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EGNOS DATA COLLECTION AND EVALUATION IN THE EASTERN AND SOUTERN EUROPE REGION – FIRST RESULTS

Boris Vassilev, Tsvetan Stoyanov

Technical University of Sofia
e-mail: tsstoianov@tu-sofia.bg

Abstract

This paper presents a summary of the activities of the Sofia branch of the Data Collection Network that Eurocontrol set up to perform data collections and analysis with the ESTB signal. The actual performance achieved at Sofia location is computed and checked against the RNP requirements, and any anomalies identified are analysed in detail to identify the cause.

1. Introduction

The existing satellite navigation systems GPS and GLONASS, as single systems, do not satisfy a number of user requirements, first of all for safety critical applications, in particular for precision approaches. The European Satellite-Based Augmentation System (SBAS) covering Europe is called the European Geostationary Navigation Overlay Service (EGNOS). EGNOS is the first phase of the European Union's policy on a global navigation satellite system (GNSS 1). EGNOS is being developed by the European Space Agency (ESA) in co-operation with the European Union (EU) and Eurocontrol.

The system provides additional signals to users of satellite navigation services, broadcast through geostationary satellites guaranteeing the integrity of GPS so that it can be used in support of life safety services such a civil aviation.

ESA is performing an extensive EGNOS verification campaign but this is focusing on the signal-in-space (SIS) as seen by a network of independent reference stations. Operational validation includes all activities that will demonstrate that EGNOS is ready to be used to support the flight operations for which it is intended.Within the frame of activities in preparation for the EGNOS operational validation, Eurocontrol has established a standardized data collection environment to perform regular EGNOS System Test Bed (ESTB) performance monitoring. ESTB is a prototype of EGNOS will a limited number of monitor stations. Monitor station have been set up at six different universities geographical by distributed around Europe. The ESTB has been providing a SIS since February 2000 to support the system development as well as to give potential users the opportunity to gain experience with EGNOS-like signals. Currently, this data collection network is using for daily records and first glance analyses and weekly and monthly data collection and evaluation, as well for analysis and assessment of the SBAS system performance. The actual performance achieved at each location is computed and can be checked against the PRN requirements, and in addition all revealed anomalies are analyzed in detail to identify the cause and the probability of re-occurrence.

2. Data Collection Activities in Sofia

The authors of this paper as representatives of the Technical University of Sofia are a part of this monitoring network since November 2003. A standardized data collection environment for the ESTB has been set up at the Department of Aeronautics. The precise position of the receiver (antenna phase center) in WGS-84 co-ordinates is:

[x, y, z] = [4313692.39, 1862642.84, 4299661.79] (in meters), and

[longitude, latitude, height (in meters)] = [23.3545800101, 42.652809391, 660.1147].

The used receiver is a NOVATEL OEM-3 “Milenium” with a Novatel Pinweel 600 S/N antenna. This L1/L2 receiver has 12 channels (11 GPS+1 SBAS). The data is logged on a personal computer using the SLOG software from Novatel. The broadcast signal complies with RTCA’s Do229A(B) Minimum Operational Performance Standards (MOPS) and is broadcast through the geostationary satellite Inmarsat IOR (PRN 131).

The data is collected at 1Hz frequency and processed with Pegasus*Plus v3.x.x software. Pegasus is software prototype capable of processing receiver-native data from a limited set of SBAS receivers and computing the position and integrity solution in accordance with the RTCA MOPS Do229 standards. It consists of three major software components. The CONVERTOR program translates receiver-native GNSS data into generic format. The WinGPSAll program uses the output of the CONVERTOR to determine a GNSS navigation solution. The ALGORITHMS programs uses the output of the CONVERTOR and the WinGPSAll programs to analyse the constellation, to determine predictive integrity monitoring qualifiers and to perform integrity monitoring using Receiver and Aircraft Autonomous Integrity Monitoring Algorithms. MATHLAB™ files are provided as a support for the user to automate and standardise the evaluation of the performance of the ESTB.

3. The ESTB Signal in Space

The raw navigation message of the SBAS contains 500 bits, transmitted in each second. It is 1/2 encoded with a Forward Error Correcting (FEC) Code. Thus, the baseline data rate of the SBAS SIS will be 250 bits per second. The block format for the 250 bits includes Preamble (8 bits), Message type identifier (6 bits), Binary message (212 bits) and Parity (24 bits). The message type identifier is a binary coded integer value (range 0-63), thus resulting in 64 different possible message types (MT) for the SBAS SIS.

4. Pegasus Data Processing

The real data collection and evaluation, together with the theoretical analysis, modeling and simulation is a part of the validation process of the EGNOS system. This process requires adequate demonstration of the accuracy, integrity, availability and continuity of the positioning service provided.

The measured pseudo range is corrected using the ESTB correction parameters. The corrected pseudo range will be [1,5]:

$$\rho = \rho_{meas} + RC_{fast} - RC_{iono} + RC_{tropo} + RC_{clock} \quad (1)$$

with ρ_{meas} - measured pseudo range; RC_{fast}, RC_{iono}, RC_{tropo} and RC_{clock} - fast, ionospheric, tropospheric and satellite clock corrections.

The position solution is then calculated by means of a weighted least square algorithm [1,5]:

(2) $x = \left(H^T W H\right)^{-1} H^T W R$,

with R – pseudo ranges; H – line-of-side matrix, W – weighting matrix. A column of the matrix H for a particular satellite is:

(3) $H_i = \left[-\cos(E)\cos(A) \;\; -\cos(E)\sin(A) \;\; -\sin(E) \;\; 1\right]$,

with E and A – elevation and azimuth of the satellite.

The weighting of the last squares is achieved by a matrix, which contains on its main diagonal a model of the pseudo range error after its correction by the transmitted ESTB parameters:

(4) $W^{-1} = \mathrm{diag}\left(\sigma_i^2\right)$.

Since the actual variance of the pseudo range measurement can not be observed in real-time, the variance for an individual satellite is modelled based on the model parameters supplied in the following equation:

(5) $\sigma_i^2 = \sigma_{iflt}^2 + \sigma_{iUIRE}^2 + \sigma_{iair}^2 + \sigma_{itropo}^2$,

with σ_{iflt}^2, σ_{iUIRE}^2 and σ_{itropo}^2 - variance of the residual error after application of fast and slow, ionospheric and tropospheric corrections, σ_{iair}^2 - variance of the contributions of the receiver to the residual error.

The contribution of the fast and slow corrections to variance of range measurement is determined mainly by the actual residual variance of each range correction and by taking the degradation of the variance with respect to time into account.

(6)

$$\sigma_{iflt}^2 = \begin{cases} \left(\sigma_{UDRE} + \delta\sigma_{UDRE} + \varepsilon_{fc} + \varepsilon_{rrc} + \varepsilon_{ltc} + \varepsilon_{er}\right)^2; & RSS_{UDRE} = 0 \\ \left(\sigma_{UDRE} + \delta\sigma_{UDRE}\right)^2 + \varepsilon_{fc}^{\;2} + \varepsilon_{rrc}^{\;2} + \varepsilon_{ltc}^{\;2} + \varepsilon_{er}^{\;2}; & RSS_{UDRE} = 1 \end{cases}$$

with σ^2_{UDRE} - variance of User Differential Range Error (MT2 – MT5, MT6); $\delta\sigma^2_{UDRE}$ - increment for the variance of the UDRE (MT 27); ε_{fc}, ε_{rrc}, ε_{cr}, ε_{ltc} - degradation parameters for fast correction data (MT 7), range rate correction data (MT 10), long term correction data (MT 10) and flight phases en-route through non-precision approach (MT 10); RSS_{UDRE} - root-sum-square flag for UDRE (MT 10).

The user Ionospheric Range Error Estimate is calculated by:

$$\sigma^2_{UIRE} = \left\{1 - \left[\frac{R_e \cos(E)}{R_e + h}\right]^2\right\}\sigma^2_{UIVE}, \tag{7}$$

with R_e – Earth radius (assumed to be 6378 km); E – elevation of satellite.

To determine an upper boundary of the vertical error for the location of the ionospheric pierce point, it is necessary to use the four or three point interpolation scheme [1,5]:

$$\sigma^2_{UIVE} = \sum_{i=1}^{4} W_i(x,y)\sigma^2_{ionogrid}, \quad \text{or} \tag{8}$$

$$\sigma^2_{UIVE} = \sum_{i=1}^{3} W_i(x,y)\sigma^2_{ionogrid}, \tag{9}$$

with $W_i(x,y)$ – weighting function; $\sigma^2_{ionogrid}$ - grid ionospheric vertical error boundary with degradation over time (MT 18 and MT 26).

The model for the residual error for the tropospheric delay estimate for a particular satellite is given as [1,5]:

$$\sigma^2_{itropo} = 0.12\left[\frac{1.001}{0.002001 + \sin^2(E_i)}\right]^2. \tag{10}$$

The standard deviation receiver noise for an SBAS satellite, including the multipath is:

$$(11) \quad \sigma^2_{iair} = \sigma^2_{inoise} + \sigma^2_{imp} .$$

The variance of a normal distribution that models the residual miltipath error of an airborne subsystem can be obtained to [1,4]:

$$(12) \quad \sigma^2_{imp} = 0.2 \exp\left(-\frac{E_i}{75}\right) .$$

As minimum requirements representing the worst case signal reception condition are used [1,4] $\sigma^2_{inoise} = 1.8$ m.

For certification of GNSS based navigation systems for aviation, it is necessary to guarantee that the user is informed of his position with sufficient integrity. The probability that the navigation system supplies the so-called hazardously misleading information (HMI) should be proven to remain extremely small. The integrity is specified in terms of the horizontal and vertical protection level (HPL and VPL), which is related to the probability that the alert limit may be exceeded. The SBAS protection levels are functions of the satellite constellation and the estimated SBAS performances. Thus, using SBAS correlation data, the protection levels can be determined without using actual pseudo range measurements. However, based on the pseudo range error model, the HPL and VPL provide an estimation of the upper boundary of the horizontal and vertical position error:

$$(13) \quad HPL = k_h \sqrt{\left(H^T WH\right)^{-1}_{11} + \left(H^T WH\right)^{-1}_{22}} \; ;$$

$$(14) \quad VPL = k_v \sqrt{\left(H^T WH\right)^{-1}_{33}} \; ,$$

with $k_h = 6.0$ (integrity risk: 2.10^{-9}) and $k_v = 5.33$ (integrity risk: 2.10)– horizontal and vertical level of integrity [3].

5. ESTB Results in Sofia

The receiver-native data obtained by the Sofia set of the SBAS receiver is processed by the PEGASUS software, and position and integrity solution are computed in conformity with the above mentioned expressions. Daily First Glance reports and weekly reports are generated. These reports summarize the results obtained after applying the proposed algorithms on the measurements. In this way are generated performance values that can be checked against the PRN requirements. Summary of the performance obtained during the ESTB campaign in Sofia is presented in Fig. 1, 2 and 3.

Fig. 1 presents the position errors (HPE and VPE) of the navigation solution with respect to the precisely surveyed antenna location. They are obtained when applying all available differential corrections (fast, slow and ionospheric corrections) from the ESTB. The accuracy requirements are derived from ICAO's GNSS Standards and Recommended Practices (SARPS). **The obtained results prove that the horizontal and vertical requirements are fulfilled for all categories (NPA, APVI, APV II and CAT I).**

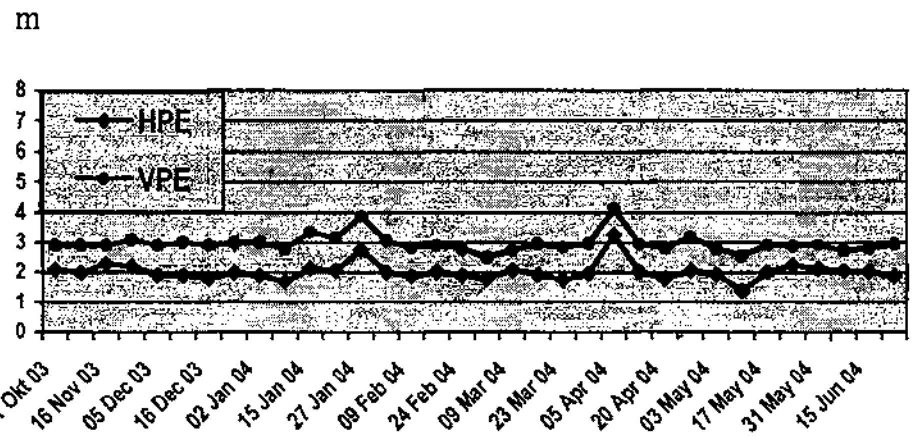

Fig. 1. Statistic data of the position errors

The computed protection levels (HPL and VPL), which represent the upper boundary of its position error are presented in Fig. 2.

The alarm limits against which a user has to compare its protection levels are defined in the ICAO's GNSS SARPS. We can see that **the**

horizontal integrity requirements for all categories are fulfilled (with one exception on January 27). The vertical integrity requirements are fulfilled for categories NPA and APV-I.

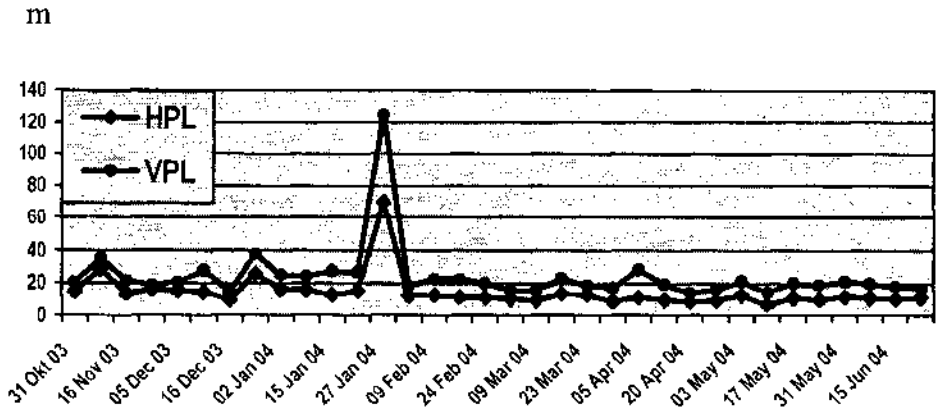

Fig. 2. Statistic data of the protection levels

The availability is defined as the percentage of time during which the system fulfils the accuracy, integrity and continuity requirements for the intended operation. The summary results obtained during the ESTB campaign in Sofia are presented in Fig. 3.

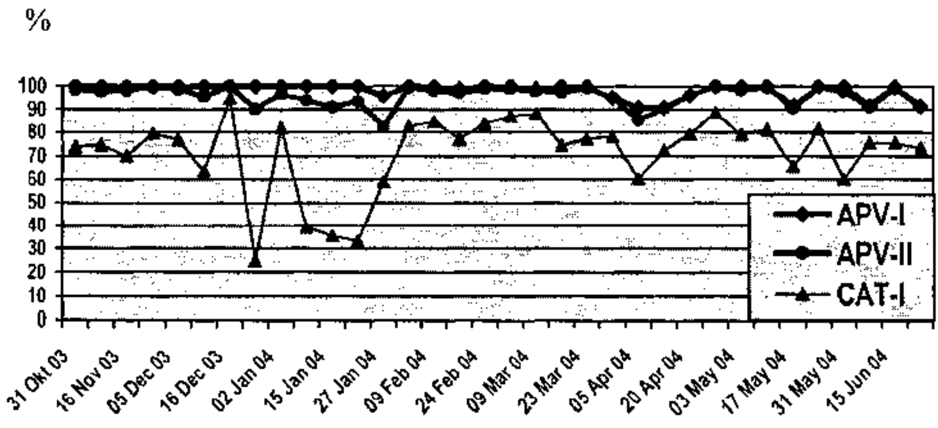

Fig. 3. Statistic data of the availability

It is important to highlight that the system was improving from the start (October 2003) to the end (July 2004) of the ESTB campaign in Sofia.

6. Anomaly Investigation

If any anomalies are encountered a detailed analysis will have to be done on possible measured integrity failures, discontinuity of service or other anomalies, to assess whether those are really related to system malfunctions or are caused by the data collection and valuation environment. The anomaly investigation aims to identify whether they were related to local effects such as multipath, antenna/receiver effects, SIS malfunctions, or other unexpected effects like ionospheric storms, GPS satellite clock malfunctions, etc.

Anomaly 1: Big jumps in XPL (sometimes reaching to several hundred meters). XPE is normal or little bigger than normal (Fig. 4).

The analysis shows that the possible reason for the integrity failures appearing is directly related to the contents of the GEO signal messages. As presented in Fig. 5 and 6, the fast corrections (MT 2 and MT 3 messages) are absent during the periods of the first and second jumps. **The cause of the third jump is the interruption of the broadcasting of all types of messages by PRN 131, except MT 0** (Fig. 7).

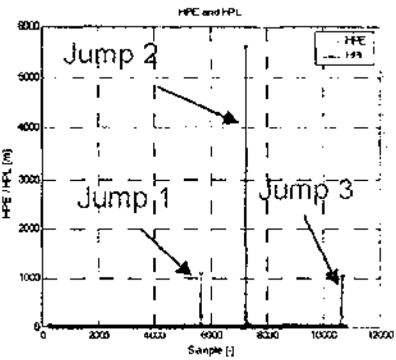

Fig. 4.

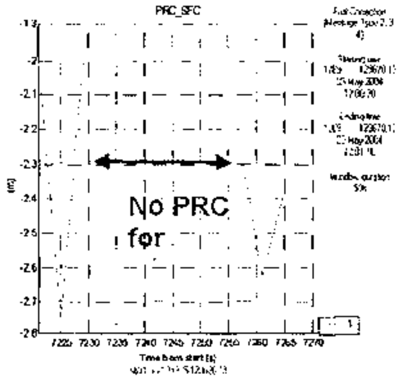

Fig. 5.

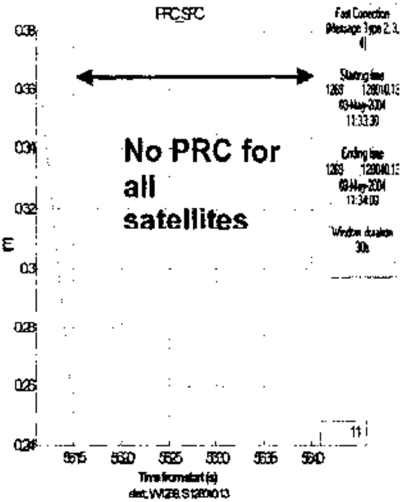

Fig. 6

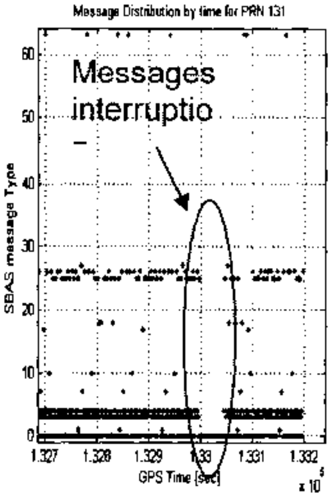

Fig. 7

Anomaly 2: No position data during a period of 7648 seconds (for GPS time from 173591 to 181239) and big peaks in XPL (sometimes reaching to several hundred meters) (Fig.8). The possible reason is the interruption of the broadcasting of all types of messages by PRN 131, including MT 0 (Fig. 9). **This causes the interruption of the ionospheric and fast corrections** (Fig. 10 and 11).

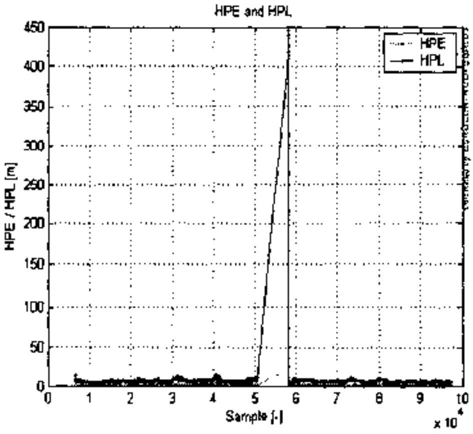

Fig. 8

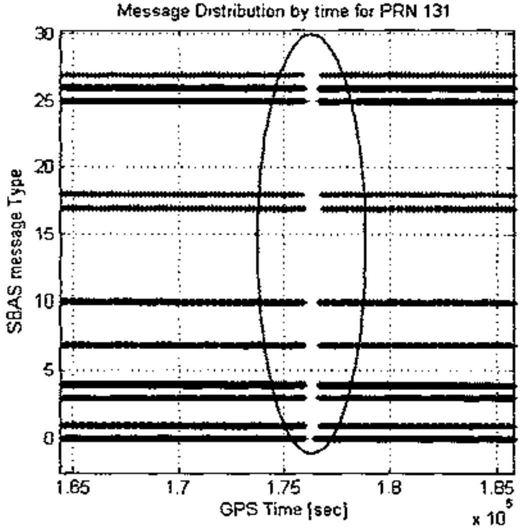
Message Distribution by time for PRN 131
SBAS message Type
GPS Time (sec)
x 10^5
0
5
10
15
20
25
30
1.65
1.7
1.75
1.8
1.85

Fig. 9

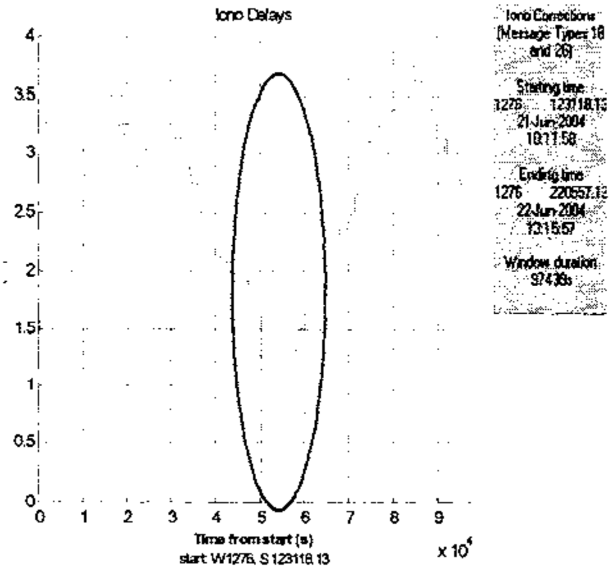
Iono Delays
Time from start (s)
start W1276, S 123118.13
x 10^4
Iono Corrections (Message Types 18 and 26)
Starting time:
1276 123118.13
21-Jun-2004
10:11:58
Ending time
1276 220557.13
22-Jun-2004
13:15:57
Window duration:
97438s

Fig. 10

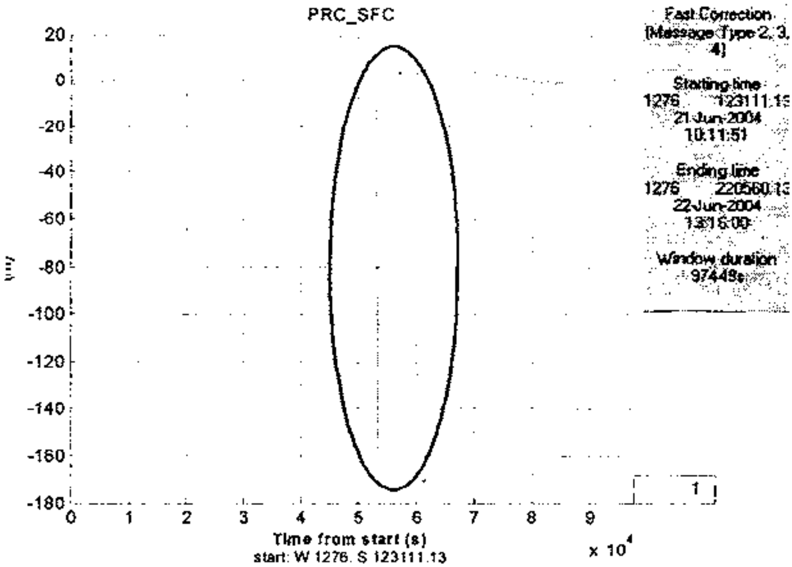

Fig. 11

Anomaly 3: A jump in the XPE with magnitude of several hundred meters and duration about 10 s. The XPL did not cover this jump (XPE>XPL>XAL for APV II and CAT I) and therefore HMI were created (Fig.12). The analysis shows that the possible causes of this event are the problems with the fast corrections. The MT 2 is transmitted at the start of the period and then repeated 4 times in the next epochs. This fact shows that there had been an "alarm situation" and that the ESTB had transmitted that information to the users (according to the standard requirements [1,2]). Since the CONVERTOR was running in SBAS mode 0/2, it interpreted an incoming MT0 with non-zero bits as MT 2. We discovered that indeed the MT0 transmissions contained bits set to"1". Thus, the explanation for XPE jump and HMI creation can be found in the ESTB SIS.

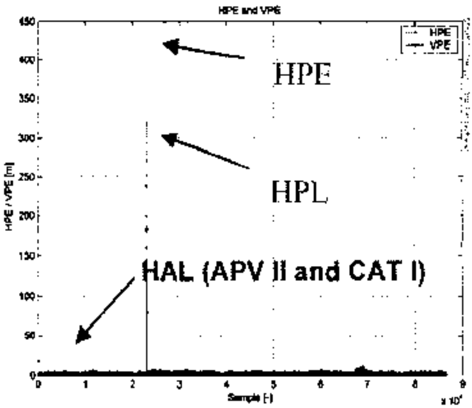

Fig. 12

7. Conclusion

The ESTB, a prototype of EGNOS, broadcasts ranging information, pseudo range corrections and integrity information for GPS. In order to gain experience with the Eastern and Southern Europe Region implementation of the SBAS system, confidence in the performance of that system has to be established. The good experimental results and their successful analysis demonstrate the working capacity and effectiveness of the ESTB monitoring station in Sofia. These results raise a lot of hope for the real EGNOS validation activity, which started in September 2004.

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СЪБИРАНЕ И ОБРАБОТКА НА ДАННИ ЗА СИСТЕМАТА EGNOS ЗА РЕГИОНА НА ИЗТОЧНА И ЮЖНА ЕВРОПА – ПЪРВИ РЕЗУЛТАТИ

Б. Василев, Цв. Стоянов

Резюме

В статията са представени първите резултати от дейността на софийския клон на мрежата, създадена от EUROCONTROL, за събиране и анализ на данни за европейската спътникова диференциална навигационна система EGNOS, намираща се в процес на валидация. Приведени са характеристиките на действащата на територията на ТУ-София станция, хардуерните и софтуерните и средства за приемане и обработка на навигационната информация. Представените резултати са получени с помощта на системата ESTB, представляваща тестови прототип на EGNOS.

В работата са изведени математическите зависимости, с помощта на които се определят основните характеристики на системата. На базата на приетите от GPS спътниците сигнали и сигналите от ретранслиращия геостационарен спътник IOR (PRN 131) от системата INMARSAT, носещи навигационни съобщения с коригиращите поправки, са изчислени характеристиките на системата (accuracy, availability, integrity и continuity) за периода на действие на системата ESTB. Идентифицирани са и са анализирани детайлно най-характерните аномалии в получените резултати, като е търсена причината за появата им.