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APPLICATION OF THE GPS/EGNOS SOLUTION FOR THE PRECISE POSITIONING OF AN AIRCRAFT VEHICLE

Summary. The results of research concerning the implementation of the GNSS technique in the area of air navigation are presented in this article. In particular, a research test was conducted for the purposes of checking the functioning of a satellite-based augmentation system (SBAS) to assist with air navigation. Ultimately, analyses of the parameters of accuracy, availability, continuity and integrity with the procedure when landing aircraft with an SBAS APV-I landing were conducted. The navigation and observation data of the GPS system and differential European Geostationary Navigation Overlay Service (EGNOS) corrections were used in the research test. The navigation and observation data of the GPS system in the RINEX format were registered through the Topcon Hiper Pro receiver placed in the cabin of pilots in the Cessna 172 aircraft during a flight experiment conducted in Dęblin in 2010. The coordinates of the Cessna 172 aircraft in the ellipsoid BLh frame were reconstructed by using the solution offered by the single point positioning (SPP) method in the RTKLIB program. The accuracy when setting coordinates of the aircraft is higher than 2.4 m in the horizontal plane and better than 4 m in the vertical plane. The integrity of the satellite positioning is higher than 15 m in the horizontal plane and better than 21.1 m in the vertical plane. The availability of the constellation of GPS/EGNOS satellites equalled 100% during the flight experiment, which confirms that the loss of continuity when determining the position of the aircraft did not occur. The parameters of the accuracy and the integrity with International Civil

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Aviation Organization (ICAO) technical standards were compared in this article. The results of the conducted test shows that the presented research methods can be applied in the precise positioning of the aircraft when using the GPS/EGNOS solution for air navigation.

Keywords: GPS; EGNOS; air transport; air navigation; SPP method

1. INTRODUCTION

Within air navigation, an SBAS system assists with the positioning of an aircraft when using the GNSS technique. The system is based on the application of differential corrections from geostationary satellites in order to improve the positioning of aircraft in almost real time, as well as during post-processing [4]. In the main, WAAS, EGNOS, GAGAN, SDCM and MSAS satellite systems support SBAS-based assistance [13]. There is an applied EGNOS satellite system in Europe for the purposes of conducting precise air navigation and air transport. The EGNOS system mainly improves accuracy when determining the position of a user on the basis of a solution involving a GPS, GLONASS or Galileo navigation system. The basic architecture of the EGNOS system consists of the space segment, the ground section and the user's section. The space segment is created by the constellation of three EGNOS satellites located in geostationary orbit, i.e., satellite numbers S120, S126 and S136. The ground segment consists of a network of reference stations running the EGNOS, i.e., the RIMS, MCC, NLES stations. Next, in the user's section, it is possible to single out online services that support precise positioning in the EGNOS system, that is, Open Service, Safety of Life and the EGNOS Data Access Service [6, 10, 18].

Tab. 1

Basic parameters of the SBAS APV-I landing procedure [2]

Air operation	Parameter	Value
SBAS APV-I landing procedure	Accuracy	16 m for horizontal plane, 20 m for vertical plane
	Availability	0.99 to 0.99999
	Time to alarm	10 s
	Continuity	$8*10^{-6}$ in any 15 s
	Integrity	40 m for horizontal plane, 50 m for vertical plane

In the case of air navigation, the principles for using the EGNOS support system were set out in the ICAO's technical standards found in Annex 10 on radio navigation aids in the Chicago Convention. In particular, the EGNOS system is applied as part of an aircraft's attempt to land according to the concept of area navigation (RNAV). Therefore, the EGNOS support system can be used in the final approach of the type SBAS APV-I [5]. The technical standards of the SBAS APV-I procedure were developed for their implementation and exploitation of the Safety of Life user service. In Table 1, basic technical parameters are presented for the SBAS APV-I approach according to ICAO recommendations [9]. Within the framework of the SBAS APV-I approach for the EGNOS system, the accuracy when determining the position of aircraft cannot exceed 16 m in the horizontal plane and must be at least 20 m in the vertical plane. The parameter of the integrity of satellite positioning cannot exceed 40 m for horizontal navigation and 50 m for vertical navigation. Moreover, the time to alarm must equal 10 s in cases in which navigational data are lost from the EGNOS system. The visibility of the constellation of EGNOS satellites and the GPS (if necessary, GLONASS or Galileo) must be higher than 0.99 throughout the entire duration of the air operation.

As part of the presented work, the possibility of using differential EGNOS corrections for the precise positioning of the aircraft was reported for the purposes of SBAS-based assistance with air navigation. Verification of the use of the EGNOS system in air navigation was carried out before the launch of a fully operational service for Safety of Life activities (i.e., before 2 March 2011). The position of the Cessna 172 aircraft was determined in a research experiment during the flight test around the military airport in Dęblin on 1 June 2010. The position of the aircraft was determined by the RTKPOST module in the RTKLIB software, based on the SPP method. During calculations, corrective EGNOS data from the S126 satellite were used in the post-processing mode.

This article is divided into three parts: Materials and Methods, Results and Discussion, and Conclusions. The mathematical models for determining the position of the aircraft using the SPP method are presented in the Materials and Methods part of this article. In addition, the flight trajectory of the Cessna 172 aircraft, the parameter of the Vertical TEC (VTEC) ionosphere, and the configurations of parameters during calculations are also presented. The availability of the constellation of GPS/EGNOS satellites and navigational continuity involved in determining the position of the aircraft are presented in Results and Discussion part of the article. In addition, the accuracy of the aircraft's coordinates are presented, the values of the MRSE parameter have been determined, the values of the HPL and VPL safety levels are given presented, and parameters of the accuracy and integrity of the ICAO technical standards are compared in this section. In the Conclusions chapter, the outcomes are summarized.

2. METHODS AND MATERIALS

The data for EGNOS correction are used in the SPP method for the determination of coordinates of the aircraft during the performed flight. Mathematical models for determining the position of the aircraft from the EGNOS solution are described below:

$$l = d + c \cdot (dtr - dts) + Ion + Trop + \mathrm{Re}l + TGD + RDCB_{L1} + PRC + \varepsilon \tag{1}$$

where:
l – pseudorange value (C/A code) for the initial frequency in GNSS system (e.g., in the GPS system)
d – geometric distance between the satellite and receiver
$d = \sqrt{(x - X_{GNSS})^2 + (y - Y_{GNSS})^2 + (z - Z_{GNSS})^2}$
(x, y, z) – the aircraft's coordinates in the geocentric frame
$(X_{GNSS}, Y_{GNSS}, Z_{GNSS})$ – GNSS satellite coordinates (e.g., GPS system)
c – speed of light
dtr – receiver clock bias
dts – satellite clock bias
Ion – ionosphere delay
$Trop$ – troposphere delay
$\mathrm{Re}l$ – relativistic effect

TGD – time group delay
$RDCB_{L1}$ – receiver differential code bias, referenced to the L1-C/A code
PRC – differential correction from the EGNOS system including long-term and fast corrections, and ionosphere and troposphere corrections
ε - measurement noise

Geocentric coordinates of the aircraft are determined by using the least-squares method in the process-based iteration for all measurement epochs as per below [8]:

$$\begin{cases} \mathbf{Qx} = \mathbf{N}^{-1} \cdot \mathbf{L} \\ \mathbf{v} = \mathbf{A} \cdot \mathbf{Qx} - \mathbf{dl} \\ m0 = \sqrt{\dfrac{[\mathbf{pvv}]}{n-k}} \\ \mathbf{C_{Qx}} = m0^2 \cdot \mathbf{N}^{-1} \\ \mathbf{m_{Qx}} = diag\left(\sqrt{\mathbf{C_{Qx}}}\right) \end{cases} \tag{2}$$

where:
$\mathbf{Qx}$ – vector with unknown parameters
$\mathbf{N} = \mathbf{A}^{\mathbf{T}} \cdot \mathbf{p} \cdot \mathbf{A}$ – matrix of normal equation frame
$\mathbf{A}$ – full rank matrix
$\mathbf{p}$ – matrix of weights
$\mathbf{L} = \mathbf{A}^{\mathbf{T}} \cdot \mathbf{p} \cdot \mathbf{dl}$ – misclosure vector
$\mathbf{dl}$ – vector including the difference between observations and modelled parameters
$m0$ – standard error of unit weight
n – number of observations, $n > 4$ for each measurement epoch
k – number of unknown parameters, $k = 4$ for each measurement epoch
$\mathbf{v}$ – vector of residuals
$\mathbf{C_{Qx}}$ – covariance matrix
$\mathbf{m_{Qx}}$ – standard deviations for unknown parameters

Set coordinates of the aircraft can also be expressed with ellipsoid BLh coordinates, as per below [14]:

$$\begin{cases} B = arc\tan\left(\dfrac{z/\rho}{1-e^2}\right) \\ L = arc\tan\left(\dfrac{y}{x}\right) \\ h = \dfrac{\rho}{\cos B} - R \end{cases} \tag{3}$$

where:
(a,b) – semi-major and semi-minor axes of the ellipsoid frame

e – eccentricity

$e=\sqrt{\frac{a^2-b^2}{a^2}}$

R – radius of the curvature of the prime vertical

$R=\frac{a}{\sqrt{1-e^2\cdot\sin^2 B}}$

$\rho=\sqrt{x^2+y^2}$

(B,L,h) – geodetic coordinates of the aircraft's position

B – latitude

L – longitude

h – ellipsoidal height

The accuracy of coordinates of the aircraft related to the geodetic BLh frame is described with parameters [12] below:

$$mB=\sqrt{\mathbf{m_{BLh}}(1,1)};\quad mL=\sqrt{\mathbf{m_{BLh}}(2,2)};\quad mh=\sqrt{\mathbf{m_{BLh}}(3,3)} \tag{4}$$

where:

$\mathbf{m_{BLh}}$ – covariance matrix in geodetic frame (BLh)

$\mathbf{m_{BLh}}=\mathbf{R}\cdot\mathbf{C_{Qx}}\cdot\mathbf{R^T}$

$\mathbf{R}$ – transition matrix from geocentric (XYZ) to geodetic frame (BLh)

mB – standard deviation in latitude

mL – standard deviation in longitude

mh – standard deviation in ellipsoidal height

Within the framework of the conducted research, the position of the Cessna 172 aircraft was determined using EGNOS correction data. A test flight was carried out in the area of the military airport in Dęblin on 1 June 2010 between the hours of 09:39:03 and 10:35:03 according to the time indicated by the GPS. The mobile geodetic Topcon Hiper Pro receiver, which was placed on board the aircraft, was designed to facilitate GNSS observation for the purposes of reconstructing the real position of the Cessna 172 aircraft in the post-processing mode [1]. The Topcon Hiper Pro receiver recorded satellite observations from the GPS and the GLONASS system with a frequency of every 1 s. Moreover, for the purposes of research tests, EGNOS correction data from the S126 satellite were used and placed on the Internet server: http://www.egnos-pro.esa.int/ems/index.html. The frequency by which differences in EGNOS corrections were recorded was also every 1 s. The final trajectory of the Cessna 172 aircraft in the coordinate frame of the ellipsoidal BLh is shown in Fig. 1.

As part of the conducted air test, the state of the ionosphere in the form of the VTEC parameter was also determined. Values of the ionosphere VTEC delay were determined in the EGNOS system by using a regular GRID with a size of about 5° on 5°. Fig. 2 presents the values of the VTEC parameter for the knot of the GRID, whose coordinates are 50° N 20° E, which are based on differential EGNOS corrections from the S126 satellite. During the flight experiment, the value of the ionosphere VTEC delay changed from 1.375 to 1.625 m. The average value of the VTEC parameter was equal to 1.530 m, while the median was equal to 1.500 m. The values of the ionosphere VTEC delay was calculated using SBAS MeNTOR 1.15 software [3].

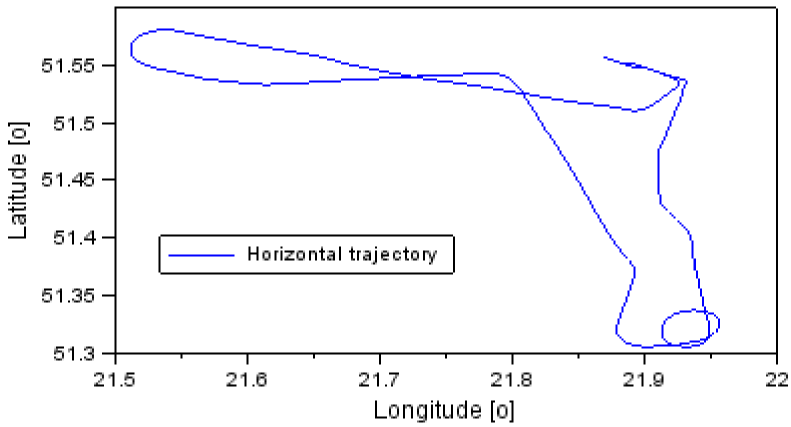

Fig. 1. Horizontal flight trajectory of the Cessna 172 aircraft

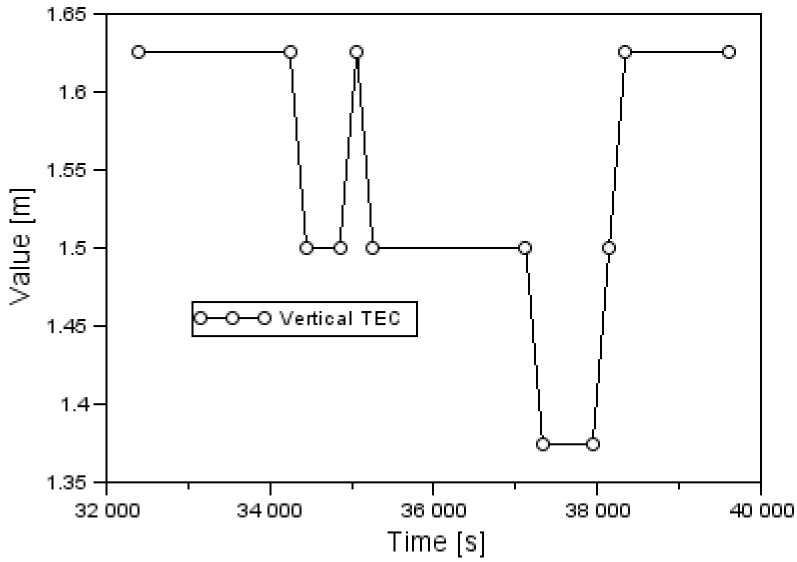

Fig. 2. Values of the VTEC parameter during the flight test

Calculations of ellipsoid coordinates of the aircraft were performed by using the SPP method in the RTKPOST module of the RTKLIB program. The GPS code observations in the RINEX 2.11 format, the GPS navigational data and differential EGNOS corrections in the EMS format were also used in the calculations. The configuration of the RTKPOST module was adjusted for the purposes of calculations, as below [16]:
- positioning mode: single
- elevation mask: 5°
- source of ionosphere delay: SBAS correction
- source of troposphere delay: SBAS correction
- source of satellite coordinates and clocks: broadcast ephemeris and SBAS message
- GNSS system: GPS + SBAS
- source of GPS observations: RINEX 2.11 file
- source of EGNOS corrections: EMS file
- reference frame of coordinates: WGS-84 datum

3. RESULTS AND DISCUSSION

Fig. 3 presents the number of visible GPS and EGNOS satellites during the flight experiment at the airport in Dęblin. The required number of satellites to determine the navigation position of the aircraft in a single measurement epoch is typically four or more. The parameter of the availability of the GPS and EGNOS constellation of satellites on 1 June 2010 amounted to 100% and the number of satellites changed from six to 10. It should be noted that, in the first stage of the flight (i.e., the start and the departure from the airport), the number of GPS and EGNOS satellites tracked by the receiver was between six and 10. In the final stage of the flight (i.e., approach to landing) the number of GPS and EGNOS satellites evolved from six to nine. The average number of visible GPS and EGNOS satellites during the experiment was more than nine. A sufficient number of visible GPS and EGNOS satellites also enabled continuity solutions for determining the positions of the aircraft with the SPP method. To this extent, there were no breaks or losses regarding the solution for determining the Cessna 172 aircraft's position.

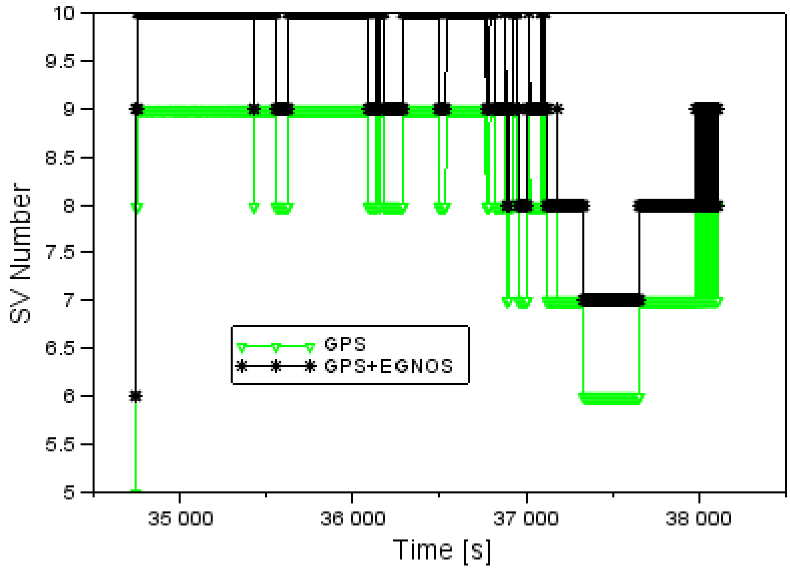

Fig. 3. The GPS/EGNOS satellite constellation during the flight test

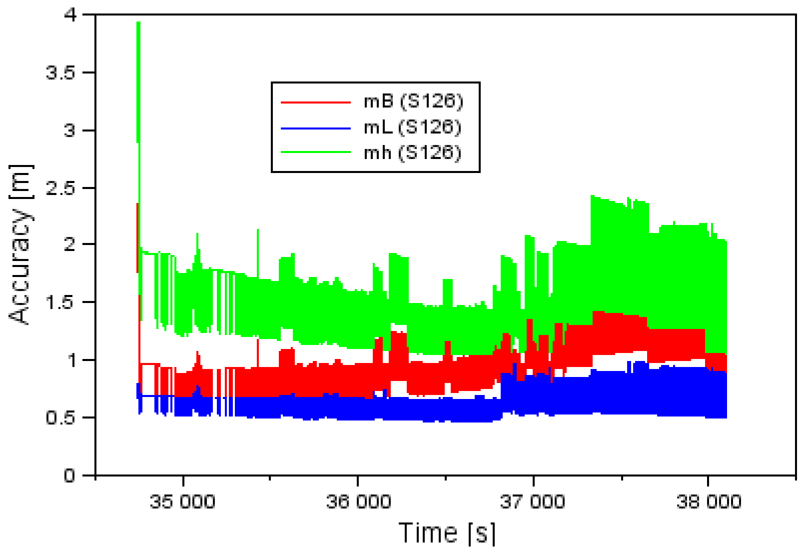

Fig. 4. The accuracy of the geodetic coordinates of the Cessna 172 aircraft

Fig. 4 presents the accuracy when setting the geodetic coordinates for the Cessna 172 aircraft during the conducted flight test. The standard deviation of the geodetic latitude width changed from 0.6 m to 2.4 m, while the average value of the accuracy of the B horizontal coordinates was equal to around 1 m. The standard deviation of the geodetic longitude changed from 0.5 m to 1 m, while the average value of the accuracy of the L horizontal coordinates was equal to around 0.7 m. The standard deviation of the ellipsoidal height h changed by 1 m to almost 4 m, while the average value of the accuracy of the vertical coordinate h was equal to around 1.6 m. The parameter of the median accuracy for the individual coordinate was equal to around 1 m for the B coordinate, 0.7 m for the L coordinate and 1.5 m for the ellipsoidal height. Moreover, it is noteworthy that the accuracy when appointing the geodetic longitude was higher than the accuracy of the geodetic latitude and ellipsoidal height.

Tab. 2

The comparison of accuracy parameters during the SBAS APV-I procedure

Parameter	Obtained accuracy for each BLh geodetic coordinates	Accuracy of SBAS APV-I procedure according to ICAO convention	Conclusions
Value	Dispersion of standard deviation in latitude was between 0.6 m and 2.4 m	16 m for horizontal plane	The obtained accuracy for latitude did not exceed the ICAO standard in the horizontal plane
	Dispersion of standard deviation in longitude was between 0.5 m and 1 m	16 m for horizontal plane	The obtained accuracy for longitude did not exceed the ICAO standard in the horizontal plane
	Dispersion of standard deviation in ellipsoidal height was between 1 m and 4 m	20 m for vertical plane	The obtained accuracy for the ellipsoidal height did not exceed the ICAO standard in the vertical plane

A comparison of the results of the geodetic BLh coordinates for the Cessna 172 aircraft and the ICAO's technical standards is presented in Table 2. The ICAO's technical standards were published in Annex 10 on radio navigation aids in the Chicago Convention [7]. Based on the obtained test results, it is possible to state that the values of the standard deviation in the coordinates of the Cessna 172 aircraft did not exceed the theoretical accuracies in the SBAS APV-I procedure. Regarding navigation in the horizontal plane, the latitude and longitude accuracy was definitely higher than 16 m. In the vertical plane, the obtained accuracy of the ellipsoidal height did not exceed 20 m. It is also necessary to emphasize that the obtained value of the standard deviation in the aircraft coordinates in the BLh ellipsoidal system can be utilized to the determine the parameter concerning the integrity of satellite positioning.

The values of the mean radial spherical error (MRSE) parameter for the conducted flight test are presented in Fig. 5. The values of the MRSE parameter were determined as follows [15]:

$$MRSE = \sqrt{mB^2 + mL^2 + mh^2} \quad (5)$$

The obtained value of the MRSE parameter was between 1.3 m and 4.7 m. Moreover, the average value of the MRSE parameter was equal to 2 m, while the median was equal to 1.9 m. The MRSE parameter is of special importance for locating aircraft in three-dimensional space.

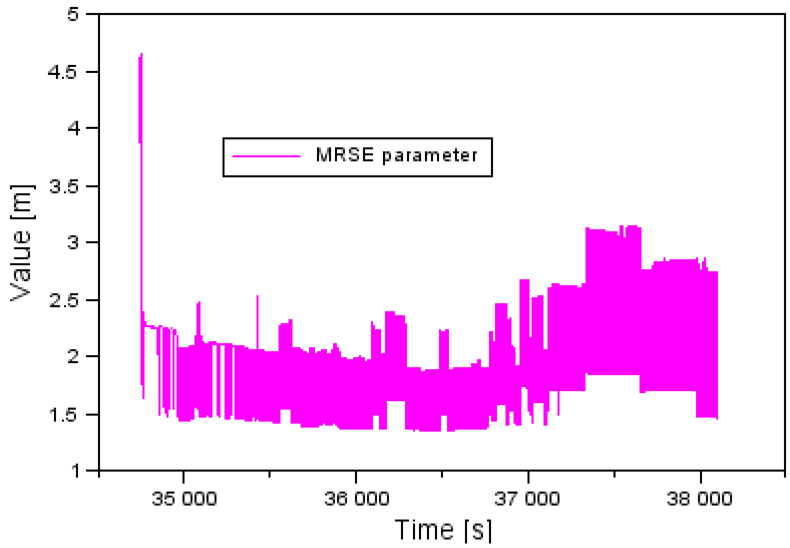

Fig. 5. The MRSE parameter values of during the flight test

Fig. 6 presents the safety level values of the flight operation in the form of the horizontal protection level (HPL) and the vertical protection level (VPL) parameters. Parameters concerning the integrity of satellite HPL and VPL positioning were determined by the following mathematical formula [11]:

$$\begin{cases} HPL = k_{HPL} \cdot \sqrt{mB^2 + mL^2} \\ VPL = k_{VPL} \cdot mh \end{cases} \quad (6)$$

where:

$k_{HPL} = 6$ (horizontal plane)

$k_{VPL} = 5.33$ (vertical plane)

The HPL and VPL safety levels parameters, which describe the integrity of the satellite positioning for the SBAS APV-I approach, are determined on the basis of the values of the accuracy of geodetic BLh coordinates. The HPL parameter assumed values between 4.7 m and 15 m. Moreover, the average value of the HPL parameter was equal to 7.3 m, while the median was appropriately 7 m. The obtained value of the VPL parameter was 5.6 m and 21.1 m, respectively. In addition, the average value of the VPL parameter was equal to 8.3 m, while the median was equal to 7.8 m. It is worth pointing out that HPL and VPL parameter values showed an increasing trend during the procedure of the final approach.

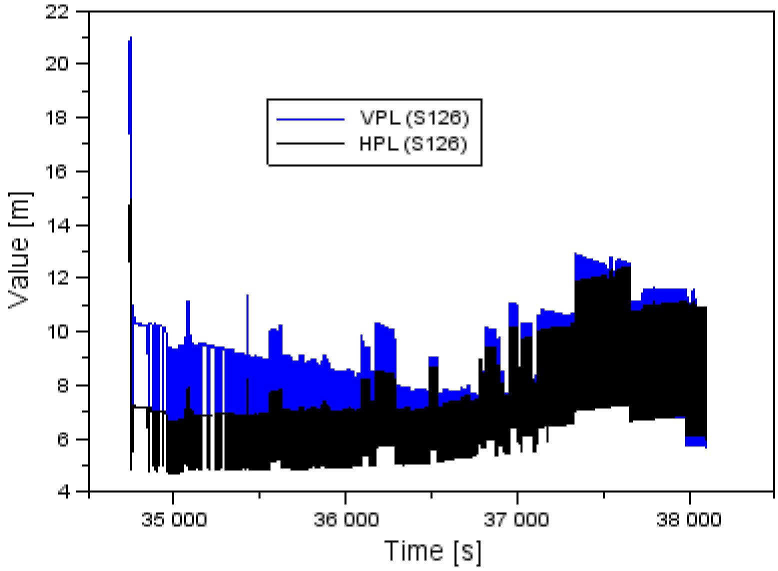

Fig. 6. The values of the HPL and VPL parameters

A comparison of the results related to the HPL and VPL integrity parameters and the ICAO's technical standards is presented in Table 3. The ICAO's technical standards were included in Annex 10 on radio navigation aids in the Chicago Convention [7]. Based on the obtained test results, it is possible to state that the HPL and VPL values did not exceed the border alerts in the SBAS APV-I procedure. As for the horizontal plane, the HPL parameter values were definitely smaller than the border level of the alarm, e.g., 40 m. On the vertical plane, the obtained results for the VPL parameter did not transgress the safety level of the flight operation for 50 m. It is also necessary to emphasize that the obtained HPL and VPL parameter values improve the integrity of the navigational solution for determining the aircraft's position during the legal procedure for the SBAS APV-I landing approach.

Tab. 3

Comparison of the integrity parameters during the SBAS APV-I procedure

Parameter	Obtained integrity for each of the BLh geodetic coordinates	Integrity of the SBAS APV-I procedure according to the ICAO convention	Conclusions
Value	Dispersion of the integrity term was between 4.7 m and 15 m	40 m for the horizontal plane	The obtained integrity parameter did not exceed the ICAO standard in the horizontal plane
	Dispersion of the integrity term was between 5.6 m and 21.1 m	50 m for the vertical plane	The obtained integrity parameter did not exceed the ICAO standard in the vertical plane

It is noteworthy that the continuity in determining the HPL and VPL parameters was maintained, while, in the course of calculations, no anomaly was detected in terms of exceeding border alerts. The parameters for the continuity of the integrity of the aircraft's position are described below [17]:

$$\begin{cases} HPL < HAL \\ VPL < VAL \end{cases} \tag{7}$$

where:
$HAL = 40 \quad m$ (maximum value of the alert in the horizontal plane)
$VAL = 50 \quad m$ (maximum value of the alert in the vertical plane)

The continuity parameter was lost when the value of the HPL exceeded 40 m and the VPL was greater than 50 m. Based on the presented results regarding the HPL and VPL parameters, the continuity of the integrity of the satellite positioning during the flight navigation was not lost.

4. CONCLUSIONS

In this article, the possibility of using the GNSS technique during an aircraft's SBAS APV-I landing procedure was presented. In the process, analyses of the parameters of accuracy, integrity, availability and continuity regarding this procedure were conducted. For the purposes of conducting the research experiment, observations and GPS navigation data and differential EGNOS corrections were used. Navigation and GPS observation data were stored in the memory of the Topcon Hiper Pro receiver during an ongoing flight test using a Cessna 172 aircraft at the airport in Dęblin on 1 June 2010. The differential EGNOS corrections from the S126 satellite were downloaded from the following web server: http://www.egnos-pro.esa.int/ems/index.html. The input data were used to recover the position of the Cessna 172 aircraft in the ellipsoidal BLh frame. RTKLIB software was used for the calculation, while the SPP research method was applied in order to set the aircraft's coordinates. This article also presented the trajectory of the aircraft in the ellipsoidal BLh, defined the ionosphere VTEC parameter, identified the availability constellation of the GPS/EGNOS satellites, and determined the navigational continuity needed to establish the aircraft's position. Furthermore, the accuracy in establishing the aircraft's position was determined, an MRSE parameter identified, and parameters of the HPL and VPL safety levels confirmed. Values of the accuracy and integrity parameters were compared with the technical standards published in Annex 10 of the Chicago Convention. According to the conducted examinations, it is possible to conclude that the calculation results met the technical parameter criteria for the SBAS APV-I approach. The availability of the constellation of GPS/EGNOS satellites equalled 100%, thereby ensuring continuity in determining the position of the aircraft. The parameters of the standard deviation in the coordinates of the aircraft did not exceed the accuracy of the limits for the procedure of the SBAS APV-I approach. Moreover, the HPL and VPL safety levels were below the border alert levels for the SBAS APV-I procedure. Future work is planned in order to check and verify the technical standards of the SBAS APV-I procedure for the aerodromes in the cities of Mielec and Chełm.

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