EXPLORATION OF THE GPS/EGNOS POSITION ERRORS AND NAVIGATION ACCURACY FOR DIFFERENT TYPES OF FINAL APPROACH PROCEDURE

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Abstract. This paper presents current results of the research activity on the GPS and EGNOS safety of live service provided for aviation in the ECAC area. Author focused his research on the method of the analysis of GNSS position error and its statistical description based on precise measurement in the vicinity of the regional airport Kunovice, south-eastern part of the Czech Republic. Based on the long-term observation of the GPS and EGNOS signal in space, there were identified several disruptions of the standard measurement model presumptions on which an aviation user relies on. Second, the navigation accuracy parameter and the method for the complete GNSS signal in space assessment are computed and presented for all approach operations. Comparison to the GNSS signal-in-space requirements with conclusion on the feasibility of different types of approach services provided by GPS/EGNOS is further presented. Finally, evaluation method and results are described to be able to be fully understood and potentially followed by other entities.

Keywords. Navigation Accuracy, Error Ellipse, Final Approach, GPS, EGNOS, GNSS

1 Introduction

1.1 Preface

Increase in regular air traffic in different regions around the world, together with strengthening the role of efficiency and safety of business and general aviation operating to/from regional airports, impose demand on the development, testing and implementation of new navigation methods and radio navigation means, that commence regional airports to be well accessible in IFR weather conditions and thus attractive for airport's customers. In today's and upcoming navigation environment with the new GNSS elements and ATC route structures to be operational, motto *Best equipped = Best served* is of vital importance for regional and general aircraft operations. In the area of European Civil Aviation Conference (ECAC) states, the new GNSS system was formed by the Global Positioning System (GPS) and the European Geostationary Navigation Overlay Service (EGNOS), started to provide Safety of Live (SoL) service. The EGNOS system is designed as wide area differential GPS system (SBAS – Satellite Based Augmentation System) for aviation to complement GPS Standard Positioning Service (SPS) to be able to reach required levels of navigation accuracy, integrity, continuity and availability. GPS/EGNOS system is intended to support the development of area navigation (RNAV) applications that are supposed to decrease CFIT risk and increase the number of instrument RWY with vertical guidance procedures. Civil aviation organizations in the Czech Republic didn't participate on the EGNOS and GPS core constellation SoL service evaluation. Recalling Air Navigation Service Provider (ANSP) responsibility for underlying navigation infrastructure to support navigation procedures published by state in sovereign airspace under its responsibility, any GNSS navigation service must follow basic ICAO Annex 10/I signal in space requirements and state is supposed to observe an evaluate GNSS signal in space before navigation service introduction in national airspace.[1] Therefore studies of SBAS performance for aviation on the area of Czech Republic are being conducted. The article presents the methods and results of the analysis of the accuracy parameter, on the example of the Kunovice airport region and all following categories of approach operations: NPA[2], LNAV/VNAV, APV I, APV II, APV 35 (~ LPV 200), CAT I.

Navigation accuracy is the first and the only standalone parameter of all four navigation performance parameters, i.e. accuracy, integrity, continuity and availability. Study of the accuracy parameter is based on the ICAO presumption of SBAS fault-free receiver concept [6]. Performance requirements on the navigation specification for individual aircraft and for the overall system include signal in space, airport facilities, radio navigation support and aircraft system ability to fly the desired trajectory. Total requirements for the system were used as a starting to derive the requirements on the characteristics of GNSS signal in space. Total system requirements on RNP or RNAV may not be confused with the GNSS signal in space requirements. In opposite to conventional ground NAVAIDs, GNSS degraded configurations have impact on much more aircrafts. Certain requirements on the signal in space are therefore more stringent because more aircrafts are exposed to incident/accident risk at once. Number of received and processed satellite signals changes with different receiver design, its position in operational coverage, etc. Exploration of the method for the assessment of how the satellite constellation affect the aviation user according to final approach operation is principal part of the method evaluated in the following paragraphs.

1.2 GPS/EGNOS Signal in Space Observation

It is well known that the level of accuracy belongs among the criteria that determine the airspace design rules (establish width of air route, the spacing of runways, and the risk of collision). Determination of the navigation accuracy of specific GNSS (Global Navigation Satellite System) system (i.e. in Europe GPS augmented by wide area differential EGNOS system) consists part of the continuing development of methods for GNSS performance assessment for aviation on the Institute of Aerospace Engineering, and thus is of author's primary concern in this contribution.

Firstly, the GPS/EGNOS static observation data were collected with the platform of geodetic Ashtech GPS/EGNOS single frequency receiver which receives and logs L1, C1, D1, navigation messages and EGNOS message, and is situated on the Campus of Brno University of Technology. Author made use of the Matlab technical language for the design of code for computation of position solution, empirical position error characteristics and navigation accuracy. Prototype for GBAS and SBAS evaluation software (EUROCONTROL) designed according to RTCA/DO-229C was used to obtain range domain components. During the period of two years regular static observation and evaluation was conducted. There were identified north-east systematic position error in EGNOS augmented GPS position solution in different locations in the eastern part of Moravia, see [3,4]. Addressed the Czech Office for Surveying, Mapping and Cadastre gathers geodetic precise GPS measurements, access to the Czech GPS permanent network (CZEPOS) observation data, that usually serves to provide commercial service, correction vectors for GPS measurements to determine highly precise geodetic position, idea of the data utilization for aviation purpose became reality. Receiver location ensures good visibility of the satellites, monitoring systems of the stations, reporting of the accuracy parameters of the stations, geodetic precision raw measurement in the Receiver Independent Exchange format (RINEX).

[1] Today, the EGNOS wide range status information is supplied by the ESSP (EGNOS Wide Area Performance Month Report, Service Provision Yearly Report and EGNOS Service Notice).

[2] NPA – mode of GPS/SBAS receiver according to [7]. If ionospheric correction are not available, receiver makes use of the inospheric Klobuchar model supplied by GPS navigation message. In the system evaluation, worst case scenarios should be studied. Therefore NPA mode was programed to make use of Klobuchar model only.

Station CHOD, which is one of the three possible CZEPOS network stations close enough to the airport Kunovice, it was selected based on the following applied criteria: integrity of data set of minimum duration of 24 hours (exact minimum period of observation is 23:55:05), frequency record of 1 Hz, average number of tracked satellites, mean square error due to signal multipath at frequency L1, number of consecutive phase slips, PDOP value, available format of measurements and navigation message. Characteristics of station CHOD: latitude 48° 50' 58.6324", longitude, 17° 7' 44.64154" E, ellipsoidal height 228.389 m, elevation mask = 5 °, receiver LEICA GRX1200PRO. Observation period, presented in the article, started on 10/06/2012 at 00:00:00 and ended at 23:55:05. EGNOS transmitted messages of PRN 120 geostationary satellite was applied.

2 Methods

2.1 Accuracy analysis introduction

The quality parameters ought to be observed by every Air Navigation Service Provider that plans the implementation of the EGNOS system to its national airspace. Accuracy is parameter whose actual value is only estimated, not known precisely. Hoffmann-Wellenhof [1] defines accuracy of the navigation system as the degree of conformance between an estimated or measured parameter of an object at a given time and the true value of this parameter. Primarily, it is supposed to be stochastic parameter, statistical measure of the system error together with a confidence level (95% is mostly used). It is often represented by a root mean square (RMS - the square root of the mean of squared errors). In the study, the statistical quality measures for *Predictable-absolute* ***accuracy*** (the accuracy of a position solution of a navigation system with respect to the true or charted position) and *Repeatable accuracy /**precision**/* (the accuracy with which a user can return to a position whose coordinates have been determined at a previous time with the same navigation system) are used. Precision describes the tendency of a set of random numbers to cluster about a number determined by the set. If zero bias is present, precision measures may also be means of representing accuracy. However, if these multiple measurements include systematic errors (biases), highly precise measurements may nonetheless yield highly inaccurate results.

Factors impacting accuracy of GNSS are primarily: *satellite geometry* (satellite de-selection, satellite mask, changing constellation availability /SBAS data not available for satellite/, ground segment (minimum number of RIMS receiving signal of the GPS satellite to create error models for time, ephemeris andionosphere), ionosphere activity, local multipath, *quality of the GNSS system errors models* (of ground and user segment), etc. Factors impacting precision are primarily: age of SBAS corrections, interruption of tracking satellite, radio-frequency interference, ionosphere scintillation, loss of corrections, jamming.

2.2 Aviation Specific Requirements and Application Method

Global navigation satellite system is non-stationary and its assessment is different from ground-based navigation systems that have reproducible error characteristics. Space segment of GNSS system is dynamic with fast geometry change, which is conventionally described by the matrix of observations, or just DOP (dilution of precision).

ICAO GNSS Manual makes use of *indirect approach of accuracy description*. The accuracy is defined as difference between estimated and actual aircraft position. For a large set of independent samples, at least 95 percent of the samples should be within the accuracy requirements. ICAO presents more applied approach in navigation accuracy statistic as is the case of Navigation Specifications for on-board RNAV/RNP system. It is the 95th percentile of aircraft total system error that is compared with accuracy standard for the navigation specification. The GNSS accuracy requirement is to be met for the *worst-case geometry (WC)* under which the system is declared available. The system should be observed at least 24 hours or more. While errors can change fast for core satellite constellation, SBAS (Satellite Based Augmentation System) and GBAS (Ground Based

Augmentation System) errors vary slower over time due to filtering. That is why periodical observations are conducted.

Applied accuracy characteristic for complete set of measurement data to be evaluated are: measured *navigation accuracy (NSE – Navigation System Error)* and *scaled navigation system accuracy (sNSE)* finally represented by 95th percentile of the measured or scaled individual samples *(scaled Horizontal Position Error – sHPE, scaled Vertical Position Error – sVPE).* In civil aviation, data must be evaluated not only for position errors introduced by the GPS system corrected by the EGNOS messages, but also for the geometry safety multiple. In practice, value of the 95th percentile of position error does not represent value to be compared against ICAO SARPS requirements, though it is often presented incorrectly this way. Resulting accuracy value also depends on the phase of flight/category of approach, for which are errors evaluated (higher rate of correction messages transportation, correction data age limited)[3]. Accuracy of navigation service can be defined as the fitness for use for a specific data set, which is appropriate for use with one application, however may not be fit for use with another. Alert Limit (*HAL, VAL*) is the largest position error which is acceptable and results in safe operation. At the same time EGNOS provides the integrity service of which core function is an estimation of the navigation error with $1*10^{-7}$ probability, Protection Level (*HPL, VPL*). Position errors that are greater than alarm limit must be indicated to aircrew, otherwise integrity has failed and flight safety is at risk. It must be emphasized, that protection level is GPS constellation geometry dependant, projection matrix determine projection of σ^{est}, which contains user and ground segment corrected position solution error contribution. Author made use of EGNOS supplied integrity protection levels and constellation geometry. Method of the user/satellite geometry, worst case scenario evaluation makes use only of the position samples, when the system is available for intended operation.

The measured accuracy is thus defined as a 95th percentile of the error distribution (δ_i = *HPE or VPE*) of all the valid samples within the assessed period and, if we consider the geometry effect for users in different locations, samples scaled with scaled factor (SF - horizontal/vertical) for the worst case geometry ($\delta_{WC,i}^{NPA}$, $\delta_{WC,i}^{PA}$ = *sHPE, sVPE*) of the orbiting satellites user might experience. Method is based on the following equations:

$$\delta_{WC,i}^{NPA} = \frac{6}{HDOP_i} * \delta_i, \ \frac{6}{HDOP_i} = SF^{NPA} \quad \textit{scaled position error of sample i [m]} \quad (2.1)$$

$$p_{95\%}^{NPA} = sNSE^{NPA} \quad \textit{navigation accuracy for NPA [m]} \quad (2.2)$$

$$\delta_{WC,i}^{PA} = \frac{AL}{PL_i} * \delta_i, \frac{AL}{PL_i} = SF^{PA} \quad \textit{scaled position error of sample i [m]} \quad (2.3)$$

$$p_{95\%}^{PA} = sNSE^{PA} \quad \textit{scaled navigation accuracy for PA}^4 \textit{ [m]} \quad (2.4)$$

$$HPL = K_{H,PA} * \sigma_{H,PA}^{est}, K_{H,PA} = 6, HAL = K_{H,PA} * \sigma_{\mathrm{H,PA}}^{\mathrm{est,MAX}} \rightarrow \sigma_{\mathrm{H,PA}}^{\mathrm{est,MAX}} = 6.67\ m \quad (2.5)$$

$$VPL = K_{V,PA} * \sigma_{V,PA}^{est}, K_{V,PA} = 5.33, VAL = K_{V,PA} * \sigma_{V,PA}^{est,MAX} \quad (2.6)$$

$$\rightarrow \sigma_{V,APVI}^{est,MAX} = 9.38\ m, \sigma_{V,APVII}^{est,MAX} = 3.75\ m, \sigma_{V,APV35}^{est,MAX} = 6.57\ m, \sigma_{V,CAT\ I}^{est,MAX} = 9.38\ m$$

Mathematical context of the studied modes and other terms used in method define by equations 2.1 – 2.6 above can be found in [7].

[3] Horizontal alert limit is 40 m for all approaches with vertical navigation; vertical alert limits for are gradually 50, 20, 35, 12, 10 for APV I, APV II, APV 35, CAT I, CAT II operations.

[4] PA – Precision Approach mode represents according to RTCA/DO 229C all GNSS APV and PA approaches.

2.3 Models Applied for Position Computation from Range Domain Measurements

To calculate and evaluate GNSS position from EGNOS corrected GPS pseudoranges, Least Square Solution (LSQ) method is justified for several reasons. First, method considers measurement errors of satellites available and their total number therefore achieves high accuracy. Unlike the Kalman filter, it is a rigorous solution which provides critical evaluation in which the model parameters are unknown, correlated sources of error are not suppressed, other sources of measurement for obtaining a better estimate are not available. It should be emphasized that using any calculation, number of satellites in constellation available today lead to highly overdetermined system of equations. Method is also standardized by the document RTCA MOPS 229C for GPS/SBAS avionics.

Any risk budget for the compound GNSS system formed by two subsystems, GPS and EGNOS, must be addressed as *core risk* for core GNSS constellation and *augmentation risk* for augmentation system. Therefore, when analysing accuracy, it is convenient to address two modes, GPS standalone and EGNOS Approach mode:

a) GPS Standalone mode: The Un-weighted Least Squares algorithm (LSQ) determines the navigation solution from the GNSS pseudorange measurement that is based on the assumption that all measurement to the satellites has the same standard deviation (estimate of residual measurement error),

b) EGNOS Approach mode: The Weighted Least Squares algorithm (WLSQ) is based on the more realistic assumption that measurement with high level of certainty should be weighted higher in a position solution that a measurement with a low level uncertainty (weights are based on SBAS model and transmitted corrections, they are represented by inverse variances of errors after all the corrections to range measurements have been applied). It is worth mention, that documents standardizing GPS navigation systems, against which the navigation receivers are certified, commonly rely on the linear model and provide a simple description of measurement model. Navigation system errors generally follow a known error distribution; usually normal distribution is relied on.

3 Results of statistical evaluation and discussion

3.1 Error Ellipse – Conventional Approach of Error Description

Characterization of the positions of a random character is best described by Probability Density function (PDF). Error ellipse (EE) is the geometric assemblage of vectors' endpoints having the equal probability density (the PDF is set equal to a constant). Horizontal cross-section of the Two-dimensional normal PDF given by equation 2.7 results in an error ellipse (ellipse of concentration); all position samples are usually included. In general ellipse rotation has implications on highly accurate and precise measurement to be usually observed in the direction of interest. However, course of air traffic route changes so the aircraft is supposed to have same probable navigation error in any horizontal direction. EGNOS certified aviation receiver uses eigen values of estimated position to compute protection levels.

When studying Figures 2, 3 and Tables 1, 2 the position bias in combined GPS/EGNOS solution was confirmed. The orientation and shape of error ellipse shows position samples not to be in a circle, which is the assumption of un-weighted LSQ solution. Components of position errors are dependant, especially for GPS Standalone mode. In the case of EGNOS corrected position solution, semimajor axis is almost identical in direction of North–South axis. When shorter intervals of hundreds or thousands of samples were selected error ellipse changes its orientation and its dimension because of strong short time data dependency. Ellipse diameter changes with height of horizontal cross-section of Two-dimensional normal distribution.

Presumption, that position errors are symmetrically distributed, i.e. smaller the value the more frequently occurring, is not valid in the tails for the observed period (Figure 1-4 for combined GPS and EGNOS on the right). Three clusters of the data in north direction of error ellipse for GPS position corrected by EGNOS lucidly show outliers, which do not follow presumptions of normal probability density function. However, such extent is not diurnal. For all other samples it holds true, that the smaller the value, the more frequently occurring. It was proved with other measurements on the Institute that such a great number of clusters of outliers are not usually present in the data. Risk of such outliers primarily comes from weak geometry of GPS, or EGNOS system not providing components of range error corrections.

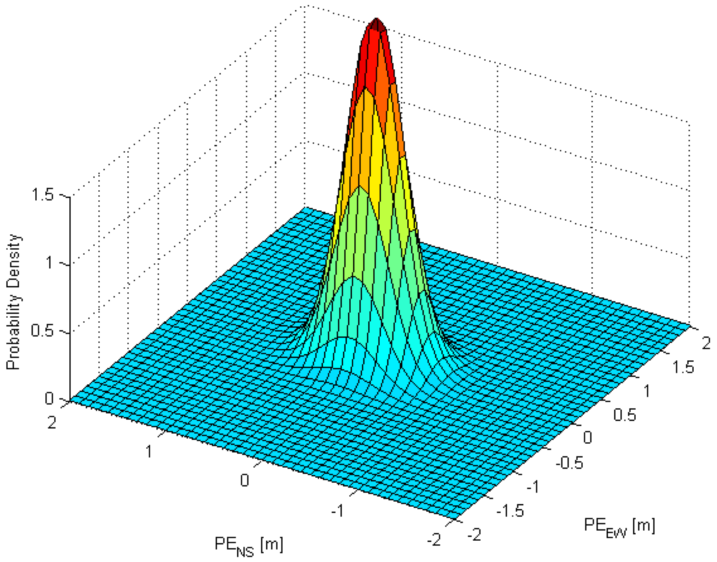

Figure 1: Two-dimensional normal distribution of the horizontal position error (GPS/EGNOS), DOY 280.

$$f(x,y)=\frac{1}{2\pi\sigma_x\sigma_y\sqrt{1-\rho^2}}e^{\left\{-\frac{1}{2\left(1-\rho^2\right)}\left[\frac{x^2}{\sigma_x^2}+\frac{y^2}{\sigma_y^2}\right]-2\rho\frac{xy}{\sigma_x\sigma_y}]\right\}} \tag{2.7}$$

$$C=\begin{pmatrix}\sigma_x^2 & \rho\sigma_x\sigma_y \\ \rho\sigma_x\sigma_y & \sigma_y^2\end{pmatrix} \tag{2.8}$$

$$Det(C-E\lambda)=0\Rightarrow\left(\sigma_x^2-\lambda\right)\left(\sigma_y^2-\lambda\right)-\rho^2\sigma_x^2\sigma_y^2=0 \tag{2.9}$$

$$a=\sqrt{\lambda_1}=\left\{\frac{1}{2}\left(\sigma_x^2+\sigma_y^2+\sqrt{\left(\sigma_x^2-\sigma_y^2\right)^2+4\rho^2\sigma_x^2\sigma_y^2}\right)\right\}^{1/2}$$

$$b=\sqrt{\lambda_2}=\left\{\frac{1}{2}\left(\sigma_x^2+\sigma_y^2-\sqrt{\left(\sigma_x^2-\sigma_y^2\right)^2+4\rho^2\sigma_x^2\sigma_y^2}\right)\right\}^{1/2} \tag{2.10, 2.11}$$

a [m] – semimajor axis
b [m] – semiminor axis
λ_1, λ_2 [m^2] – eigen values of the dispersion matrix C; eigen values constitute matrix spectrum
C – dispersion matrix (variance-covariance matrix)
E – unit matrix
σ_x^2, σ_y^2 [m^2] – error variance in x and y axis of the local coordinate (topocentric) system with reference in antenna phase centre.
$\rho\sigma_x\sigma_y$ [m^2] – actual covariance in x and y axis
x – East-West (EW) axis of local coordinate frame
y – North-South (NS) axis of local coordinate frame.

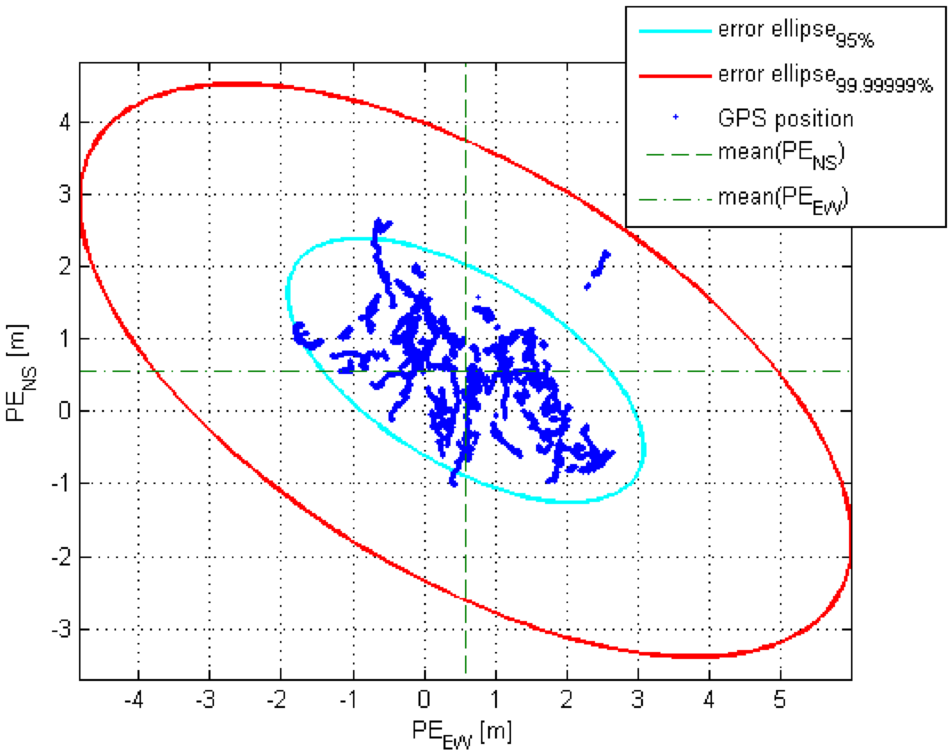

Figure 2: Error ellipses for GPS Standalone solution; the area within which it is 95% (cyan) or 99.99999% (red) probable that the true position lays, DOY 280.

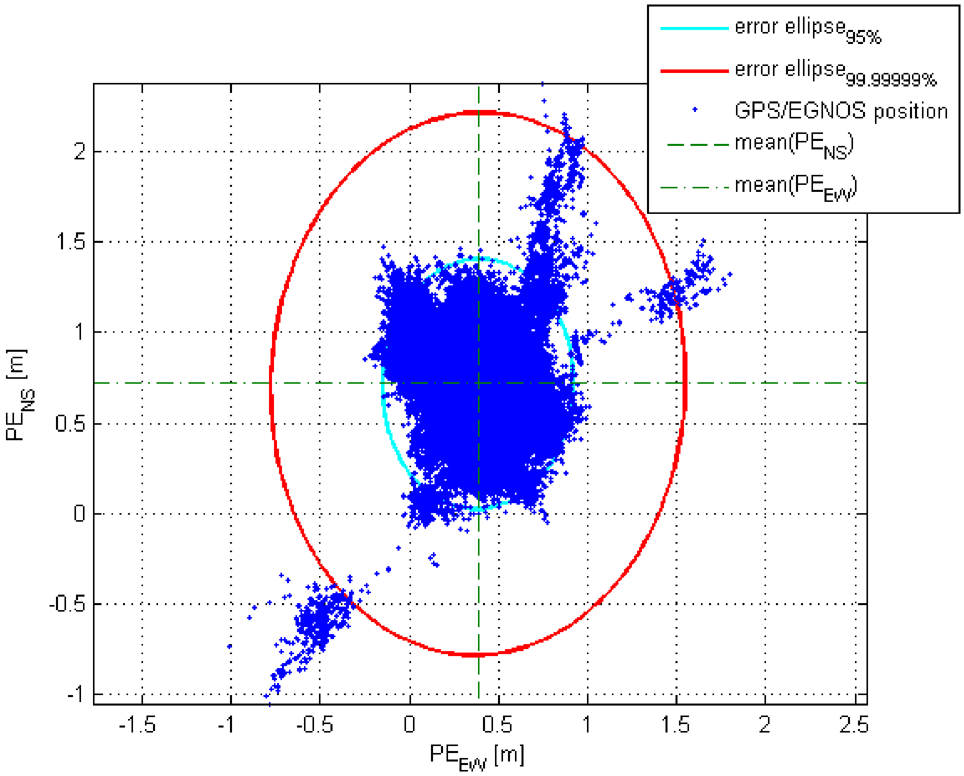

Figure 3: Error ellipses for EGNOS augmented solution on the right; the area within which it is 95% (cyan) or 99.99999% (red) probable that the true position lays, DOY 280.

3.2 Navigation Accuracy and Position Error Characteristics

Quality of user navigation accuracy can be readably interpreted with use of parameters defined in 2.1 and 2.2. Tabulated results of analysis are in the Table 1 and Table 2. Effect of GNSS geometry, besides GPS system orbit inclination, is presented with Number of Satellite Vehicle used (NSV_{USED}). Weighted LSQ measurement model utilization was proved to obtain better results.

Computed scaled navigation accuracy reached values of 0.25 to 8.7 times higher than position error measured (usually presented to readers and audience), depending on the category of approach. User of navigation system GPS/EGNOS is provided with relatively small bias with respect to aviation requirements on GNSS SIS during approach that may come from variety of sources. However, measurement must be treated with care and bias should be more analysed by the EGNOS system designers of possible causes with statistical and step-by-step correction implementation method. That is beyond the scope of this article. Today, the extent of bias has no limitation on aviation user during final approach of EGNOS today's primary categories APV I. However, vertical limit of scaled navigation accuracy of 6 meters for category APV 35 GPS/EGNOS may not fulfil requirement during 95% of the flight time, see Figure 5, 7. Reducing bias would help to mitigate this risk. Next development of GNSS realized by the multi-frequency and multi-constellation SBAS systems probably makes approach procedure LPV 200.

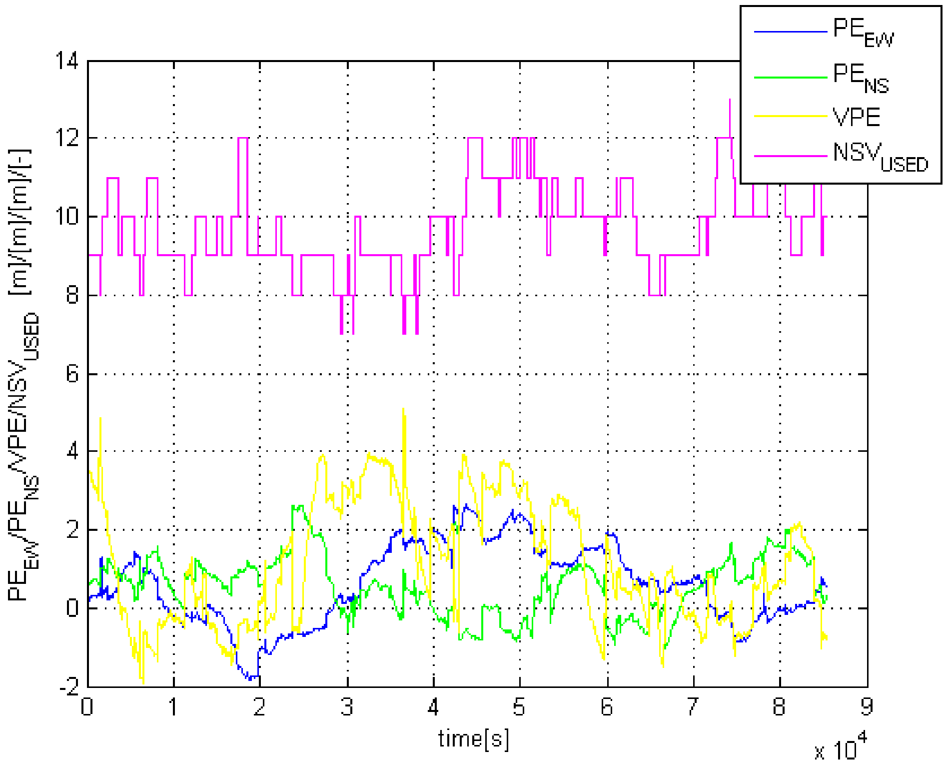

Figure 4: Time series of position errors of the GPS Standalone mode, DOY 280.

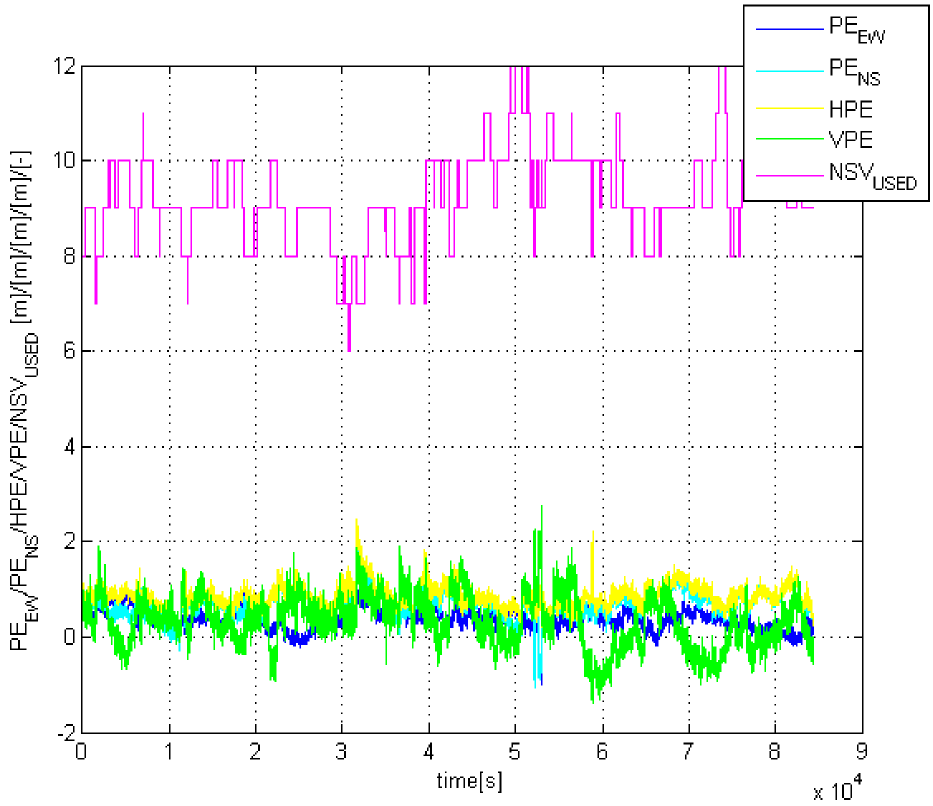

Figure 5: Time series of the EGNOS Approach mode position errors, DOY 280.

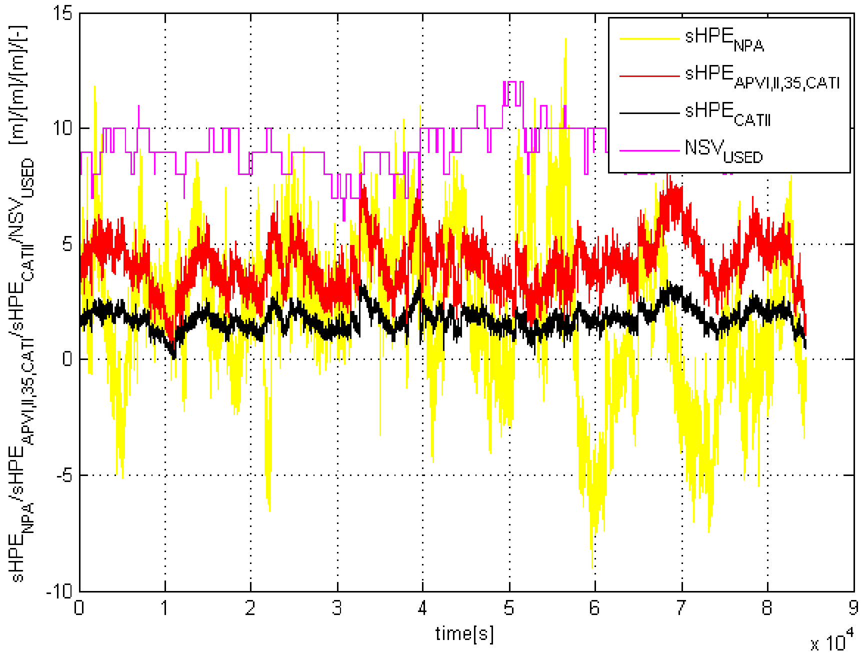

Figure 6: Time series of scaled horizontal position errors of the EGNOS Approach, DOY 280.

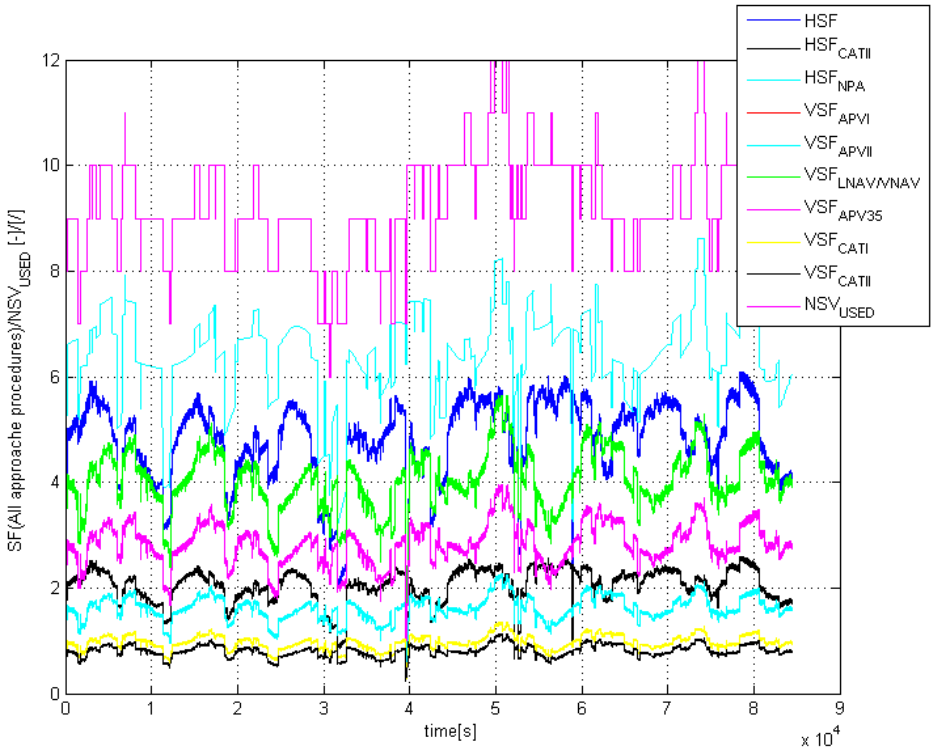

Figure 7: Time and position dependent scaled factors for all considered approach operations, DOY 280.

Estimated parameters		GPS+EGNOS				GPS			
		EW [m]	NS [m]	HPE [m]	VPE [m]	EW [m]	NS [m]	HPE [m]	VPE [m]
min	x_{min}	-1.00	-1.05	0.01	-1.39	-1.82	-1.02	0.11	-1.95
max	x_{max}	1.79	2.37	2.49	2.73	2.64	2.65	3.39	5.07
mean	$\bar{x}$	0.39	0.71	0.85	0.33	0.58	0.57	1.38	1.13
median	$\tilde{x}$	0.38	0.70	0.83	0.34	0.60	0.61	1.13	0.85
std	s	0.28	0.21	0.24	0.52	1.01	0.74	0.59	1.56
range	$x_{(n)}-x_{(1)}$	2.80	3.42	2.47	4.12	4.46	3.67	3.28	7.02

Table 1: Statistical characteristics of position errors.

	NPA			LNAV/VNAV			APV I		
	Meas	Scal	Req	Meas	Scal	Req	Meas	Scal	Req
HNSE (95%)[m]	1.40	9.81	220	1.25	83.63	220	1.25	6.02	16
VNSE (95%) [m]	-	-	-	1.13	4.28	20	1.13	4.28	20
	APV 35			APV II			CAT I		
	Meas	Scal	Req	Meas	Scal	Req	Meas	Scal	Req
HNSE (95%) [m]	1.24	6.02	16	1.24	6.02	16	1.15	5.80	16
VNSE (95%) [m]	1.13	3.00	6	1.13	1.71	8	0.92	1.02	4

Table 2: HNSE and VNSE parameters for all the categories of studied approach operations.

4 Conclusion

In the article, the character of systematic error is presented and is consistent with previous measurement on the Campus of BUT. Scaled HPE and VPE mean values from Table 2 with K-factors from equation 2.5 and 2.6 provide us possible implications of bias projection. Methods for studying position errors and exploration of the GNSS signal in space accuracy are outlined and tested. Scaled factors are firstly presented with time reference. With use of the scaled accuracies and protection levels, ANSP is able to compute and assess corresponding availability and continuity of any approach operation under worst case scenarios and thus to be consistent with the wording of ICAO SARPS regulation.

Based on the observation of the geodetic station CHOD traditional method on the position error assessment (not application dependent) is providing reader with general information on position error characteristic. Together with application specific method of scaled accuracies for the GNSS air navigation operations, complete set of investigated parameters are presented to be compared with usual position error assessment. There are several important results of the study. The bias in the GPS/EGNOS position solution of long term observation is of primary concern. It must be examined to which extend the system behaves/not behaves according to linear measurement model. Combined GPS/EGNOS system fulfils ICAO SARPS requirements on the accuracy limits. It is clear that EGNOS system significantly increases aviation user navigation accuracy compared to un-weighted GPS Standalone mode. It was showed on the Figure 2, that there is dependency of GPS Standalone position solutions and during on-going study there was proved time correlation between consecutive samples for both modes (autocorrelation and spectral density analysis are beyond the scope of the article). Presence of outliers usually causes non-normal behaviour of the error distribution in the tails (see Figure 3, outliers are present in area beyond the 99.99999% probability of occurance); cause normality test to be rejected on different probability levels. This state is becoming more occassionall than it used to be only 1 or 2 years ago, due to improvements in EGNOS design and new EGNOS Szstem release. Such outliers are usually present EGNOS augmented position solution because augmentation system doesn’t compensate increasing range error timely and sufficiently.

Today the SBAS systems increase aviation safety and can be expected to be more often part of the receiver architecture design to support decreases of the risk introduced by navigation and guidance. Readers are encouraged to contact author for further information or subject related concerns.

Acknowledgment

1. Activity has been conducted in the frame of the project “New Technologies and Procedures for the Sustainability of IFR Air Traffic on Regional Airports”, FSI-J-12-1758, supported by the Specific University Research at the Brno University of Technology.
2. Author wishes to thank Czech Office for Surveying, Mapping and Cadastre, and Honeywell Advanced Technology in Brno (GNSS SATNAV Laboratory) to provide author with data measurement from permanent GNSS monitoring facilities and thus enable him to conduct study of observation data from number of geodetic receivers and certified avionics for aviation development purpose.

References

[1] HOFMANN-WELLENHOF, Bernhard – LEGAT, Klaus - WIESER, Manfred. Navigation: Principles of Positioning and Guidance. Wien: Springer Wien New York, 2003. 427 s. ISBN 3-211-00828-4.

[2] KEVICKÝ, Dušan; KALAŠOVÁ, Alica. Satelitné navigačné systémy. 1. vyd. Žilina : Žilinská univerzita v Žilině, 2004. 197 s. ISBN 80-8070-295-0.

[3] PTÁČEK, Pavel. Analýza prostředků pro zvyšování kapacity a propustnosti vzdušného prostoru a realizace návrhu sledování a hodnocení služby GNSS. Výzkumná zpráva LU 60-2011-HRC.OST. 31. 10. 2011, Letecký ústav VUT v Brně.

[4] PTÁČEK, Pavel. Today's GNSS Navigation Accuracy with Combined GPS/EGNOS. Zvyšovanie kvality a bezpečnosti v civilnom a vojenskom letectve, pp.251-261, ISBN 978-80-554-0519-3, (2012), Žilinská univerzita v Žilině - EDIS.

[5] VOSECKÝ, Slavomír. Základy leteckých navigačních zařízení I. Brno : Vydavatelství Vojenské akademie Antonína Zápotockého, 1988. 396 s.

[6] ICAO Annex 10/I: Aeronautical Telecommunications: Volume I: Radio Navigation Aids. Montreal: ICAO, November, 2006.

[7] Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment (SC-159) [online]. Washington (D.C.) : RTCA, Inc., 2001. RTCA/DO-229C, November 28, 2001.