Study of EGNOS accuracy and integrity in eastern Poland

G. Grunwald
g.grunwald@kgsin.pl
University of Warmia and Mazury in Olsztyn
Department of Satellite Geodesy and Navigation
Olsztyn
Poland

M. Bakuła
Polish Air Force Academy in Dęblin
Aeronautics Faculty
Dęblin
Poland

A. Ciećko
University of Warmia and Mazury in Olsztyn
Department of Satellite Geodesy and Navigation
Olsztyn
Poland

ABSTRACT

The ionosphere is one of the main factors affecting the accuracy and integrity of satellite-based augmentation system positioning systems. This paper presents the results of a 30-day study of the accuracy and integrity of the European Geostationary Navigation Overlay Service (EGNOS) conducted at the EPOD airport belonging to the Aeroclub of Warmia and Mazury in Olsztyn, in northeastern Poland (the area until recently considered as the edge of EGNOS coverage). Analyses of the parameters characterising the accuracy and integrity of positioning were performed in three calculation variants/modes: with the original EGNOS ionospheric correction, with correction determined by means of Klobuchar algorithm, and finally with modified ionospheric coefficients developed by the CODE. Studies have shown clearly that the original EGNOS ionospheric model gives the best integrity and accuracy results allowing to use EGNOS for approach with vertical guidance procedures, while the Center for Orbit Determination in Europe and Klobuchar models could only be used for non-precision approach operations.

Keywords: SBAS; EGNOS; SBAS integrity; GNSS navigation; RNAV navigation

NOMENCLATURE

AL	alarm limits
APV-1	approach with vertical guidance
ASAS	African Satellite Augmentation System
ASG-EUPOS	Aktywna Sieć Geodezyjna EUPOS
c	speed of light
C/A	course/acquisition
CODE	Center for Orbit Determination in Europe
DGPS	differential global positioning system
EGNOS	European Geostationary Navigation Overlay Service
EUPOS	European Position Determination System
GAGAN	GPS aided GEO augmented and navigation system
GBAS	ground-based augmentation system
GNSS	global navigation satellite systems
GPS	global positioning system
HPE	horizontal position error
HPL	horizontal protection level
ICAO	International Civil Aviation Organization
IGS	International GNSS Service
ITRF2000	International Terrestrial Reference Frame 2000
ITRS	International Terrestrial Reference System
MI	misleading information
MOPS	minimum operational performance standards
MSAS	MTSAT satellite augmentation system
NPA	non-precision approach
OS	open service
PA	precision approach
PRN	pseudorandom noise
RIMS	ranging and integrity monitoring stations
RNAV	area navigation
S	projection matrix
SBAS	satellite-based augmentation systems
SDCM	Russian wide area augmentation system
SI	safety index
SLM	single layer model
SoL	safety of life service
SPS	standard positioning service
TEC	total electron content
VPE	vertical position error
VPL	vertical protection level
WAAS	wide area augmentation system
WRS	RIMS station located in Warsaw
$d_E^2,\ d_N^2, d_U^2$	variances of the east, north and up (vertical) components of the position solution expressed in a topocentric system
d_{EN}^2	covariance between the east and north axes
F_{PP}	obliquity factor (transforms vertical delay to slant)

K_H	a factor bounding user's horizontal position with a probability of 10^{-9} (for en route navigation $K_H = 6.18$ and for precision approach $K_H = 6.0$)
K_V	a factor bounding the user's vertical position with a probability of 0.5×10^{-7} ($K_V = 5.33$)
$S_{E,i}$	the partial derivative of position error in the east direction with respect to the pseudorange error on the ith satellite
$S_{N,i}$	the partial derivative of position error in the north direction with respect to the pseudorange error on the ith satellite
$S_{U,i}$	the partial derivative of position error in the up (vertical) direction with respect to the pseudorange error on the ith satellite
W_n	weighting function
T_{iono}	ionospheric corrections of Klobuchar error model
xSI	horizontal or vertical safety index
xPE	horizontal or vertical position error
xPL	horizontal or vertical protection level
x_{PP}, y_{PP}	coordinates of interpolation grid points
σ_i^2	full variance of the pseudorange measurement
$\sigma_{i,flt}^2$	variance of the residual error after the application of fast and slow corrections
$\sigma_{i,\,UIRE}^2$	variance of the residual error after the application of ionospheric correction
$\sigma_{i,air}^2$	variance of the contribution of the receiver to the residual error
$\sigma_{i,\,tropo}^2$	variance of the residual error after the application of tropospheric correction
$\sigma_{n,ionogrid}^2$	grid ionospheric vertical error bound with degradation over time
σ_{GIVE}^2	grid ionospheric vertical error bound
ε_{iono}^2	degradation of ionospheric correction information
Φ_m	geomagnetic latitude (in degrees) of ionospheric pierce point

1.0 INTRODUCTION

The aim of Satellite-Based Augmentation Systems (SBASs) systems is to support Global Navigation Satellite Systems (GNSSs) positioning in their area of operation[1]. Through the work of ground stations and geostationary satellites, SBAS systems transmit data to improve the quality of positioning and information on the integrity of GNSS systems[2]. Operational SBAS systems include the American Wide Area Augmentation System (WAAS), the European Geostationary Navigation Overlay Service (EGNOS), Japanese MTSAT Satellite Augmentation System (MSAS) and the GPS-Aided GEO Augmented and Navigation System (GAGAN). Russia is finalising the work on their Russian Wide Area Augmentation System (SDCM). Work is also underway on the new GNSS supporting systems—for example, the African Satellite Augmentation System (ASAS) under development in Africa[3].

EGNOS supports the SPS of GPS and operates in Europe[2]. This is done by using the L1 frequency and the C/A code. Providing correction data and integrity information, EGNOS improves satellite positioning, navigation and timing services. Performance of the system has changed significantly over the last few years. Open Service (OS), which improves GPS performances for the users of general-purpose applications has been operational since 2009, while Safety of Life Service–SoL (based on data integrity transmitted by geostationary satellites) has been available since 2011. Gradual improvements of the EGNOS system caused a significant expansion of its area of operation and improvement of positioning results.
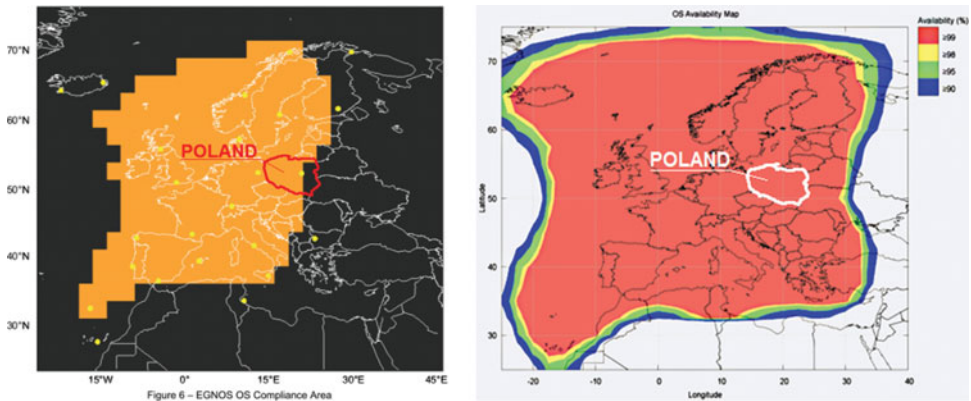
Figure 1. (Colour online) EGNOS OS compliance area presented in 2009 (left) and in 2014 (right)[2,11].

EGNOS can be used in air transport in the case of approaches and landing types based on Area Nagviation (RNAV)[4]. Non-Precision Approach (NPA) uses EGNOS only for lateral guidance. APV-1 is an instrument procedure, which does not meet the precision approach requirements, but uses lateral and vertical guidance. To implement EGNOS in aviation, it is necessary to fulfil a number of requirements and adjust to existing international guidelines developed by the International Civil Aviation Organisation (ICAO)[2].

Monitoring the EGNOS performance should be done locally, because in different places you may expect different results of positioning[5,6]. The research on the quality of the EGNOS in Poland carried out in recent years has shown that a lack of a RIMS station east of Warsaw impairs the quality of the system (especially in eastern Poland, where Differential Global Positioning System (DGPS) was usually used instead)[7-10]. However, in 2014, a new document was published by the European Commission's Directorate-General for Enterprise and Industry that the declared area of EGNOS OS coverage was greatly expanded east of the WRS station located in Warsaw. Figure 1 shows the EGNOS OS compliance area presented by the European Commission's Directorate-General for Enterprise and Industry in 2009 and in 2014.

In addition, in November 2013 an agreement was signed between the European Commission and Ukraine to include the territory of Ukraine in the range of the EGNOS[12]. The creation of a RIMS station in Ukraine would definitely also improve the performance of the EGNOS in Poland (especially the eastern regions). However, prior research carried out in 2012 in this country already shows a significant improvement in EGNOS performance (APV-1 approach requirements were met) but does not guarantee the full coverage of the system throughout the country. Thus, studies on EGNOS quality seem to be reasonable in an area that, according to the declaration of the European Commission's Directorate-General for Enterprise and Industry (2014), has been greatly expanded despite the lack of RIMS station in Ukraine.

Since the ionosphere is the main source of errors in GNSS positioning, research on this parameter and its role in Global Positioning System (GPS)/EGNOS positioning in Poland is very important[13]. In case of basic single-frequency GPS receivers the ionospheric delay is determined based on coefficients transmitted in the navigation message[14]. They are determined by virtue of Klobuchar model, which is characterised by a simple process of calculation and uncomplicated structure[14,15]. It is defined as an SLM, since in the calculation

of the theoretical delay, it uses the layer of the ionosphere at an altitude of 350 km above the Earth's surface. The Klobuchar model generates different delay values for daytime and nighttime. It eliminates the ionospheric delay by 50-60% on the base of the TEC (total electron content) coefficient between the satellite and the receiver. Its effectiveness is dependent on solar activity and user location.

In contrast, SBAS systems use a thin-shell approximation of the ionosphere and send the delay values determined for the grid points[16]. Based on that, the algorithm computes the delay for ionospheric pierce point (at an altitude of 350 km). For middle latitudes, grid points are spaced every 5° latitude and 5° longitude, and for the high latitudes the spacing is 30°[17].

Receivers using the Galileo system for positioning use the NeQuick ionosphere model, which was originally used in the analysis of the EGNOS system[18,19].

Since 2000, the Center for Orbit Determination in Europe (CODE) has been providing Klobuchar-style coefficients[20]. They are formed on the basis of the International GNSS Service (IGS) GPS observation data[21]. Using the post-fit coefficients gives much better positioning results than the original Klobuchar coefficients transmitted in the navigation message[22]. However, they are determined with several days' delay, so they can be only used in post-processing studies. Nevertheless, the CODE also provides predicted coefficients, which, according to the authors, should give better positioning results than the traditional Klobuchar model[21]. The results of studies conducted so far related to the Klobuchar-style coefficients provided by CODE showed better positioning accuracy than that provided through the original Klobuchar model[15].

2.0 ACCURACY AND INTEGRITY OF GPS/EGNOS POSITIONING IN AIR NAVIGATION

According to the US government's Federal Radionavigation Plan[23], the accuracy of an estimated or measured position at a given time is the degree of conformance of that location with the true position of the receiver at that time (it should be given with uncertainty in position that applies).

The results of positioning using EGNOS are expressed in the EGNOS Terrestrial Reference Frame, which is the realisation of the ITRS [2]. The difference between the EGNOS Terrestrial Reference Frame and the ITRF2000 reaches a value of a few centimetres (such as between systems EGNOS Terrestrial Reference Frame and WGS84). Thus, for navigation analyses, it can be assumed that the results of the GPS/EGNOS positioning are expressed in the ITRF2000 frame.

GPS/EGNOS positioning accuracy in Polish territory can be examined on the basis of true coordinates of the receiver determined by a network of reference stations of ASG-EUPOS system (the Polish part of the European Position Determination System (EUPOS)). The coordinates of the ASG-EUPOS reference stations are expressed in the Polish PL-ETRF2000 frame (reference epoch 2011.0 of the European Terrestrial Reference Frame 2000)[24, 2]. Thus, the reference coordinates expressed in the PL-ERTF2000 system can be easily transformed into the ITRF2000. The Horizontal Position Error (HPE) and Vertical Position Error (VPE) for each epoch can be calculated by comparing the determined position with the reference.

Integrity can be defined as a probability measure, which guarantees to contain the calculated horizontal position provided by the navigation system[23].

To express the level of integrity in real time, protection levels in the horizontal and vertical planes are used[25].

Horizontal Protection Level (HPL) is defined by the radius of the circle in the horizontal plane (with the centre on the real position), which describes the zone that is guaranteed to contain the horizontal position calculated. Vertical Protection Level (VPL) is the length of half of the cylinder's axis (with the centre on the real position) corresponding to the zone guaranteed to contain the vertical position calculated[1]. It is recognised that integrity is met when the protection level values do not exceed the defined alarm limit thresholds for a given phase of flight[25,26].

The values of protection levels are calculated on the basis of these formulae[1,27]:

$$HPL = K_H d_{major}, \qquad \ldots (1)$$

$$VPL = K_V d_U, \qquad \ldots (2)$$

where:

K_H is a factor bounding user's horizontal position with a probability of 10^{-9} (for en-route navigation $K_H = 6.18$ and for precision approach $K_H = 6.0$),

K_V is a factor bounding the user's vertical position with a probability of 0.5×10^{-7} ($K_V = 5.33$).

$$d_{major} = \sqrt{\frac{d_E^2 + d_N^2}{2} + \sqrt{\left(\frac{d_E^2 - d_N^2}{2}\right)^2 + d_{EN}^2}}, \qquad \ldots (3)$$

$$d_E^2 = \sum_{i=1}^{n} S_{E,i}^2 \sigma_i^2, \quad d_N^2 = \sum_{i=1}^{n} S_{N,i}^2 \sigma_i^2, \quad d_{EN} = \sum_{i=1}^{n} S_{E,i} S_{N,i} \sigma_i^2, \quad d_U^2 = \sum_{i=1}^{n} S_{U,i} \sigma_i^2,$$
$$\ldots (4)$$

where:

S is the projection matrix,

d_E^2, d_N^2 and d_U^2 are variances of the east, north and up (vertical) components of the position solution expressed in a topocentric system,

d_{EN}^2 is the covariance between the east and north axes,

$S_{E,i}$ is the partial derivative of position error in the east direction with respect to the pseudorange error on the ith satellite,

$S_{N,i}$ is the partial derivative of position error in the north direction with respect to the pseudorange error on the ith satellite,

$S_{U,i}$ is the partial derivative of position error in the up (vertical) direction with respect to the pseudorange error on the ith satellite.

$$\sigma_i^2 = \sigma_{i,flt}^2 + \sigma_{i,UIRE}^2 + \sigma_{i,air}^2 + \sigma_{i,tropo}^2 \qquad \ldots (5)$$

σ_i^2 is the full variance of the pseudorange measurement,

$\sigma_{i,flt}^2$ is the variance of the residual error after the application of fast and slow corrections,

$\sigma^2_{i,\ UIRE}$ is the variance of the residual error after the application of ionospheric correction,

$\sigma^2_{i,air}$ is the variance of the contribution of the receiver to the residual error,

$\sigma^2_{i,\ tropo}$ is the variance of the residual error after the application of tropospheric correction.

$$\sigma^2_{i,\ UIRE} = F^2_{PP}\sigma^2_{i,\ UIVE}, \qquad \ldots(6)$$

$$\sigma^2_{i,\ UIVE} = \sum_{n=1}^{4} W_n(x_{PP}, y_{PP})\, \sigma^2_{n,ionogrid}, \qquad \ldots(7)$$

$$\sigma^2_{n,ionogrid} = \sigma^2_{GIVE} + \varepsilon^2_{iono}, \qquad \ldots(8)$$

where:

F_{PP} is the obliquity factor (transforms vertical delay to slant),

W_n is the weighting function,

$\sigma^2_{n,ionogrid}$ is the grid ionospheric vertical error bound with degradation over time,

x_{PP}, y_{PP} are the coordinates of interpolation grid points,

σ^2_{UIVE} is the grid ionospheric vertical error bound, and

ε^2_{iono} is the degradation of ionospheric correction information.

In case of the NPA (non-recision approach) and the phases of flight other than PA, instead of the original EGNOS model of ionosphere, the regular model (Klobuchar model) used in GPS SPS can be used. The error of the delay determination is then calculated based on the maximum value taken from the set of two elements described in this formula[1]:

$$\sigma^2_{i,\ UIRE} = max\left(\left(\frac{cT_{iono}}{5}\right)^2,\ (F_{PP\ \tau vert})^2\right), \qquad \ldots(9)$$

where c is the speed of light and T_{iono} is the ionospheric corrections of the Klobuchar error model.

The τ_{vert} is dependent on the geomagnetic latitude of ionospheric pierce point calculated on the basis of Klobuchar algorithm:

$$\tau_{vert} = \begin{cases} 9\ m, & 0 \le |\Phi_m| \le 20 \\ 4.5\ m, & 20 < |\Phi_m| \le 55, \\ 6\ m, & 55 < |\Phi_m| \end{cases} \qquad \ldots(10)$$

where Φ_m is the geomagnetic latitude (in degrees) of ionospheric pierce point.

When using Klobuchar-style (CODE) predicted coefficients for research purposes, the formulas in Bakul[9] and in Popielarczyk and Templin[10] can be used to determine the values of protection levels.

The test results of the accuracy and integrity of satellite positioning are used to verify the applicability of a particular navigation system in aviation. Based on the results of the long-term analyses, it can be determined if the system is ready for use in the flight procedure or in

Table 1
EGNOS accuracy and integrity requirements in aviation[26]

Typical Operation	Accuracy		Integrity	
	Horizontal (95%)	Vertical (95%)	Horizontal Alert Limit (HAL)	Vertical Alert Limit (VAL)
En route (oceanic/continental low density)	3.7 km	N/A	7.4 km	N/A
En route (continental)			3.7 km	N/A
En route, Terminal	0.74 km	N/A	1.85 km	N/A
Initial approach, Intermediate approach, Non-Precision Approach (NPA), Departure	220 m	N/A	556 m	N/A
Approach operations with vertical guidance (APV-I)	16 m	20 m	40 m	50 m

Figure 2. (Colour online) GNSS antenna and computer set with GNSS receiver installed in the building of the Aeroclub of Warmia and Mazury.

the approach and landing of an aircraft. Table 1 presents the requirements of the accuracy and integrity of satellite positioning systems used in air navigation.

3.0 PRACTICAL STUDIES

In order to examine the accuracy and the parameters characterising the integrity of positioning, detailed analyses of GPS/EGNOS measurements were performed. Data were acquired at a permanent EGNOS monitoring station at the airport Olsztyn-Dajtki EPOD in northeastern Poland. The observations were recorded on 6-30 June 2014 with a Septentrio AsteRx2e receiver connected to a choke-ring antenna mounted on a specially adapted mast (Fig. 2). The selected location had been previously tested for the presence of potential interference of
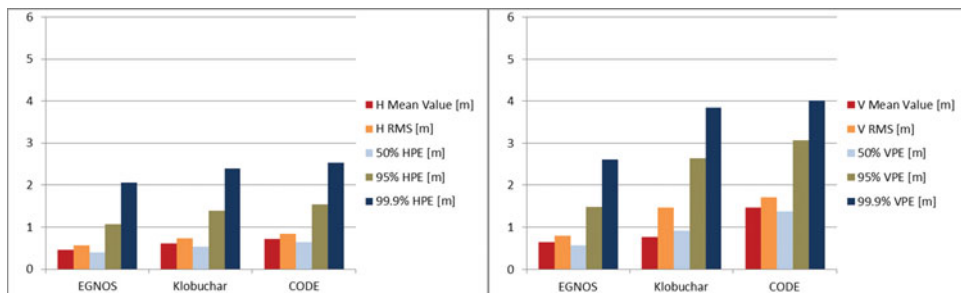
Figure 3. (Colour online) Horizontal (left) and vertical (right) position error deviations from reference on 1-10 June 2014 for the original EGNOS ionospheric correction, the Klobuchar model and the CODE Klobuchar-style predicted ionospheric correction.

the GNSS signal with signals generated by the communications equipment installed at the airport.

The data were collected in 10-day sessions at 1-second intervals. Altogether, three full sessions were collected over 30 days. These were developed using the Septentrio Post Processing SDK application, a self-created PP-SBAS Analyser application and PEGASUS software, which is a set of tools that allows for the analysis of data collected from a variety of GNSS, SBAS and GBAS systems using algorithms defined in the MOPS documents.

Measurement data were processed in three variants of calculation:

- The original ionospheric GPS/EGNOS correction,
- Klobuchar ionospheric correction,
- CODE ionospheric model correction.

Each of the three variants is characterised by the same configuration parameters: elevation mask of $5°$, exclusion from pseudorange positioning geostationary satellites, data recording intervals of one second, and EGNOS PRN125 satellite used (in case of unavailability of data from this satellite, data from PRN120 satellite were used). For the calculations only, the data which were not considered faulty during recording and processing (valid samples) were used. The ionosphere in the period from 1 June 2014 to 30 June 2014 was stable, except on 7, 8 and 18 June, during which the values of the Kp factor characterising the activity of the Earth's electromagnetic field exceeded the limit values (Kp $= 4$).

3.1 Accuracy analyses

Figures 3-5 present horizontal (HPE) and vertical (VPE) position error analyses in the examined period based on the three variants of calculations. The detailed error analyses were performed including mean value of the absolute position error (H/V mean value), root mean square (RMS) and the errors characterised by confidence levels of 50%, 95% and 99.9%.

On the basis of the presented accuracy analyses, it can be concluded that the model developed by EGNOS gave the best results of horizontal and vertical accuracy for all examined errors. In the period from 1-10 June 2014, the error characterised by the 95% confidence level for EGNOS model achieved the following values: HPE $= 1.1$ m, VPE $= 1.5$ m. In the period from 11-20 June 2014, HPE $= 1.0$ m and VPE $= 1.4$ m, and in the period from 21-30 June 2014, HPE $= 1.1$ m and VPE $= 1.4$ m. Results that were slightly worse but
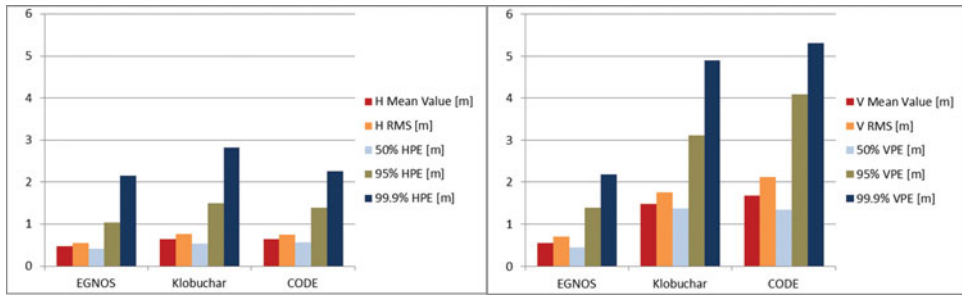
Figure 4. (Colour online) Horizontal (left) and vertical (right) position error deviations from reference on 11-20 June 2014 for the original EGNOS ionospheric correction, the Klobuchar model and the CODE Klobuchar-style predicted ionospheric correction.
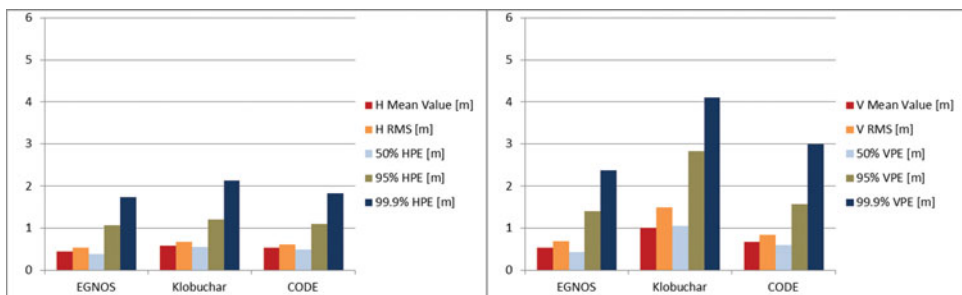
Figure 5. (Colour online) Horizontal (left) and vertical (right) position error deviations from reference on 21-30 June 2014 for the original EGNOS ionospheric correction, the Klobuchar model and the CODE Klobuchar-style predicted ionospheric correction.

on the same order of precision were noted for the CODE and Klobuchar model. In the period from 1-10 June 2014, the CODE model reached values of HPE = 1.6 m VPE = 3.1 m, while Klobuchar model achieved values of HPE = 1.4 m and VPE = 2.6 m. In the period from 11-20 June 2014, CODE values were HPE = 1.4 m and VPE = 4.1 m while Klobuchar values were HPE = 1.5 m, VPE = 3.1 m. In the period from 21-30 June 2014, CODE values were HPE = 1.1 m and VPE = 1.6 m while Klobuchar values were HPE = 1.2 m and VPE = 2.8 m.

Nevertheless, the analysis of the average accuracy values obtained in the same periods points to very different conclusions. The best performance is undoubtedly characterised by the original EGNOS ionospheric model. The Klobuchar model gave better results than CODE for both HPE and VPE in the first analysed period, while in the third it was the opposite (CODE was better than Klobuchar). In the second analysed period, HPE was better for the CODE model while VPE was better for Klobuchar. It must be emphasised that all three calculation variants are characterised by the accuracy results meeting the requirements of the SBAS system during the APV-1 approach.

3.2 Integrity analyses

For aviation, the integrity of the information transmitted by the system is more important than accuracy. The presentation of the analysis of the integrity of the GPS/EGNOS positioning is made using position error/protection level (xPE/xPL) for each measurement epoch (Figs 6-8). According to Table 1, for approach operations with vertical guidance (APV-1) the HPE and
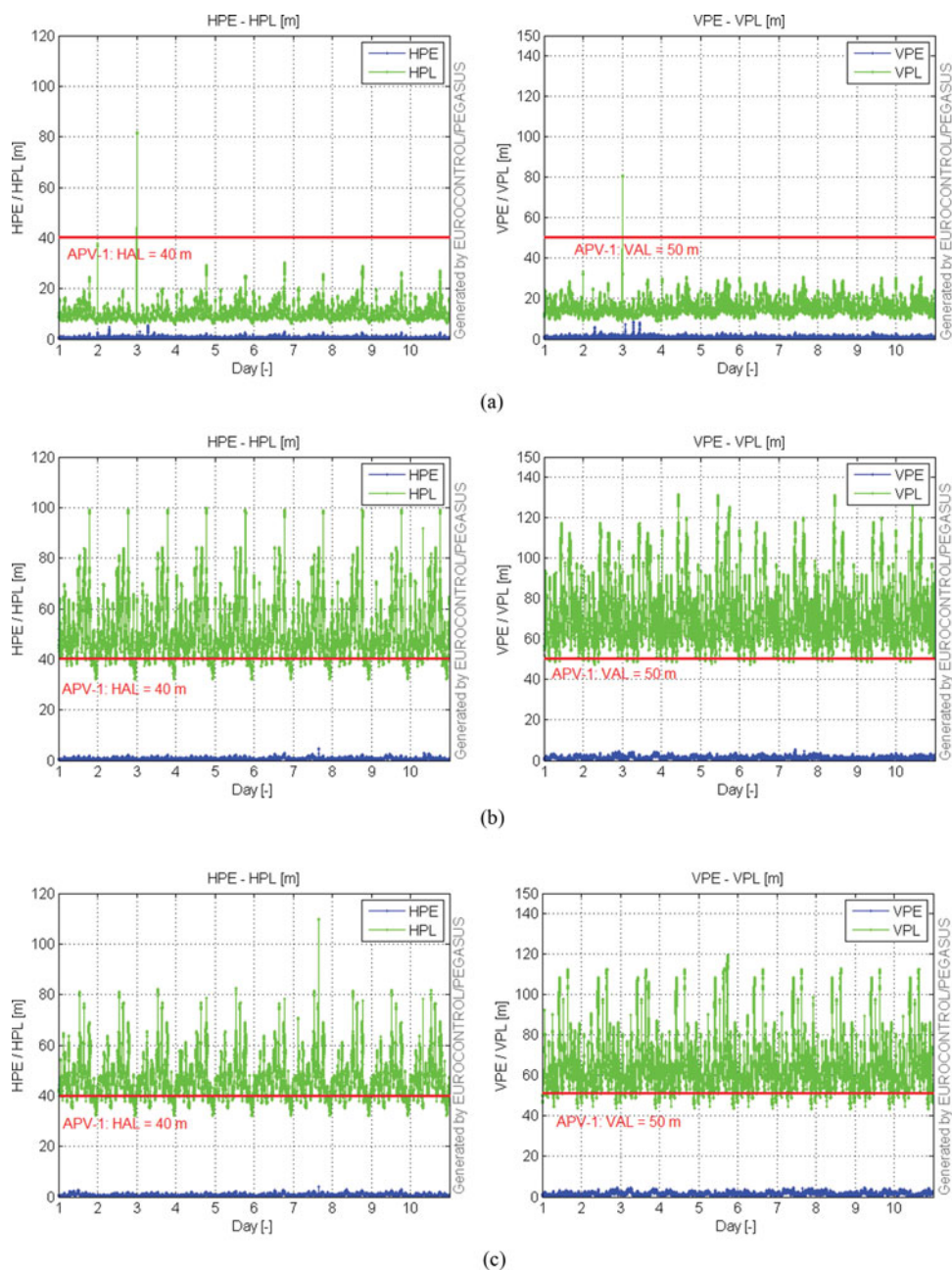
Figure 6. (Colour online) Horizontal (left) and vertical (right) positioning accuracy and protection level based on 1-10 June 2014 for: a) the original EGNOS ionospheric correction, b) the Klobuchar model, c) the CODE Klobuchar-style predicted ionospheric correction.
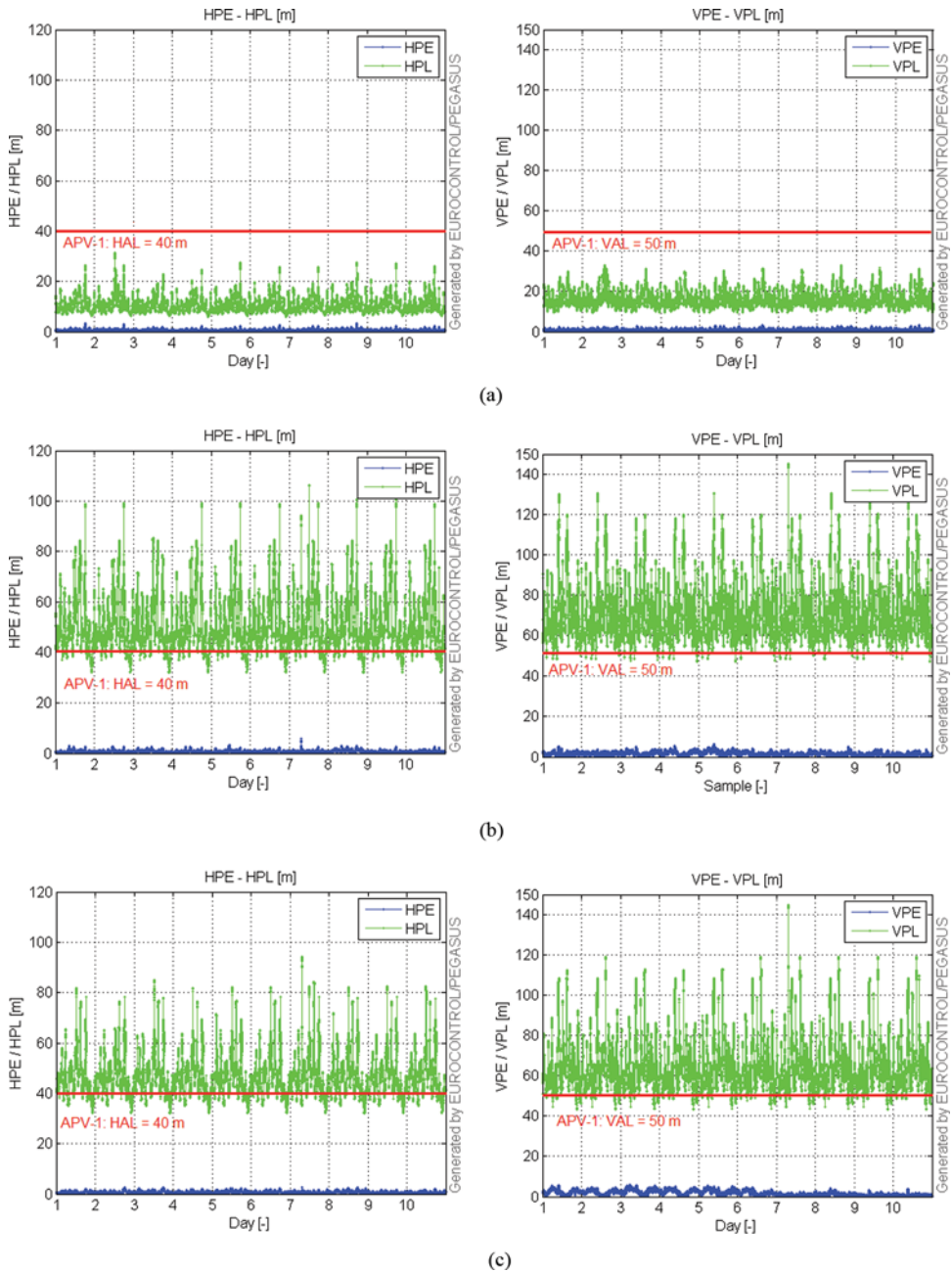
Figure 7. (Colour online) Horizontal (left) and vertical (right) positioning accuracy and protection level based on 11-20 June 2014 for: a) the original EGNOS ionospheric correction, b) the Klobuchar model, c) the CODE Klobuchar-style predicted ionospheric correction.
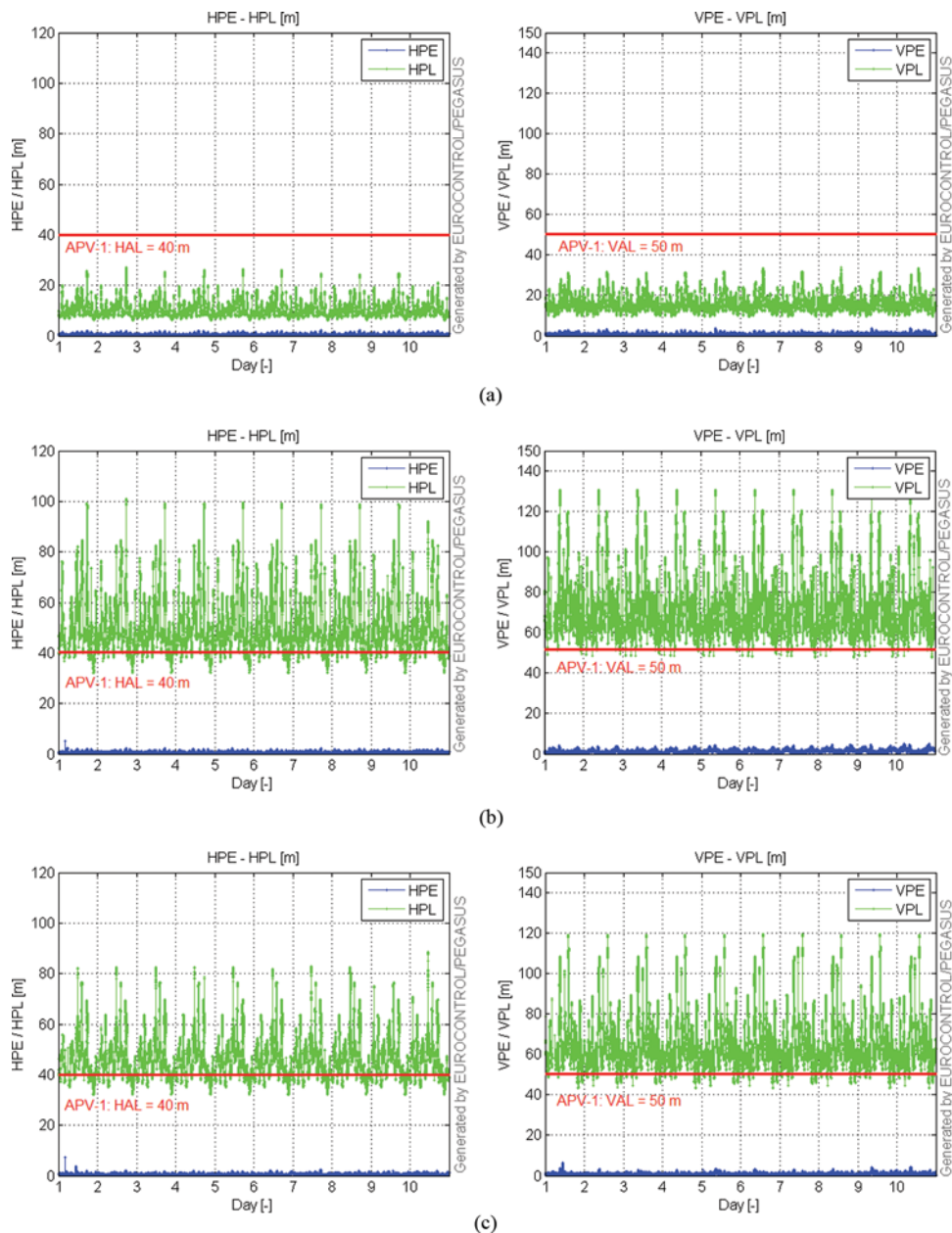
Figure 8. (Colour online) Horizontal (left) and vertical (right) positioning accuracy and protection level based on 21-30 June 2014 for: a) the original EGNOS ionospheric correction, b) the Klobuchar model, c) the CODE Klobuchar-style predicted ionospheric correction.

VPE must not exceed 16/20 m, while HPL and VPL must not exceed 40/50 m respectively. In addition, the position domain Safety Index (SI) must also be examined. Position domain SI is defined as the ratio between the true navigation system error and the corresponding protection

level[28]:

$$xSI = \frac{xPE}{xPL} \qquad \qquad \dots (11)$$

where:

    xSI is the horizontal or vertical safety index,

    xPE is the horizontal or vertical position error, and

    xPL is the horizontal or vertical protection level.

There is a potential misleading-information (MI) situation if SI is larger than 0.75. There is real MI every time the instantaneous SI exceeds 1.

Based on the above analyses of the integrity, it can be concluded that the original EGNOS ionospheric model presents the best results in the examined period. During the measurement session recorded on 1-10 June 2014, only 47 epochs did not meet the requirements of the horizontal and vertical APV-1 (protection of levels above of 40 m and 50 m respectively). In the period from 22-30 June 2014, 100% of measurement data meet these requirements. In case of CODE and Klobuchar modes, it can be clearly seen that integrity for APV-1 is not provided. For the CODE model. only 24% of HPL and 8% of VPL meet the requirement of APV-1. For the Klobuchar model, the results are even worse, meeting the APV-1 requirements for 15% of HPL and 1% of VPL. However, it should be emphasised that for both CODE and Klobuchar models 100% of measurement data meets the requirements of NPA (HPL below 556 m).

It should be noted that for some epochs in the EGNOS mode (Fig. 6a) in the first analysed period during Day 2 and 3, there are few peaks of position errors. These epochs were analysed in detail showing that protection levels do not lead to potential MI (SI is less than 0.75).

4.0 CONCLUSION

The subject of the study was to analyse the parameters affecting the quality of positioning using EGNOS in northeastern Poland. The results obtained with the use of the original EGNOS ionospheric model, the Klobuchar model, and the modified Klobuchar-style coefficients model developed by CODE were compared. The accuracy and the values of parameters characterising the integrity of positioning were determined taking into account the three studied variants.

Analyses showed that in the examined period, the original EGNOS model presents best values of position errors and protection levels, meeting the requirements of the integrity of positioning used in APV-1 procedures. The CODE and Klobuchar models are characterised with good accuracy results, which can be applied to users of EGNOS Open Service and NPA operations. These models, however, should not be used in the case of any PA operation, since both HPL and VPL requirements are not met.

The results presented in the studied period do not define the EGNOS performance for the selected location but definitely give insight into trends emerging for the effects of each analysed model of the ionosphere.

ACKNOWLEDGEMENTS

REFERENCES

1. Radio Technical Committee for Aeronautics: Minimum Operational Performance Standards for Airborne Equipment Using Global Positioning System/Wide Area Augmentation System, Doc. DO-229D, 2006.
2. European Commission Directorate-General for Enterprise and Industry, Safety of Life Service Definition Document, **2.1**, 2014.
3. Ilcev, D. S. Development and characteristics of African satellite augmentation system (ASAS) network, *Telecommunications Systems,* 2013, **52**, (1), pp 121-137.
4. International Civil Aviation Organization: European Region Area Navigation (RNAV), guidance material, 2003.
5. Felski, A. and Nowak, A. On EGNOS monitoring in local conditions, *Artificial Satellites*, 2013, **48**, (2), pp 85-92.
6. Vassilev, B. and Vassileva, B. The satellite navigation system EGNOS and safety of life service performance in Sofia, *Information Technologies and Control*, April 2011, pp 32-39.
7. Felski, A., Nowak, A. and Woźniak, T. Accuracy and availability of EGNOS: results of observations, *Artificial Satellites*, 2011, **46**, pp 111-118.
8. Grzegorzewski, M., Świątek, A., Oszczak, S., Ciećko, A. and Ćwiklak, J. Study of EGNOS safety of life service during the period of solar maximum activity, *Artificial Satellites*, 2012, **47**, pp 137-145.
9. Bakuła, M. Network code DGPS positioning and reliable estimation of position accuracy, *Survey Review*, 2010, **42**, pp 82-91.
10. Popielarczyk, D. and Templin, T. Application of integrated GNSS/hydroacoustic measurements and GIS geodatabase models for bottom analysis of Lake Hancza: the deepest inland reservoir in Poland, *Pure Applied Geophysics*, 2014, **171**, pp 997-1011.
11. European Commission Directorate-General for Enterprise and Industry, *Service Definition Document Open Service*, 1.1, 2009.
12. Konin, V. and Shyshkov, F. Extending the reach of SBAS: some aspects of EGNOS performance in Ukraine, *Inside GNSS*, 2015, **1**, pp 50-54.
13. Świątek, A., Stanisławska, I., Zbyszyński, Z. and Dziak-Jankowska, B. Extension of EGNOS ionospheric correction coverage area, *Acta Geophysica*, 2014, **62**, (1), pp 259-269.
14. Klobuchar, J.A. Ionospheric time-delay algorithm for single-frequency GPS users, *IEEE Transactions on Aerospace and Electronic Systems,* 1987, AES-23, pp 325-331.
15. Yuan, Y., Huo, X., Ou, J., Zhang, K., Chai, Y. et al. Klobuchar ionospheric coefficients based on GPS observations, *IEEE Transactions on Aerospace and Electronic Systems*, 2008, AES-44, pp 1498-1510.
16. Arbesser-Rastburg, B. Ionospheric and tropospheric modelling and monitoring for GNSS at the European space agency, IEEE in General Assembly and Scientific Symposium 2011 XXXth URSI, 2011, pp 1-4. http://www.ursi.org/proceedings/procga11/ursi/FG-1.pdf
17. Jakowski, N., Borries, C. and Wilken, V. Introducing a disturbance ionosphere index, *Radio Sci.*, 2012, **47**, RS0L14, doi:10.1029/2011RS004939.
18. Angrisano, A., Gaglione, S., Gioia, C., Massaro, M. and Robustelli, U. Assessment of NeQuick ionospheric model for Galileo single-frequency users, *Acta Geophysica*, 2013, **61**, (6), pp 1457-1476.
19. Radicella, S.M. The NeQuick model genesis, uses and evolution, *Annals of Geophysics*, 2009, **52**, (3/4), pp 417-422.
20. Mageed, K.M.A. Effect of using Klobuchar, CODE, and No-ionosphere models on processing single frequency GPS static medium baselines, *Int J Scientific and Engineering Research.*, 2014, **5**, (5), pp 363-371.

21. http://aiuws.unibe.ch/ionosphere/#cgim (accessed 2 December 2014).

22. ØVSTEDAL, O. Absolute positioning with single-frequency GPS receivers, *GPS Solutions*, 2002, **5**, (4), pp 33-44.

23. Department of Defense, Department of Homeland Security, and Department of Transportation. Federal Radionavigation Plan, 2012, Springfield, Virginia, US.

24. http://www.asgeupos.pl/index.php?wpg_type=news_show&news_id=159 (accessed 15 December 2014).

25. AZAOLA-SAENZ, M. and COSMEN-SHORTMANN, J. Autonomous Integrity, *Inside GNSS*, 2009, **4**, pp 28-36.

26. ICAO Standards and Recommended Practices (SARPS), Annex10 Volume I (Radio Navigation Aids) (International Civil Aviation Organization), 2006.

27. OLIVEIRA, J. and TIBERIUS, C. Quality control in SBAS: Protection levels and reliability levels *J Navigation*, 2009, **62**, pp 509-522.

28. VASSILEY, B. and VASSILEVA, B. EGNOS performance before and after applying an error extraction methodology, *Annual of Navigation*, 2012, **19**, (2), pp 121-130.