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RESEARCH PAPER

A new technique for SBAS availability improvement

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To protect a worst-case user, Satellite-Based Augmentation System (SBAS) transmits inflated integrity information for protection level computation. In this work, a novel user-based technique for autonomous protection level computation is proposed. Its quality is examined over Key Performance Indicators tests for integrity and availability using real European Geostationary Navigation Overlay Service (EGNOS) data. The accomplished experiments confirm that this technique allows significant availability improvement without breaches of the integrity.

Keywords: SBAS, Protection Levels, Integrity, Availability

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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. The availability of EGNOS to aviation announced on March 2, 2011 by the European Commission, means that aircraft will soon be able to use satellite technologies to establish their vertical positioning during approaches. The system basic parameters 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 protection level and vertical protection level (*HPL* and *VPL*) are computed to protect users from potential degradation of the system, expressed in terms of horizontal position error and vertical position error (*HPE* and *VPE*) above certain user levels, called horizontal alert limit and vertical alert limit (HAL and VAL). The key to the integrity concept in SBAS lies in the protection levels. The protection levels are monitored in flight and as long as they do not exceed the corresponding alert limits, integrity is said to be guaranteed. 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 and often "cost" availability. As a means of the system availability improvement, the USA GNSS Evolutionary Architectural Study recommends a shift of the integrity responsibility toward the user receiver [1]. Two autonomous approaches for computing xPL are suggested in the literature [2], namely Measurement Rejection Approach (MRA) and Error Characterization Approach (ECA). MRA operates on the principle of rejecting "faulty" measurements. ECA is used to characterize measurement errors and to compute a protection level to protect against them, without the need for identifying and removing degraded measurements. Both approaches can lead to the same level of integrity, the trade-off being a matter of protection level sizes and their associated availability.

In this work, a novel ECA technique for user-based computation of the xPL is presented. The main objective is to obtain availability improvement without integrity sacrifice. The technique presented below is very simple to implement and has low computational cost. It works directly in the position domain and uses velocity measurements with high accuracy.

II. XPL COMPUTATION USING BROADCAST INTEGRITY INFORMATION

The SBAS position solution is separated into East, North, and vertical components. The norm of the East and North error components forms the *HPE* and the absolute value of the Vertical, or Up component forms the *VPE*:

$$HPE = \sqrt{\Delta\hat{x}_E^2 + \Delta\hat{x}_N^2}, \quad VPE = |\Delta\hat{x}_V|. \qquad (1)$$

The SBAS xPL is defined as a bound on the xPE with a probability of hazardously misleading information (HMI) (integrity risk) derived from the integrity requirements. According to the International Civil Aviation Organization (ICAO) [3], the one-sided probabilities of integrity risk P_{HMI} (probabilities of HMI) per landing approach, are 10^{-9} and 10^{-7} for the horizontal and vertical components, respectively.

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The current protection level equations are based on Gaussian statistics [4, 5]: all errors are characterized by a zero-mean Gaussian distribution which is an upper bound of the true distribution in a certain sense [5]. This approach is very practical: the calculations are simple and the receiver computing load is small. To take into account non-zero mean and/or non-Gaussian errors, the SBAS system broadcasts error bounds (called overbounds) that conservatively represent the actual error distributions for each satellite, in order to guarantee integrity. This approach inflates confidence values to protect the worst-case user as opposed to the typical user.

The EGNOS xPL is computed by the user receiver using a bound of the standard deviation (std) of the corrected range measurement errors for each satellite contributes to the position solution. Each individual std is made up of four terms:

$$\sigma_i^2 = \sigma_{i,flt}^2 + \sigma_{i,UIRE}^2 + \sigma_{i,air}^2 + \sigma_{i,tropo}^2. \qquad (2)$$

The first two terms are based on values broadcast to the user, the third term bounds the local receiver's thermal and multipath error, and the final term is specified by tropospheric correction model. The *flt* term stands for fast and long-term corrections. It bounds the satellite clock and ephemeris error terms and is derived from broadcast user differential range error and degradation parameters. The *UIRE* term stands for ionospheric range error and is based on the interpolated value of the individually broadcast grid ionospheric vertical error terms. The knowledge of the bounds of the $i = 1{:}N$ stds in the measurement domain (related to the N satellites which contribute to the position solution) allows the computation of the bound of the std for each component y (East, North, and vertical) of the position domain:

$$\sigma_y = \sqrt{\sum_{i=1}^{N} s_{y,i}^2 \sigma_i^2}, \qquad (3)$$

where $s_{y,i}^2$ are geometrical parameters defined in [6]. Simplified, geometrical parameters provide information for the position of the N satellites to each other from the view of the user receiver. This information is used in forming the projection matrix (that relates the range domain measurement errors to the position domain errors) for weighted least squares position solution. The *VPL* and *HPL* are computed as:

$$VPL = K_V \sigma_V,$$
$$HPL = K_H \sqrt{\frac{\sigma_E^2 + \sigma_N^2}{2}\sqrt{\frac{\sigma_E^2 - \sigma_N^2}{2} + \sigma_{EN}^2}}, \qquad (4)$$

where σ_V^2, σ_E^2, and σ_N^2 are the variances of the vertical, East, and North components of the position solution, σ_{EN}^2 is the East–North covariance. The factors K_V and K_H correspond to the expected integrity risk probabilities for a unit variance zero-mean Gaussian:

$$K_V = \sqrt{2}\, erfc^{-1}(10^{-7}) = 5.33,$$
$$K_H = \sqrt{2}\, erfc^{-1}(10^{-9}) = 6.0. \qquad (5)$$

III. THE NEW XPL COMPUTATION

As stated in [1, 7, 8] the composite approach that treats the zero-mean noise and bias errors separately is very promising. According to this approach, the bounds of both the noise and bias errors are added together to obtain composite xPL:

$$xPL = xPL_{noise} + xPL_{bias}. \qquad (6)$$

The algorithm described below is based on the composite approach. Its generalized block scheme is presented in Fig. 1. This algorithm is realized as follows:

- First, the measured user position and velocity in each component (East, North, and vertical) are passed through autoregressive-moving average filter. In this way, high-quality estimation of the centered (zero mean) position error in each component is obtained. These estimations are used to form the *HPE* and *VPE* components due to noise.

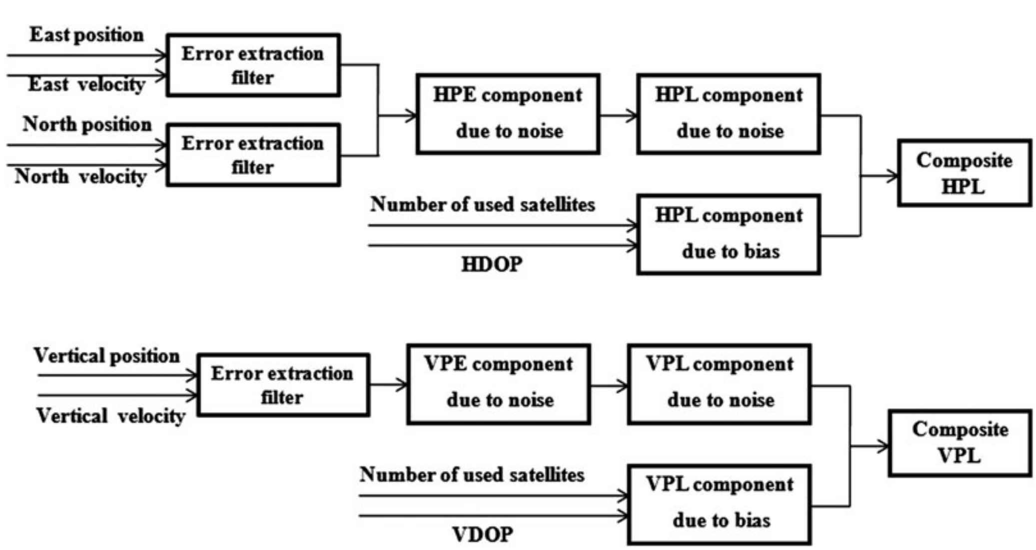

Fig. 1. Generalized block-scheme of the new xPL computing algorithm.

- Then the xPL component that arises only from the noise component of the error sources is calculated. To do this, an algorithm, which uses reference window of estimated xPE and holds constant rate of integrity risk (according to ICAO requirements), is realized. It is a modification of the well-known radar processor, named cell averaging constant false alarm rate (CA CFAR).
- 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 dimensionless geometrical parameter dilution of precision (xDOP).
- Finally, the new xPL is obtained as a sum of both xPL components.

The measured user position in each position component is a sum of the true position $x(i)$ and measurement error $\xi(i)$:

$$y(i) = x(i) + \xi(i). \tag{7}$$

As the direct estimation of the $\xi(i)$ values is difficult, it would be very helpful to remove the position variable. To do this, position $y(i)$ and velocity measurements $v(i)$ are used as follows [9]:

$$\begin{aligned}\bar{u}(i) &= y(i) - 2y(i-1) + y(i-2) - \frac{1}{2}[v(i) - v(i-2)]T \\ &= \xi(i) - 2\xi(i-1) + \xi(i-2) - \frac{1}{2}[\eta(i) - \eta(i-2)]T,\end{aligned} \tag{8}$$

where T is the sample period and $\eta(i)$ is the velocity measurement error. This error is assumed zero-mean white Gaussian noise [10]. Passing $\bar{u}(i)$ through filter with transfer function $F(z) = 1/(1-\rho z^{-1})^2$, where $0 < \rho \leq 1$, the output with z-transform:

$$u(z) = \frac{(1-z^{-1})^2}{(1-\rho z^{-1})^2}\xi(z) + \frac{(1-z^{-2})}{2(1-\rho z^{-1})^2}T\eta(z), \tag{9}$$

is obtained. In this way, centered error $u(i) \approx \bar{\xi}(i)$ can be extracted by setting $\rho \approx 1$. To do this, the influence of the receiver velocity error std is estimated using the second term in (9). The results show it is negligible (0.05–0.08 m) for receiver with high velocity accuracy (std $<$ 0.01 m/s) [9]. Such quality of information can be provided also by Inertial Navigation Systems (which accuracy in measuring the acceleration is 10^{-4} g, where g is the intensity of earth gravity).

It must be noted that using estimations of the centered errors, a more precise user position evaluation can be achieved.

The xPL component due to centered xPE (noise) is calculated by modified CA CFAR algorithm. In radar processing CA CFAR supposes zero mean Gaussian-distributed noise of unknown power level [3]. Its input is the magnitude of the signal envelope. Hence (see Section II), appropriate CA CFAR modification can be usable for current $xPL_{noise}(n)$ computation, as follows:

$$\begin{aligned} xPL_{noise}(n) &= \frac{S(n)}{M}(P_{HMI}^{-1/M} - 1), \\ S(n) &= \sum_{i=n-M+1}^{n-M/2} wE(i) + \sum_{i=n-M/2+1}^{n}(2-w)E(i). \end{aligned} \tag{10}$$

The proposed 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:

$$E(i) = \begin{cases} \sqrt{\beta[\bar{\xi}_E^2(i) + \bar{\xi}_N^2(i)]}, & \text{for noise component of } HPE \\ \beta|\bar{\xi}_V(i)|, & \text{for noise component of } VPE \end{cases}, \tag{11}$$

and factor β represents the upper bound of the ratio between the input and output error std. This factor is evaluated analytically and is tabulated for various values of the filter parameter ρ. For this purpose, an appropriate exponential model of the autocorrelation of the position error components is used [9].

Nowadays, SBAS signal uses the frequency L1 1575.42 MHz and its messages do not contain bias errors information. New SBAS signals planned for the L5 1176.45 MHz frequency offer an opportunity to broadcast range bias information [1]. In this work, 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 (μ_{max}), number of used satellites N and dilution of precision $xDOP$ [1, 7], as follows:

$$xPL_{bias}(n) = \alpha\mu_{max}\sqrt{N(n)} \cdot xDOP(n), \tag{12}$$

where α is an inflation factor required to increase the unweighted bias bound to bound the weighted bound in the horizontal/vertical position [7]. xDOP is a dimensionless parameter that relates the contribution of relative satellite geometry to the errors in horizontal/vertical position determination [10]. A low xDOP value represents a better GPS positional precision due to the wider angular separation between the satellites used to calculate a GPS unit's position. Finally, the new xPL is obtained as a sum of both xPL components (see (6)).

The main objective is to obtain low, but conservative xPL, because to maintain availability, the xPL cannot be unduly conservative. Theoretically, the new xPL must hold constant rate of given integrity risk probability. Oliveira and Tiberius [11] extend the common documented approach of integrity through xPL to reliability on the basis of statistical hypothesis testing, and as such provides a safeguard against model misspecifications as anomalies and outliers in the measurements.

IV. SOME EXPERIMENTAL RESULTS

The results presented below are obtained using data collected during 1 month, from September 19 to October 18, 2011, at the EGNOS Monitoring Station placed in Sofia (antenna position: latitude – 42.65282663°; longitude – 23.354327455°; height – 658.899 m) by Eurocontrol. The static tests were carried out with Septentrio PolaRx 2 single frequency L1 receiver. For this type of receiver horizontal velocity error std is 1.5 mm/s and vertical velocity error std is 2.8 mm/s. The true position for the static test is known with high accuracy and this enables the proper assessment of the real xPE. One should bear in mind the following:

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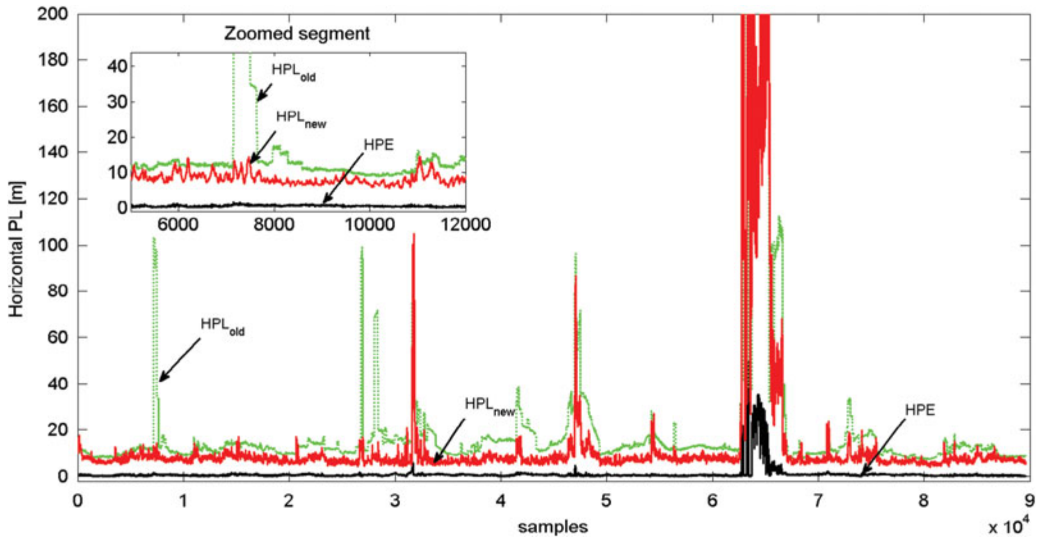

Fig. 2. *HPE*, conventional *HPL*, and new user-based *HPL* for September 27, 2011.

- For APV-I, APV-II, and CAT-I services the HAL equals to 40 m and VAL equals 50, 20, and 12 m, respectively.
- Sofia is situated in the border area on the European Civil Aviation Conference region.
- The presented results are obtained using Inmarsat AOR-E (PRN 120) signals.
- As integrity safety index (*SI*) is defined as the ratio between the true navigation system error and the corresponding protection level $SI = xPE/xPL$. There is potential misleading information situation if SI is bigger than $SI_{th} = 0.75$.
- Availability means percentiles of measured samples that are available for service category divided by the total number of samples. The local availability of the EGNOS for services of interest shall be better than 99% over the nominal operational lifetime of the service.
- The new xPL are calculated for maximal position error due to satellite bias of magnitude $\mu_{max} = 1.125\ m$ [1] and algorithm parameters: $\rho = 0.98$, $M = 40$, $\alpha = 1.1$, $w = 0.5$, $\beta = 1.2$.

The results are compared with these for xPL, which are computed using external information and PEGASUS software [12]. They show significant availability improvement without integrity sacrifice. Figures 2 and 3 show xPE, "old" xPL which is computed using external information and "new" user-based xPL for September 27 (a major storm, hit earth this day). These figures show also zoomed views of the same plots in order to better illustrate the abilities of the "new" xPL. As expected, the ability of the proposed algorithm to follow the behavior of xPE is better. 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 0.33 and the maximum vertical *SI* is 0.43, i.e. much less than the misleading information threshold $SI_{th} = 0.75$. The biggest vertical *SI* value of 0.54 ($SI = 0.28$ for "old" *VPL*) is registered on September 22. For this day, the APV-I, APV-II, and CAT-I availabilities, calculated for "old" xPL are 85.53, 59.66, and 0.84% respectively.

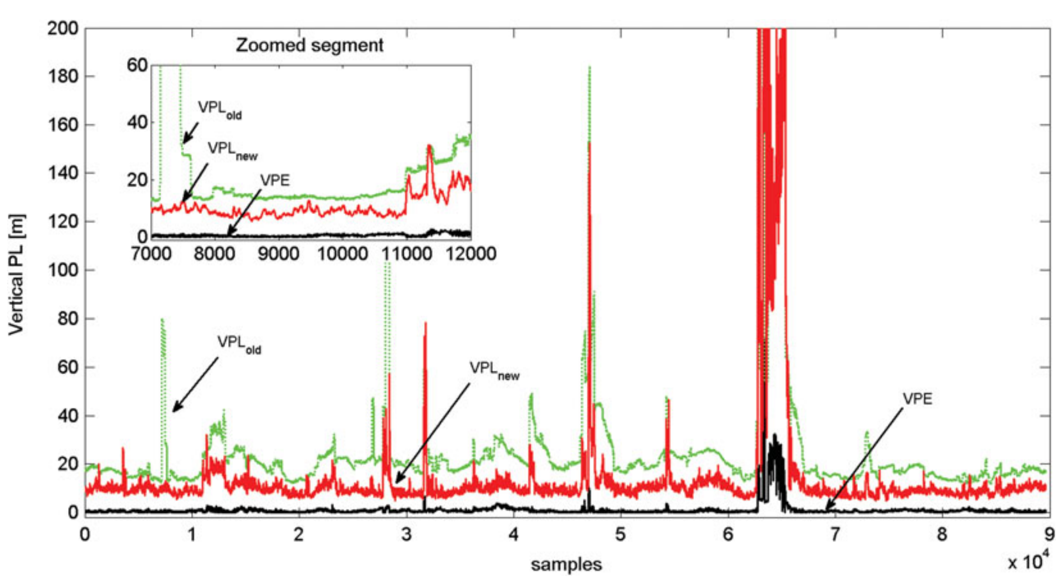

Fig. 3. *VPE*, conventional *VPL*, and new user-based *VPL* for September 27, 2011.

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Table 1. Arithmetic means (from September 19 to October 18, 2011).

SI (horizontal/ vertical)		Availability					
		APV-I		APV-II		CAT-I	
Ext	New	Ext	New	Ext	New	Ext	New
0.15/0.17	0.36/0.45	92.5	98.06	49.1	93.82	0.52	79.76

The corresponding availabilities, calculated for "new" xPL are as follow: 97.59, 91.83, and 78.75%.

The experimental results are summarized in Table 1, which shows month's arithmetic means of the daily *SI* maximum and availability. It can be seen that although "new" *HPL* and *VPL* are significantly lower, they remain very conservative. There is not real misleading information situation ($SI > 1$), or potential misleading information situation ($SI > 0.75$). The achieved availability improvement is significant.

V. CONCLUSION

The current SBAS protection level equations are based upon covariance propagation of zero-mean Gaussian errors. 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. The main objective of this work is to present a user-based technique for protection levels computation. The accomplished experiments confirm that this technique allows significant availability improvement without breaches of the integrity. Although experiments will always be an important element of any system performance verification, they will never provide sufficient data to back-up a claim on system conformance to its integrity requirements. Simulations and models will be needed as additional tools in the system verification.

It should be noted that the focus of this work is methodological and the used algorithm parameter values serve only as an illustration.

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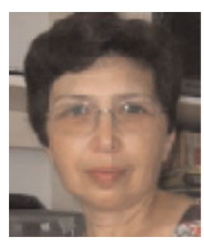

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