Inmarsat AOR-E (PRN 120) signals;
— the new xPE are calculated for filter parameter ρ=0.98;
— the new xPL are calculated for maximal position error due to satellite bias of magnitude $\mu_{\max} = 1.125\ m$ [7] and algorithm parameters: ρ=0.98, M=50, α=1.1, w=0.5, β=1.2.

All results are presented in plots showing the achieved EGNOS performance before ('old') and after ('new') applying of the EE based algorithms. These results are briefly commented in the context of basic KPI of the system.

Fig. 1–4 visualized the xPE and xPL performance for 17th of February 2012. The zoomed views of the plots are shown in order to better illustrate the abilities of the 'new' xPE and xPL. For this day the 'new' maximal xPE are more than 4 meters lower than the 'old' ones, because the EE is very useful for filtering of high peaks in position errors (see fig. 1 and fig. 4). It allows reduction of the error standard deviation.

Fig. 2 and 3 illustrate the ability of the proposed algorithm to follow the behavior of xPE. The 'new' HPL and VPL are significantly lower, as a rule and there are not unreasonably high jumps. Protection levels remain conservative, because the maximum Horizontal SI is 0. 28 and the maximum Vertical SI is 0.31, i.e. much less than the misleading information threshold $SI_{th} = 0.75$. The APV-I, APV-II and CAT-I availabilities, calculated for 'old' xPL are 96.96%, 74.26% and 1.68% respectively. The corresponding availabilities, calculated for 'new' xPL are as follow: 99.33%, 97.72% and 86.55%. They show significant availability improvement.

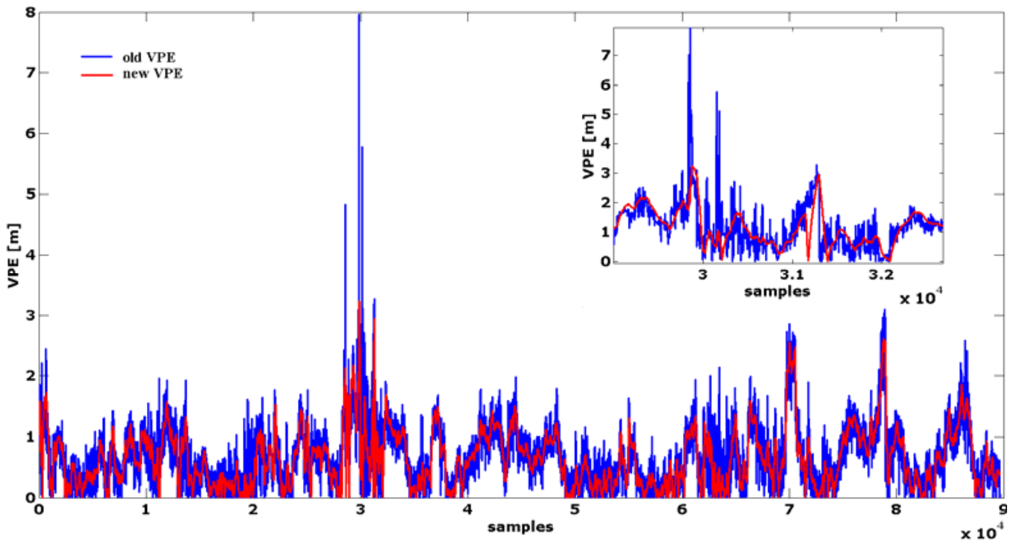

Fig. 1. Vertical Position Error for 17th of February 2012 ($\rho = 0.99$) [own study]

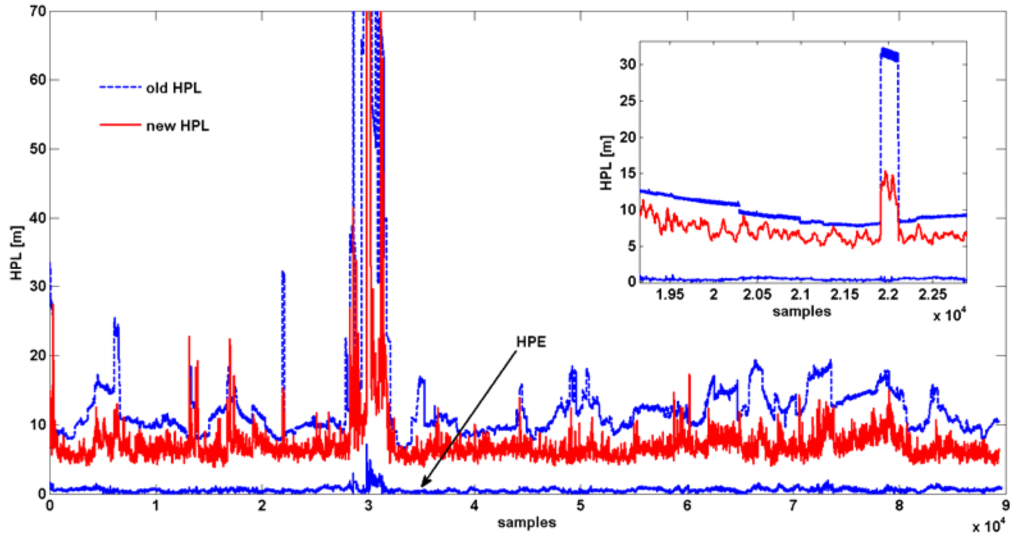

Fig. 2. Horizontal Protection Level for 17th of February 2012 [own study]

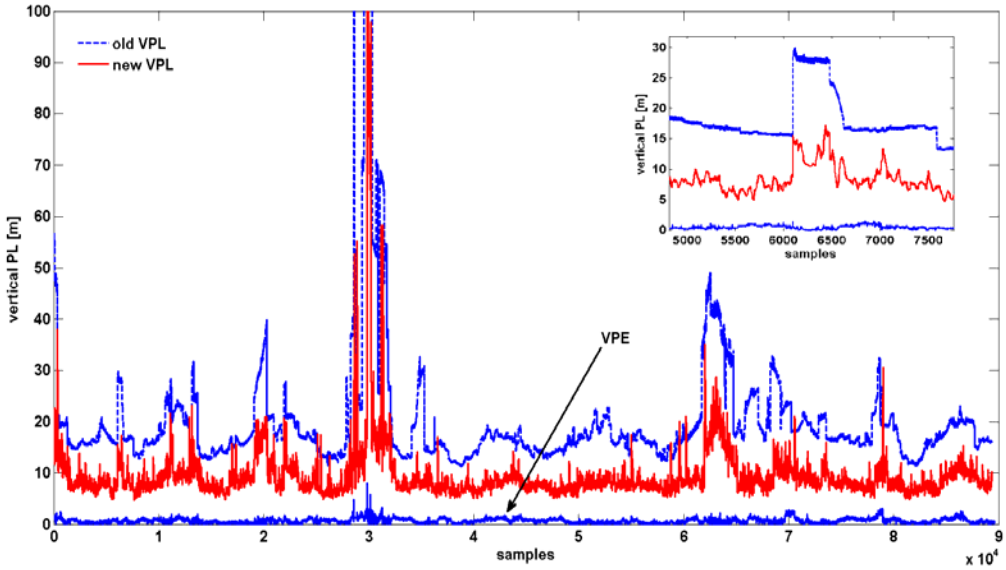

Fig. 3. Vertical Horizontal Protection Level for 17th of February 2012 [own study]

Fig. 5–13 show EGNOS performance results, obtained using data collected during a month. As a rule the 'new' maximal xPE are lower (and never higher) than 'old' ones (see fig. 5 and fig. 6). Because of the xPL decreasing, the 'new' xSI increased significantly, but there are not cases of MI or potential MI (see fig. 7).

The 'new' availability for APV-I service becomes more than the required 99%. An exception is observed on March 8, when a very strong magnetic storm hit the Earth (see fig. 8). Unlike the 'old' availability, the 'new' APV-II availability becomes more than the required 99% for 13 days of the observed period and increased by more than 10–15% (see fig. 9). The biggest changes in system availability are observed for CAT-I service. While the 'old' availability is a few percent, the 'new' one is more than 85% (see fig. 10).

After applying EE methodology in xPL calculations, the probability of system discontinuity for APV-I decreases as a rule (see fig. 11). The probabilities of discontinuity for APV-II and CAT-I are reduced more than ten times (see fig. 12 and fig. 13).

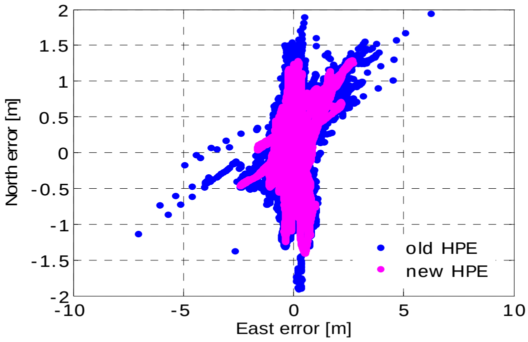

Fig. 4. Horizontal Position Error for 17th of Feb 2012 [own study]

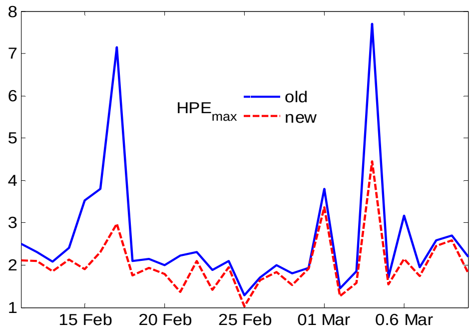

Fig. 5. Maximum of the daily Horizontal Position Error [own study]

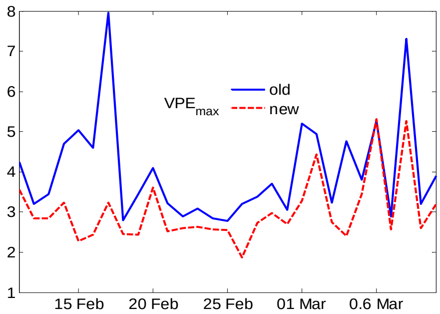

Fig. 6. Maximum of the daily Vertical Position Error [own study]

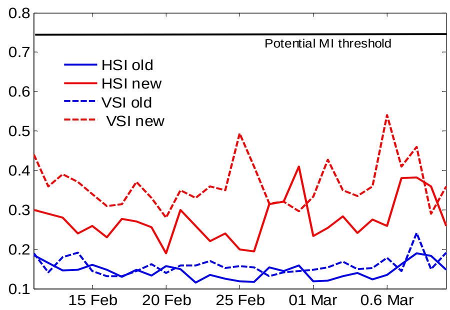

Fig. 7. Maximum of the daily Horizontal and Vertical Safety Index [own study]

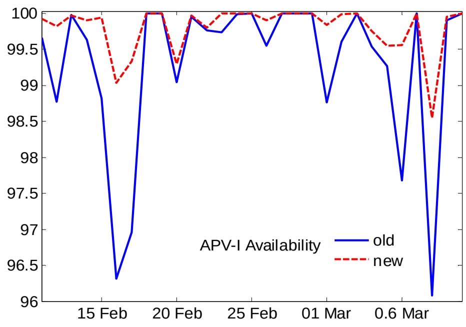

Fig. 8. APV-I availability [own study]

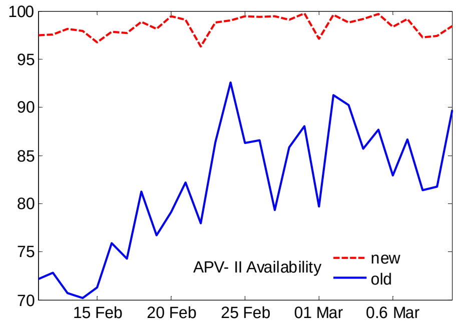

Fig. .9. APV-II availability [own study]

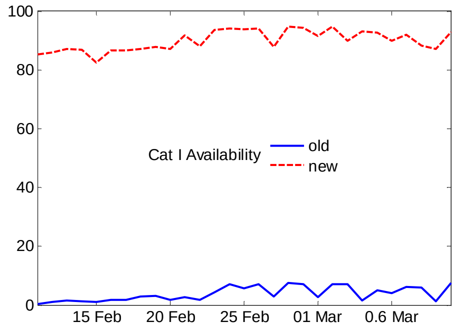

Fig. 10. Cat-I availability [own study]

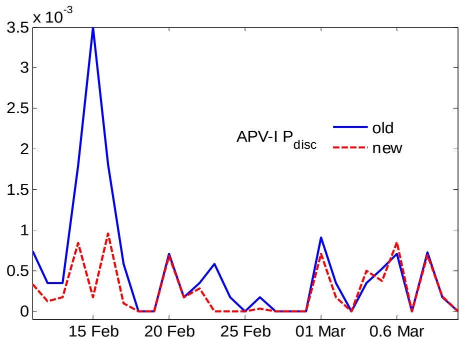

Fig. 11. APV-I probability of discontinuity [own study]

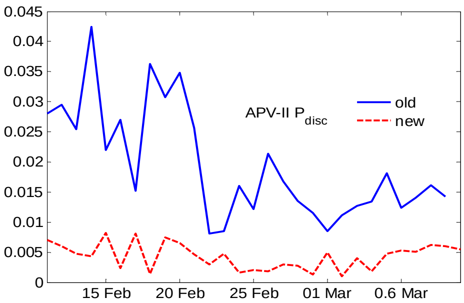

Fig. 12. APV-II probability of discontinuity [own study]

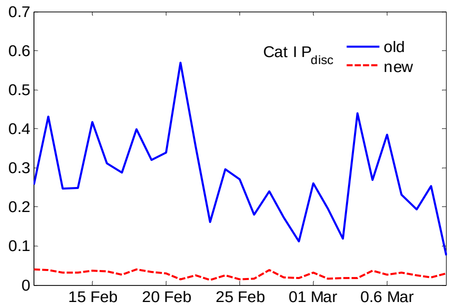

Fig. 13. Cat-I probability of discontinuity [own study]

CONCLUDING REMARKS

The accomplished experiments confirm that the designed new algorithms, based on the EE methodology, are very promising. They allow reduction of the error standard deviation and significant availability improvement (especially for APV-II and CAT-I) without breaches of the integrity. For APV-II and CAT-I the probabilities of system discontinuity decrease substantially. Many experiments, analogous to the presented, were conducted in 2011. All results are similar to the above presented. It should be noted that the used algorithm parameter values serve only as an illustration. Although experiments are an important element of any system performance verification, simulations and models are needed as additional tools in the system performance verification.

Acknowledgments

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