Number III, Volume VI, July 2011

MONITORING OF THE EUROPEAN WIDE AREA GNSS-1 THE NAVIGATION APPLICATION OF CIVIL AVIATION

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Summary: In the paper, the overview of the conducted observation and experimental test evaluation model of the European satellite augmentation service for navigation application in air traffic is summarized after an extensive review of the EGNOS civil aviation monitoring aspects and needs. Idea of air navigation service provision and the basic quality parameters of satellite navigation augmentation system monitoring together with practical test are presented from an applied GNSS signal in space observation station to data processing scheme that covers conceptually applicable basis for Air Navigation Service Provider. Finally author suggests continuing observation but particularly statistical instruments to be performed further.

Key words: Global Navigation Satellite System, Augmentation Service, Quality Monitoring, Satellite Based Augmentation System, European Geostationary Navigation Overlay Service

INTRODUCTION

A fundamental step in the process of practical air navigation is to locate antenna of an object in airspace so as to provide safe guidance on a specified path. Implementation of a safe navigation must involve two main aspects: the reliability and accuracy provided. Active navigation with use of orbiting satellites for all flight phases (take-off/cruise/landing) is one of the Single European Sky ATM Research Programme (SESAR) key technologies under research and development. International Civil Aviation Organization (ICAO) defined in Global Air Navigation Plan that Global Navigation Satellite Service becomes worldwide primary means of radio navigation according to Global Air Navigation Plan (Doc 9750). There has been done an extensive research effort to establish European system of wide area augmentation service of today's core Global Navigation Satellite Service constellation, the Global Positioning System (GPS). System concept is defined by ICAO as the Satellite Based Augmentation Service; European realization is called European Geostationary Navigation Overlay Service (EGNOS). Today's policy of the United States, owner of the GPS, encourages its worldwide adoption. Together with EGNOS systems they form the GNSS-1, the primary means of navigation defined by ICAO for Instrument Flight Rules (IFR) operations from the en-route to final approach phase of flight, and in European airspace will be applicable for all air transport which must operate under IFR. Today EGNOS service is provided by central Air Navigation Service Provider (ANSP) based in Toulouse, the European Satellite Service Provider (ESSP SAS), appointed by European Commission.

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We are aware of the fact, that EGNOS is predecessor of the European global navigation system Galileo, the core element of the European navigation infrastructure in 21st century. The Galileo system should have enabled the GNSS Landing System - GLS CAT I throughout the world yet and thus assist replacement of the conventional systems, and finally ensured accurate approach to airports where conventional ILS couldn't be established. This was the original European perspective and ICAO vision of the future GNSS deployment from the 90s. Nevertheless, Full Operational Capability (FOC) of Galileo SoL service is not anticipated today before 2019/2020. Impending situation of Galileo system should have been available yet enabling global application of new navigation concepts and thus being able to cope with lack of airspace capacity, stresses the idea of global extension and broader utilization of SBAS systems[2] capable to support new procedures Approach with Vertical Guidance (APV) and at the same time create public demand on continuous research and development in this area.

When applying European augmentation service to national airspace, working agreements between ESSP and ANSP are first intended to cover legal aspects of contractual and technical elements required. However, current wording of the ICAO legislation (GNSS Manual) is: *"By approving GNSS operations, a State accepts responsibility to ensure that such operations can be completed safely. This is the case irrespective of whether the operations are based on non-augmented satellite navigation system, aircraft-based augmentation system or an augmentation system provided by a service provider in another State"* (5). Service areas for a particular Satellite Based Augmentation Service (SBAS) must be established by state within an SBAS coverage area and state is supposed to implement the service according to supported air route. The ICAO Airspace Concept Handbook demands inter alia evaluation of navigation sources if the system is supposed to be applied. We understand the Czech ANSP is responsible for supplied quality of any satellite navigation services in the sovereign airspace of the Czech Republic.

However, Czech ANSP did not took apart on the development projects of joint taskforce of EUROCONTROL (the European Organisation for the Safety of Air Navigation) and group of European ANSPs under EGNOS performance evaluation net; thus the interest from the Czech ANSP in the conceptual design of independent record/monitoring of EGNOS performance in user domain according to (5, 6, 7) is to be expected. The Aerospace Research Centrum at the Institute of Aerospace Engineering, Brno University of Technology, conduct research in evaluation of supplied navigation service of the Signal In Space (SIS) of the GPS/EGNOS system for the aviation Navigation Application of two different performance levels, APV-I and APV-II (6) Recommendation of ICAO and EUROCONTROL towards common EGNOS monitoring activities has been considered and can be found in (9). Other applicable documentation can be found in (8).

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[2] There are following realized or planned SBAS systems in the world: EGNOS, WAAS, MSAS, GAGAN, SDCM, SNAS and Pak-SBAS.

1. MOTIVATION & BACKROUND

1.1 EGNOS monitoring institutional considerations

Institutional and technical backgrounds haven't been discussed yet. Therefore, further discussion on particularities of the conducted research effort of the Aerospace Research Centrum follows. The Concept of navigation of the Czech Republic until 2020 (1) represents the official strategy of the Czech Republic and the intention to apply the EGNOS service to Czech national airspace. The implementation process of a new satellite navigation system also arise novel demand on the knowledge of national authorities engaged in the implementation process of the novel satellite navigation information system to air traffic. Staff in the regulatory and service provider organizations is supposed to pass training in order to understand how GNSS could influence their airspace (5).

ICAO Standards and Recommended PracticeS (SARPS) adopted by the Czech Republic in the regulation (7) define GNSS operational parameters to be recorded and GNSS SIS performance requirements to be supplied to user (see below Tab 2.). According to the regulation, monitoring support for periodic confirmation of GNSS performance compliance/non-compliance in the EGNOS service area of state responsibility can be used for evaluation. In order to have evidence used for post incident/accident, it is necessary to record information utilized by the GNSS system for both land augmentation, and for satellites augmentation. Limited number of locations of the service area might be recording all the parameters available to the user within the service area, provided independent assurance that the GNSS is working properly. Data can be used to establish some measure of estimated user performance. Regulatory requirements suppose recording GNSS data continuously on the rate of 1 Hz (7).

1.2 GPS Standard positioning services technical deficiencies

The European Organisation for the Safety of Air Navigation highlights EGNOS asset as it supply aviation user with much detailed ionosphere model broadcast then that of GPS. That could be a very valuable mitigation to cope with some of the effects the solar activity on the GPS signals, which is one of the major technical obstacles of the sole service concept. There exist other random errors observed on GPS space segment and elaborated. Cohenour and Van Grass made a study (3) on International GNSS Service (IGS) data from June 2005 to June 2008 that proved GPS Standard Positioning Service (SPS) non compliance with presumed Navstar GPS Space Segment/Navigation User Interfaces requirements listed in GPS Interface Document, ICD-GPS-200D. There were measured and proved 13 anomalies when GPS satellite SIS supplied User Range Accuracy (URA) in navigation message didn't bound actual User Range Error when satellite status was set "health". This is larger than the anticipated three per year for a 32 satellite constellation given in the SPS Performance Standard. It directly affects SIS GPS integrity if there are not enough satellites to stay within reliability limits provided by Receiver Autonomous Integrity Monitoring (RAIM) or FDE (Fault Detection and Exclusion) defined for every phase of flight. EGNOS architecture enables independent measurement and evaluation by the net of receiver integrity monitoring stations.

Another example of U.S. positioning system error observed and reviewed occurred at 16:00 on 10 April, 2007 when a forecast delta-V manoeuvre was performed on SVN54/PRN18 with the satellite health set to healthy. This created a 600 meter radial error which was observed by U.S. SBAS system WAAS and by IGS (3).

2. APPLIED METHODS FOR THE OBSERVATION STUDY AND EXPERIMENTAL TEST ON GPS /EGNOS AUGMENTATION SERVICE MONITORING

Analysis of the practical realisation of SBAS concept and its implementation to effectively achieve operational capability regarding the elementary parameters result and monitoring aspects of ANSP should be conducted. Author's idea of the test platform for simultaneous research observation and experimental evaluation of EGNOS supplied quality to the user is linked with up-to-date applied techniques of EUROCONTROL.

2.1 Introduction to basic navigation performance quality parameters

Hofmann-Wellenhof specifies in (4) the performance of a navigation system by a set of following quality parameters: accuracy, availability, capacity, continuity, integrity, coverage, dimension, reliability and update rate. Although the detailed description of radio-navigation system performance parameters is beyond the scope of this article, basic quality parameters which are used to monitor actual user navigation performance defined by ICAO are specified hereinafter by description of the navigation system quality flow is given (see Fig 1). It is generally reported that all navigation systems show a statistical dispersion in their indication of position and velocity and are characterized by quality stochastic parameters that establish the width of air routes, spacing of RWY and probability of aircraft collision, task was to compute navigation system errors.

Acceptance of GNSS as a sole means navigation aid necessitate user to meet requirements for on-board GNSS avionics. Aircraft on-board navigation system performance parameters requirements are defined in ICAO PBN Manual Doc 9613 [6] for the aircraft and the overall system, which includes the signal in space, airport facilities and the ability of aircraft to fly along the desired trajectory conventional resources ("complete navigation system"). ICAO used on-board navigation requirements on the entire system to establish stringent requirements on SIS GNSS as specified in Table 3.7.2.4-1 in SARPS (5). Consideration of reasonable risk of the failure or any degradation of GNSS that would affect more aircraft/users than with that of conventional resources must have been taken into account. Combining elements of GNSS user receiver failure with that of the signal in space must fulfil requirements. In our case of SBAS, the fault-free receiver concept must fulfil all performance requirements, so as not affect navigation service integrity, availability and continuity supplied to user.

Fault-free receiver algorithms were replaced by SBAS avionics "look alike" receiver software simulation in our study. Technical standards are defined by fundamental document issued by Radio Technical Commission for Aeronautics that published the Minimum

Performance Specification on Wide Area Augmentation System - WAAS (MOPS DO 229D). This concept is used as a means of defining the performance of various combinations of elements of GNSS (4). Together with stated requirements on-board navigation system must supply navigation performance required by Navigation Specification on particular route or within particular airspace defined by state authority.

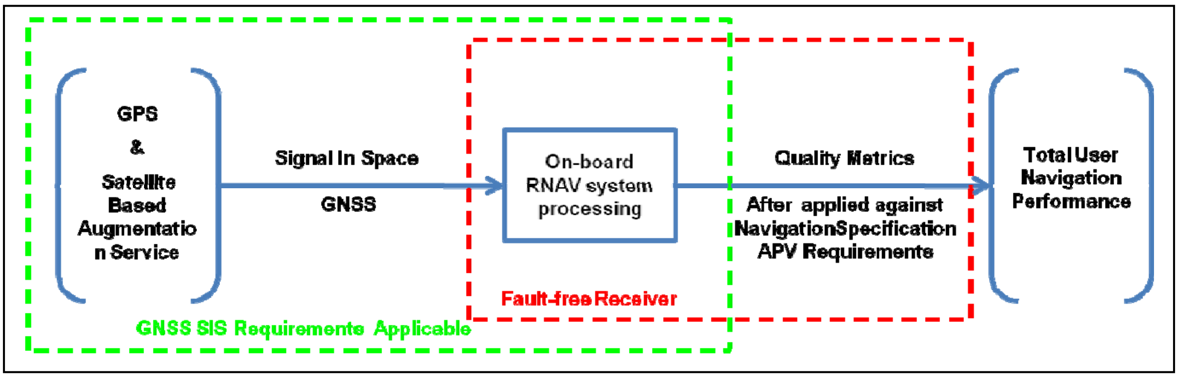

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Fig 1. – Quality flow of the navigation system performance from space segment to the user segment

2.2 GNSS SIS performance quality parameters

The combination of GNSS elements and a fault-free GNSS user receiver shall meet the signal-in-space requirements. The subject of the intended test was the proper evaluation of EGNOS navigation performance quality. The performance parameters are often incorrectly perceived. Aeronautics distinguishes two sets of performance requirements. First it is applicable to Total Use Navigation Performance which is used to derive final in-flight on-board navigation performance. Fault-free receiver approach was applied during our experimental verification of basic performance parameters.

Accuracy is a statistical measure of a system error typically provided with confidence level, mostly 95 %, predictable (or absolute) error (with respect to reference point) and repeatable accuracy (the accuracy with which a user can return to a position whose coordinates have been determined at previous time). According to (5), accuracy is defined as GNSS position error, the difference between the estimated position and the actual position. The requirement is to be met for the worst-case geometry under which the system is declared available. All expressions were evaluated in Tab 2. Accuracy in generally unknown to the aviation user plus raw data samples should be collected over a longer period of time. Integrity is a measure of the trust which can be placed in the correctness of the information supplied by the total system. If the monitoring system doesn't provide information message on integrity risk, i.e. navigation error being out of the specified limits, within Time To Alert (TTA_{APV-I} = 10 sec, TTA_{APV-II} = 6 sec) it is called Hazardously Misleading Information (HMI) when HPE ≥ HAL ≥ HPL or VPE ≥ VAL ≥ VPL and Misleading Information (MI) when HAL ≥ HPE ≥ HPL or VAL ≥ VPE ≥ VPL. The continuity of a system has been interpreted for the purpose of analysis as the ability of the total system to perform its function without interruption whatever cause. Regarding the availability of a navigation system the ability of the system means to provide the required function at the start of the intended operation (5).

2.3 Observation study of experimental monitoring/observation and processing scheme

2.3.1 Designing the observation scheme

There exist generally accepted pattern for localization of monitoring station (7) Antenna of the test receiver should be located so as to reduce interference, multipath signals with the desired signal. Full-grown vegetation may not shade signal in space; sharp metal objects should not be located in antenna near field. As well as being applicable to aeronautical data by PBN Manual, following conditions are also applicable to experimental observation and navigation data determined from its survey: all the data coordinates must be referenced to the World Geodetic System – 1984; samples should be collected over a longer period of time. Generally accepted basic continuous interval is 24 hours.

All surveys must be based upon the International Terrestrial Reference Frame, all data must be traceable to their source and equipment used for surveys activity must be calibrated adequately. Test of the GNSS Core constellation (GPS), that is standardized by document ICD-GPS-200D is established on the standard SPS receiver with mask angle set to 5 degrees, using all SV in view geometry position and time solution, ECEF of WGS-84, compensated Doppler effect, inoperable satellites excluded, using actual timing and navigation information and loosing operational status as GPS system stops to transmit C/A code. These data are not sufficient and must be supplemented. These requirements have been taken into account when planning an experiment.

Tab. 1 - Collected and processed data by observation and experimental station

GNSS observation data and external data input for analysis	
L1	Phase measurement
C1	Code measurement (C/A)
D1	Doppler measurement
S/N	Signal To Noise Ratio
EMS MT	EGNOS Message Server Message Transport
RINEX Corr	CZEPOS Local Differential Correction

Source: Author, (7)

To assess the quality of the data we first made an exploration through aviation regulation. After we proposed a measurement procedure, observation and processing scheme local survey showing suitability (elevated position without obstacles, barriers in the form of stand, precise coordinate with geodetic reference to evaluate accuracy of local differential correction etc.) had to be carried out. On the geodetic GPS measurement reference point

"U střelnice" located 1 km from the central part of University campus, first receiver separate and then in use of two identical Ashtech/Thales (receiver/antenna) GPSP/EGNOS signal in space were observed. Redundant observations were made to account for local effects and verify receiver status suitable/unsuitable for high construction/building in Campus. The EGNOS service basic quality characteristics were finally tested on the geodetic reference point.

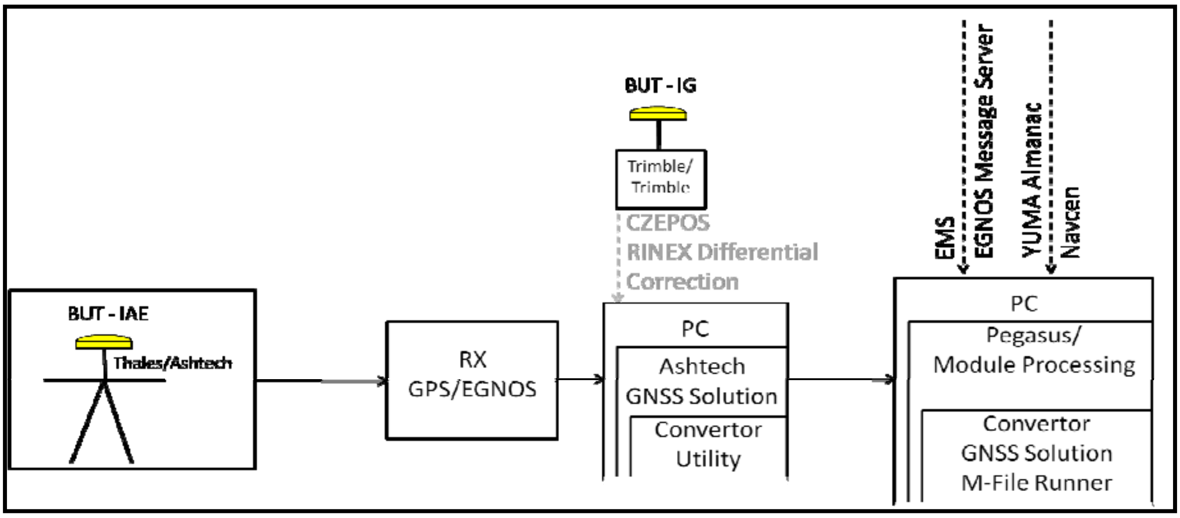
After receiver is fixed on the extension of 19th storey building of University campus, where signal of unlocked space surrounds antenna, location of the antenna reference point was computed after GPS RINEX local differential correction from dual frequency Trimble monitoring station TUBO were applied during computer post processing. Dual frequency highly precise Trimble receiver is operated by the Institute of Geodesy, Brno University of Technology and the distance between Trimble antenna on the Institute of Geodesy and Thales Antenna on the extension of Campus building of the Institute of Aerospace Engineering is only 2.5 km. It is general knowledge that quality of GNSS differential corrections is decreasing with increasing distance from the reference, because time and area correlation decreases. Application of APV procedure supported by EGNOS are so far planned in test mode on the Brno-Tuřany Airport that is situated just 11.5 km south-east of the receiver; from the wide area differential GPS point of view it is representative whether in relation to the correlation of time and space.

Inconvenient local conditions can affect EGNOS service availability. Data logging is the process strongly influenced by appropriate selection of local conditions. If wrong selected the received signal power failures, cycle slips or filtering initialization problem might occur. Furthermore, reliable statistics demonstration of the availability of SIS on the basis of one receiver might not be redundant enough. The use of procedures endorses experience of the GNSS Supervisory Authority, which suggested the continuity parameter test by applying MT provided by the EGNOS system part - Performance Assessment and Check-out Facility (PACF). More can be found in summary contained in (9). Accounting for possible discontinuities we have included the data processing of consolidated EGNOS Message from the EGNOS Message Server (EMS) as depicted on Fig 2. Central part of the station used for experiment consists of the Ashtech GPS/SBAS/DGPS 14 channel receiver with raw data measurements (2 SBAS channel), external power supply connection and Thalles Antenna. To further minimize potential local impacts an aluminium shielding plate of 30 cm diameter was mounted below the antenna stand (See Fig 2.).

Using common exchange format independent of the receiver we were then able to deliver raw observation data (See Tab. 1), GPS navigation messages and navigation messages from geostationary satellites (GEO). The concept assumes SBAS receiver reducing the impact of multipath signal propagation to the user segment. On the basis of cooperation with partners in the development of navigational aids there was created data interchange channel by the schematic approach of parallel computing. Finally three independent stations' data were analysed. Direct comparison method based on number of discontinuities which with no divergence approved. Improper placement of the facility could result in a concept breach of fault-free receiver that would own measurements.

2.3.2 *Design data processing scheme*

The observed data and the navigation data are stored in receiver-dependent binary format. The data of the measurement campaign were converted to Receiver Independent Exchange Format (RINEX) before further processing, which is standardized ASCII format, for our purpose, the observation data file and the navigation message file (raw measurement data) (2). The planned status on EGNOS ESSP EU provides in European SBAS planned service status[3]. Status message of the GPS performance is provided by GPS status advisory (GSA), Notice to Navstar User (NANU) messages is provided by operator (U.S. Coast Guard). Input to the data analysis comprise Observation file, Navigation file (Ephemeris), GPS Almanac and MT message. Binary data must have been downloaded and converted to RINEX format. Check test covered the EGNOS Service Notice check: PRN 120 and PRN 124 Service Available (Message Type 2), ESSP Status 1, PRN126 Under Test (Message Type 0), ESSP Status 4.



Source: Author

Fig. 2 – Designed observation and processing scheme

Using an exchange format that is independent of the receiver, we were able to deliver observation data, GPS navigation messages, navigation messages from the geostationary satellites. EGNOS supplied quality is observed and briefly analysed on regular manner as required by (8). Our regular observations are available for ANSP. Designed scheme for data measurement and processing reflects ICAO SARPS requirement.

[3]There are used following status on PRN SIS Transmission: 1. No Planned Maintenance Activities that could impact the Signal Availability, 2. Planned Signal Outage, 3. No Planned Maintenance Activities (TBC one week in advance), 4. No detailed information available (satellite used for EGNOS Tests), EGNOS Signal Availability is not guaranteed, 5. Risk of signal outage

3. RESULTS OF EGNOS SERVICE EVALUATION IN NAVIGATION APPLICATION DOMAIN

The institute provides periodical sampling of the GPS/EGNOS. Day of the presented test experiment (See Tab. 2) in this article is 17th January 2011 (DOY 017, GPS Week 1619), from 10:57 to 18th January 2011 11:29 with 87 927 valid samples, i.e. 99.53 % and 1 Hz applied sample rate. GEO PRN 120 was used to augment 31 available satellites of GPS constellation during observation period. PRN 124 service was also available, but PRN 126 is still in industrial testing phase. The sample rate of 1 Hz is limited due to the fact that uncorrelated samples are generally required. EGNOS Messages were logged together with GPS SIS. However, for the analysis of MT for individual PRN were obtained from EGNOS Message Server. Total message count was 97,191. Maximum computed value was HPL_{max} = 8.87 m and VPL_{max} = 13.84 meters. These are used to assess represent level of integrity risk which was much bellow required 50 meters (HAL) and 40 meters (VAL). Conventional navigation system errors are traditionally specified by Root Mean Square; for EGNOS $RMS_{APV\text{-}I\ HPE}$ = 1.02 m for HPE, and $RMS_{APV\text{-}I\ VPE}$ = 0.73 m for VPE. For 95th percentile HPE = 1.55 m and for VPE = 1.36 m. Standard deviation was 0.35 m for HPE and 0.42 m for VPE. Maximal valid solution values were HPE_{max} = 2.20468 m, VPE_{max} = 2.70364 m and HPL = 6.30267 m, VPL = 9.49792 m. Detailed examination of integrity risk properties can be interpreted by the portion of position error and corresponding protection level $(HPE/HPL)_{MAX}$ = 0.243002 m and $(VPE/VPL)_{MAX}$ = 0.20621 m. After simulation process is finished, 7 registered for APV-II with duration of 1063 seconds and 0 for APV-I. During measurement only APV-II continuity and availability requirements were out of tolerance. All other parameters for both analysed operations were sufficient.

Tab. 2 - Designed observation and processing scheme output – basic quality parameters

Operation analysed			APV I			APV II		
			Availability					
Valid solutions [-]		87927	87927			85872		
Minimum required.	[%]		99			99		
Availability	[%]		100.000			97.663		
			Continuity					
Events	[-]		0			193		
			Integrity					
			MI			HMI		
Total	[-]		0			0		
Horizontal	[-]		0			0		
Vertical	[-]		0			0		
			Accuracy					
	Probability	Measured	Scaled	Req.	Measured	Scaled	Req.	

HNSE [m]	95%	1.55	7.22	16	1.56	6.69	16
VNSE [m]	95%	1.36	5.33	20	1.36	1.44	8
Operation/Alert limit			APV I			APV II	
HAL [m]			40			40	
VAL [m]			50			20	

Source: Author

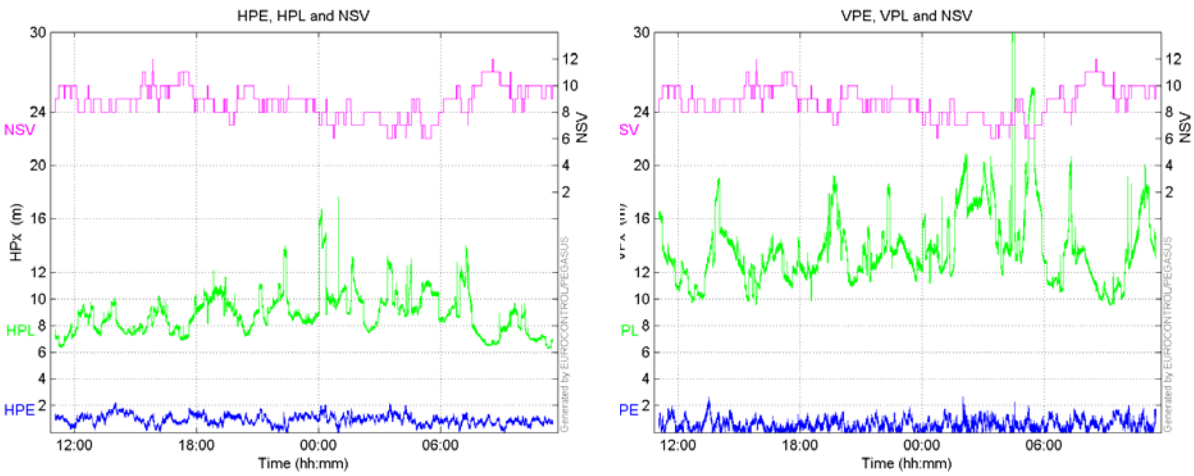


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Fig 3. – Navigation system errors and related protection levels during 24-hour interval

4. CONCLUSION

Establishment of real time ANSP monitoring tool r EGNOS service is not a trivial task if we are to implement new SBAS NOTAM system, or to cope with implementation of navigation application of approach with vertical guidance supported by wide area GNSS-1, creates potential of applied proposal of the GNSS SIS monitoring and evaluation that can be employed. When enough data set from periodical sampling and evaluation of GNSS-1 will have been observed and analysed, a database shall be created and accessed to ANSP. In the paper, elementary thoughts and practical examples of today's GNSS-1 with monitoring test based on the basic performance quality indicators have been presented. Finally the EGNOS category approach APV - I compliance and category approach APV - II non compliance is summarized.

Author recommends in this paper to continue the proposed idea of research in navigation-technical domain of satellite navigation system quality supplied for SoL applications. It is necessary to extend navigation performance evaluation process by using analysis of SIS out of tolerance risks usually defined by HPE/HPL ratio and the corresponding probability density function. Following research, today on-going at Aerospace Research Centrum contains: Time series analysis (GNSS samples were not filtered for independent samples even though; according to (7) GNSS errors change slowly due to data filtering in augmentation systems and user receivers); Frequency domain analysis of the errors and protection levels (power spectrum analysis) – analysis of systematic error (biases) and random error, impact on the integrity of the provided quality of services; there is necessary to establish unified methodology for performance assessment and ANSP monitoring/logging station design; Verification of service to be SBAS MOPS 229D compliant and performances from the parameters of stochastic design point of view with special interest in the integrity of risk; Estimated and real time performance characteristic; Application of higher statistical method to verification process of the EGNOS position domain integrity characteristic.

5. ACKNOWLEDGEMENTS

1. Activity has been conducted in the framework of the Aerospace Research Centrum 1M0501 –MSM 1/M, MEYS CZ, Object F2, Activity A0F201 – Analysis of Possible Means of Airspace Capacity and Permeability Increase.
2. EUROCONTROL NAV Domain provided the Prototype EGNOS and GBAS Analysis System Using SAPPHIRE, which was used as a frame for raw (observation) data evaluation.

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