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RESEARCH OF ACCURACY OF THE AIRCRAFT POSITION USING THE GPS AND EGNOS SYSTEMS IN AIR TRANSPORT

The article presents and describes results of research in determination of the aircraft positioning accuracy with use of the GPS and EGNOS satellite systems in the air navigation. The article, in particular, makes a comparison of the designated aircraft coordinates in the GPS and EGNOS systems in relation to the reference position, determined from the precision differential RTK-OTF technique. The experimental test was conducted in Slovakia, in the vicinity of Kosice airport. In the test, a trial flight by Cessna aircraft was executed over the village of Bidovce (LZBD) in Slovakia, in East-Central Europe. Within the conducted investigations, the GPS and EGNOS positioning accuracies were determined in real time during an in-flight experimental test. Based on the conducted investigations, it was found that the accuracy of the GPS positioning in the air navigation equals ±10 m throughout the most part of the air test. In the same period the EGNOS positioning accuracy in air navigation is equal to ± 5 m.

Keywords: *EGNOS, GPS, ICAO, aviation test, accuracy*

1 Introduction

The ICAO has introduced global systems of the GNSS satellite navigation to be used in civil aviation, during the execution of air operations. Amongst the GNSS navigation systems, it is possible to distinguish the NAVSTAR GPS and GLONASS satellite systems. Furthermore, in order to improve the performance of the GNSS satellite systems in aviation, it is possible to exploit ABAS, SBAS and GBAS augmentation systems. The GPS satellite system allows determining the accuracy of the determined aircraft position in air navigation, as follows [1-2]:

- an average accuracy equals 9 m in the horizontal plane,
- an average accuracy equals 15 m in the vertical plane,
- the worst accuracy equals 17 m in the horizontal plane,
- the worst accuracy equals 37 m in the vertical plane.

In addition, the accuracy of the GPS system in accordance with the PBN recommendation in the air transport is determined for each stage of the flight path, as below [2-3]:

- en-route operation: 3.7 m in the horizontal plane, in the vertical plane there are no recommendations or technical standards,
- terminal operation: 0.74 km in the horizontal plane, in the vertical plane there are no recommendations or technical standards,
- initial approach: 220 m in the horizontal plane, in the vertical plane no recommendations or technical standards,
- indirect approach: 220 m in the horizontal plane, in the vertical plane no recommendations or technical standards,
- Non-Precision Approach (NPA): 220 m in the horizontal plane, in the vertical plane there are no recommendations or technical standards,
- airport departure: 220 m in the horizontal plane, in the vertical plane there are no recommendations or technical standards.

Moreover, the accuracy of the EGNOS system in accordance with the PBN recommendation in air transport is determined for each stage of the flight path, as below [2-3]:

- approach and landing operations with vertical guidance APV-I: 16 m in the horizontal plane, 20 m in the vertical plane,
- approach and landing operations with vertical guidance APV-II: 16 m in the horizontal plane, 8 m in the vertical plane,
- LPV200 approach: 16 m in the horizontal plane, 4 m in the vertical plane.

The aim of this study is to verify and determine the positioning accuracy of the aircraft, using the GPS system and the EGNOS system in air navigation. The research work is universal for conducting air navigation in the area of Slovakia. The obtained results are practical for the execution of the air operations in Slovakia, in East-Central Europe. Therefore, the GPS and EGNOS positioning accuracy, obtained in this paper, appear to be innovative for pilots and navigators in this part of Europe.

2 Mathematical model

The basic observation equation of the GPS positioning method in air navigation can be expressed as [4]:

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$$l = d + c \cdot (dtr - dts) + Ion + Trop + \mathrm{Re}l + TGD, \quad (1)$$

where:

l - pseudorange (code measurement) at the frequency of L1 in the GPS system,

d - geometrical distance between the satellite and the receiver, it takes into account the correction of the Sagnac effect,

$$d = \sqrt{(X - X_{GPS})^2 + (Y - Y_{GPS})^2 + (Z - Z_{GPS})^2}, \quad (2)$$

(X,Y,Z) - the aircraft coordinates, the parameters determined in the process of developing the GPS code observations,

$(X_{GPS}, Y_{GPS}, Z_{GPS})$ - coordinates of the GPS satellites in the geocentric XYZ frame are determined based on the model of a Kepler orbit,

c - speed of light,

dtr - correction of the receiver clock, parameter determined based on the aircraft coordinates,

dts - correction of the satellite clock bias, measured based on the polynomial 2nd degree from a GPS navigation message,

Ion - ionospheric correction, in the SPP method, determined based on the Klobuchar model,

$Trop$ - tropospheric correction, determined based on the deterministic model of a tropospheric delay,

$\mathrm{Re}l$ - relativistic effect, determined based on the navigation message data,

TGD - a group delay in sending a code measurement for GPS satellites based on the navigation message data.

The basic observation equation of the EGNOS positioning method in air navigation can be expressed, as [5]:

$$\begin{aligned} l = d^* + c \cdot (dtr - dts^*) + Ion^* + Trop^* + \\ + \mathrm{Re}l + TGD + PRC \end{aligned}, \quad (3)$$

where:

l - pseudorange (code measurement) at the frequency L1 in the GPS system,

d^*- geometrical distance between the satellite and the receiver, it takes into account the correction of the Sagnac effect as well as the fast-term and long-term corrections in the EGNOS system,

$$d^* = \sqrt{(X - X^*_{GPS})^2 + (Y - Y^*_{GPS})^2 + (Z - Z^*_{GPS})^2}, \quad (4)$$

(X, Y, Z)- coordinates of the aircraft, the parameters determined by using the EGNOS corrections,

$(X^*_{GPS}, Y^*_{GPS}, Z^*_{GPS})$ - coordinates of the GPS satellites in the geocentric XYZ frame are determined based on the model of a Kepler orbit, and also by using fast-term and long-term corrections in the EGNOS system,

c- speed of light,

dtr- correction of the receiver clock, parameter determined based on the aircraft coordinates,

dts^*- correction of satellite clock bias, measured based on the polynomial 2nd degree from a GPS navigation message, using the fast-term and long-term corrections in the EGNOS system,

Ion^* - ionospheric correction, determined from the regular grid model GRID, using polynomial interpolation parameter VTEC,

$Trop^*$ - tropospheric correction, determined from the model of the troposphere RTCA-MOPS,

$\mathrm{Re}l$ - relativistic effect, determined based on the navigation message data,

TGD - a group delay in sending a code measurement for GPS satellites based on the navigation message data,

PRC - fast-term corrections in the EGNOS system.

The unknown aircraft coordinates from Equations (1) and (2) in the XYZ geocentric frame are determined, as instructed by the ICAO, with the least squares method in the stochastic process. The stochastic process does take into account the weight of code measurements, typically in the function of the angle of elevation. The process of determining the aircraft coordinates is conducted for all the registered measuring epochs. In the case of conducting the air navigation, the aircraft coordinates should be expressed in the ellipsoidal BLh frame, as [6]:

$$\begin{bmatrix} B \\ L \\ h \end{bmatrix} = \begin{bmatrix} arc\tan\left(\frac{Z/\rho}{1-e^2}\right) \\ arc\tan\left(\frac{Y}{X}\right) \\ \frac{\rho}{\cos B} - R \end{bmatrix}, \quad (5)$$

where:

(a,b) - semi-major and semi-minor axes of the BLh ellipsoidal 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 aircraft's position in the BLh ellipsoidal frame,

B - Latitude,

L - Longitude,

h - ellipsoidal height.

The determined aircraft coordinates in the ellipsoidal BLh frame will form the foundation for further deliberations in this article. It should be stressed that based on Equation (3), it was possible to determine the position of the aircraft, separately for the GPS solution - see Equation (1), and independently for the EGNOS solution - Equation (2).

3 The research test

For the purposes of this publication, an air experiment, which involved the Cessna, was conducted in Bidovce (LZBD), Slovakia, in East-Central Europe [7]. The research experiment was performed jointly by the Faculty of

Figure 1 *The onboard receivers in the Cessna plane [photo by: Marek Grzegorzewski]*

Table 1 *Results of the standard deviation of the Cessna reference trajectory*

Parameter	Standard deviation for Latitude [m]	Standard deviation for Longitude [m]	Standard deviation for ellipsoidal height [m]
Minimum value	0.02	0.01	0.01
Maximum value	0.50	0.20	0.68
Mean value	0.04	0.01	0.10

Aeronautics of Deblin Air Force University and the Faculty of Aeronautics of Košice Technical University. A dual-frequency satellite receiver Septentrio AsteRx2 (see Figure 1) was mounted on board the Cessna. The GNSS navigation receivers recorded the GPS/EGNOS satellite observations in real time. The test flight took place in the vicinity of Kosice airport. En-route of the Cessna, there was one physical reference station CORS. Moreover, for the sake of the computations in the post-processing mode, two virtual reference stations in the ASG-EUPOS in the POZGEO-D service were generated. In this way, it was possible to recover the precise reference trajectory for the flight of the Cessna in the RTK mode for three independent computations in the OTF mode. Next, the Cessna reference position was averaged, as [8]:

$$B_{ref} = \frac{\sum_{i=1}^{n} B_{RTK-OTF,i}}{n}; L_{ref} = \frac{\sum_{i=1}^{n} L_{RTK-OTF,i}}{n}; \quad h_{ref} = \frac{\sum_{i=1}^{n} h_{RTK-OTF,i}}{n}, \tag{6}$$

where:
n = 3,
i = 1,2,3,
$B_{RTK-OTF,i}$ - estimated Latitude from the RTK technique from a single OTF solution,
$L_{RTK-OTF,i}$ - estimated Longitude from the RTK technique from a single OTF solution,
$h_{RTK-OTF,i}$ - estimated ellipsoidal height from the RTK technique from a single OTF solution,
B_{ref} - estimated reference trajectory for Latitude,
L_{ref} - estimated reference trajectory for Longitude
h_{ref} - estimated reference trajectory for ellipsoidal height.

For the reference position, the positioning accuracies were determined, as well in the form of standard deviations of coordinates (B_{ref}, L_{ref}, h_{ref}). The values of standard deviations of reference coordinates (B_{ref}, L_{ref}, h_{ref}) were determined based on the relationship [9]:

$$mB_{ref} = \frac{(B_{RTK-OTF,i} - B_{ref})}{n-1}; \quad mL_{ref} = \frac{(L_{RTK-OTF,i} - L_{ref})}{n-1}; \quad , mh_{ref} = \frac{(h_{RTK-OTF,i} - h_{ref})}{n-1}, \tag{7}$$

where:
mB_{ref} - standard deviation of the reference trajectory for Latitude,
mL_{ref} - standard deviation of the reference trajectory for Longitude,
mh_{ref} - standard deviation of the reference trajectory for ellipsoidal height.

Table 1 shows the values of standard deviations for the designated precision trajectory of the Cessna flight reference. The average value of the standard deviation is 0.04 m for coordinate B, 0.01 m for coordinate L, and 0.10 m for coordinate h. In turn, the lowest values of standard deviations equal respectively: 0.02m for coordinate B, 0.01 m for coordinate L and 0.01 m for coordinate h. The highest values of standard deviations are 0.50 m for the coordinate B, 0.20 m for the coordinate L and 0.68 m for the coordinate h, respectively.

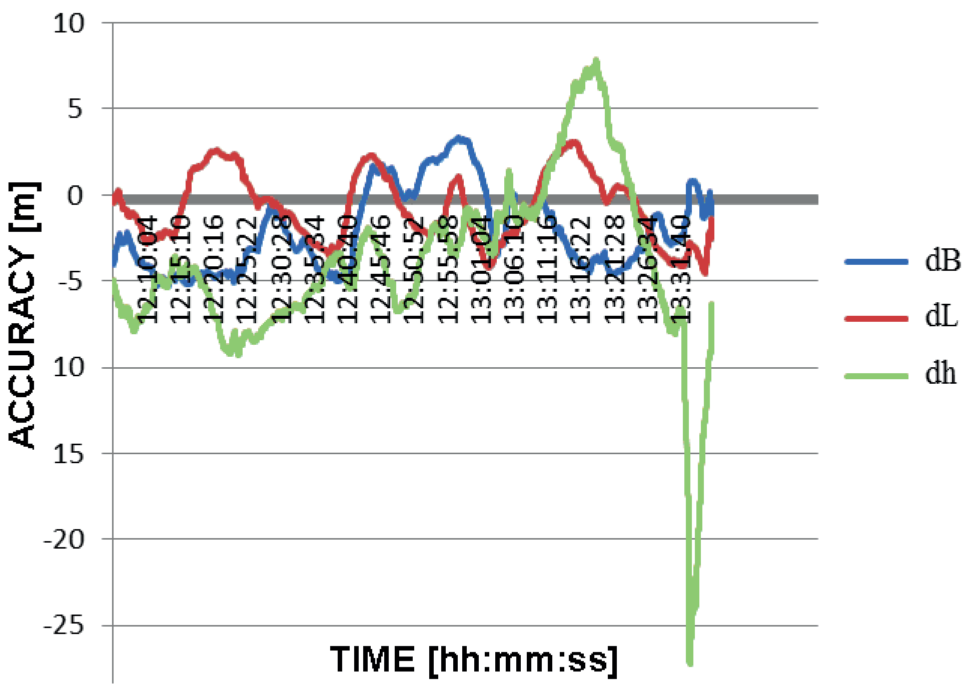

Figure 2 *Accuracy of the Cessna plane position based on the GPS solution*

Table 2 *Comparison of the GPS accuracy to the ICAO technical standards*

Parameter	GPS solution	ICAO technical standards	Conclusion
Accuracy of Latitude	± 5 m	17 m	did not exceed the accuracy limit of GPS system in aviation
Accuracy of Longitude	± 5 m	17 m	did not exceed the accuracy limit of GPS system in aviation
Accuracy of ellipsoidal height	± 27 m	37 m	did not exceed the accuracy limit of GPS system in aviation

4 Results and discussion

In the framework of the research into the air experiment, first and foremost, it was possible to determine the accuracy of the GPS positioning in the air navigation. For this purpose, a comparison was made between the ellipsoidal BLh coordinates determined from Equations (1) and (5), and precise trajectory coordinates of the Cessna flight reference from Equation (6), as [8, 10-11]:

$$\begin{cases} dB = B_{GPS} - B_{ref} \\ dL = L_{GPS} - L_{ref} \\ dh = h_{GPS} - h_{ref} \end{cases}, \qquad (8)$$

where:
B_{GPS} - estimated Latitude from the GPS solution, based on Equation (1) and (3),
L_{GPS} - estimated Longitude from the GPS solution, based on Equation (1) and (3),
h_{GPS} - estimated ellipsoidal height from the GPS solution, based on Equations (1) and (5),
dB - accuracy of aircraft position for the Latitude axis in the GPS system,
dL - accuracy of aircraft position for the Longitude axis in the GPS system,
dh - accuracy of aircraft position for the ellipsoidal height axis in the GPS system.

Figure 2 shows values of the GPS satellite positioning accuracy in the air navigation in the research test. The accuracy of the horizontal coordinate B changes from -5 m to +3.5 m. Besides that, the accuracy of the horizontal coordinate L changes from -5 m to +3 m. In addition, the accuracy of the vertical coordinate h changes from -27 m to +7.5 m. However, for the major part of the duration of the flight, the accuracy of the vertical h ranges from -9 m to +7.5 m.

Table 2 shows results of the GPS positioning accuracy in aviation in relation to the limit error values of the aircraft

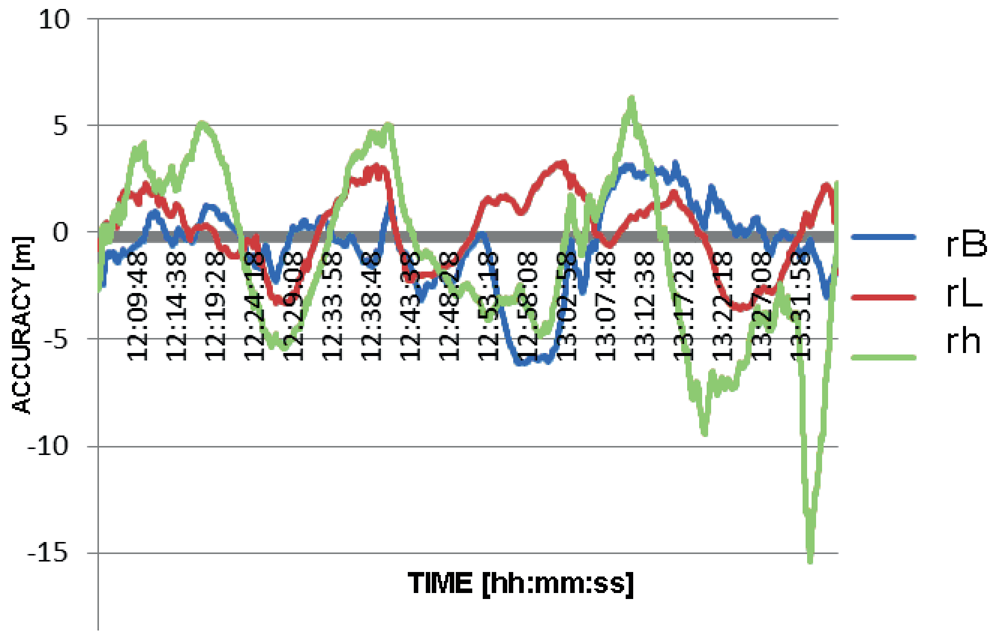

Figure 3 *Accuracy of the Cessna plane position based on the EGNOS solution*

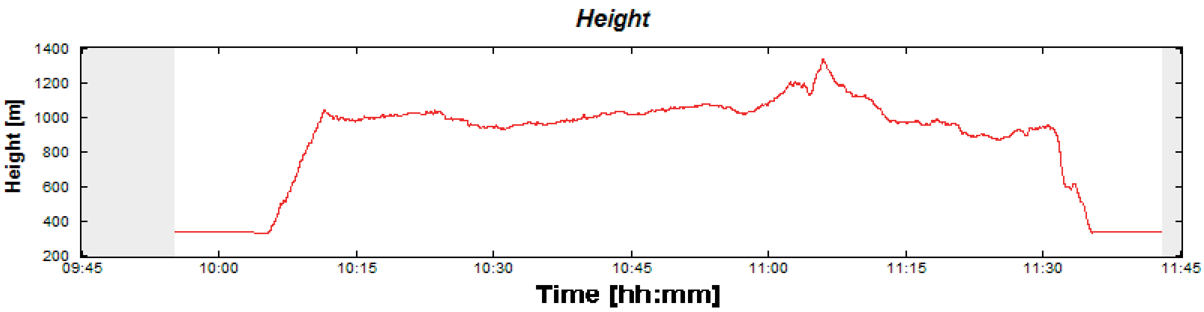

Figure 4 *The vertical profile of the Cessna plane at a flight test*

position in accordance with the ICAO recommendations. Based on the comparison, it can be seen that:

- the lowest accuracy of the horizontal coordinate B in the air test equalled ± 5 m and it did not exceed the limit value of 17 m for navigating in the horizontal plane LNAV,
- the lowest accuracy of the horizontal coordinate L in the air test equalled ± 5 m and it did not exceed the limit value of 17 m for navigating in the horizontal plane LNAV,
- the lowest accuracy of the vertical coordinate h in the air test equalled ± 27 m and it did not exceed the limit value of 37 m for navigating in the horizontal plane LNAV.

Therefore, the obtained results, with regard to the GPS positioning accuracy, meet the ICAO recommendations for using this sensor in aviation to conduct the LNAV horizontal and VNAV vertical navigation [12].

In the second stage of the research, the accuracy of the EGNOS positioning in the air navigation was determined. For this purpose, a comparison was made between the ellipsoidal BLh coordinates determined from Equations (3) and (5), and precise trajectory coordinates of the Cessna flight from Equation (6), as [8, 10-11]:

$$\begin{cases} rB = B_{EGNOS} - B_{ref} \\ rL = L_{EGNOS} - L_{ref} \\ rh = h_{EGNOS} - h_{ref} \end{cases}, \qquad (9)$$

where:

B_{EGNOS} - estimated Latitude from the EGNOS solution, based on Equation (3) and (5),

L_{EGNOS} - estimated Longitude from the EGNOS solution, based on Equation (3) and (5),

h_{EGNOS} - estimated ellipsoidal height from the EGNOS solution, based on Equation (3) and (5),

rB - accuracy of aircraft position for the Latitude axis, based on the EGNOS solution,

rL - accuracy of aircraft position for the Longitude axis, based on the EGNOS solution,

rh - accuracy of aircraft position for the ellipsoidal height axis, based on the EGNOS solution.

***Table 3** Comparison of the GPS accuracy at phase of landing to the ICAO technical standards of NPA procedure*

Parameter	GPS solution	ICAO technical standards	Conclusion
Accuracy of Latitude	± 3 m	220 m	did not exceed the accuracy limit of GPS system in NPA procedure
Accuracy of Longitude	± 5 m	220 m	did not exceed the accuracy limit of GPS system in NPA procedure
Accuracy of ellipsoidal height	±27 m	Not active	No comparison

***Table 4** Comparison of the EGNOS accuracy at phase of landing to the ICAO technical standards of APV-I procedure*

Parameter	EGNOS solution	ICAO technical standards	Conclusion
Accuracy of Latitude	±3 m	16	did not exceed the accuracy limit of EGNOS system in APV-I procedure
Accuracy of Longitude	±3 m	16	did not exceed the accuracy limit of EGNOS system in APV-I procedure
Accuracy of ellipsoidal height	±15 m	20	did not exceed the accuracy limit of EGNOS system in APV-I procedure

Figure 3 shows values of the positioning accuracy of the EGNOS satellite navigation in the experimental test. The accuracy of the horizontal coordinate B changes from -6 m to +3.5 m. Besides that, the accuracy of the horizontal coordinate L changes from -3 m to +3.5 m. In addition, the accuracy of the vertical coordinate h changes from -15 m to +6.5 m. However, for the major part of the duration of the flight, the accuracy of the vertical coordinate h ranges from -9 m to +6.5 m.

Figure 4 shows a vertical flight trajectory during the air test. The approach to landing of the Cessna started at 11:30:00 hours in accordance with the GPST. At the same time, the GPS positioning accuracy was as follows: ± 3 m for the component B, ± 5 m for the component L, ± 27 m for the component h. It can be observed that in the case of the h coordinate, there was a dramatic degradation of the GPS accuracy of positioning in aviation. This phenomenon proves very dangerous for the execution of the approach to landing procedure by an aircraft. In the EGNOS solution, the positioning accuracy during the approach to landing was as follows: ± 3 m for the component B, ± 3 m for the component L, ± 15 m for the component h. Similarly to the GPS solution, in the EGNOS solution there was also a degradation in the positioning accuracy of the vertical coordinate h.

Table 3 presents results of the GPS positioning accuracy in the NPA procedure in relation to the ICAO recommendations. Based on the comparison, it can be observed that:

- the lowest accuracy of the horizontal coordinate B in the approach to landing procedure equalled ± 3 m and it did not exceed the limit value of 220 m for navigating in the horizontal plane LNAV,
- the lowest accuracy of the horizontal coordinate L in the approach to landing procedure equalled ± 5 m and it did not exceed the limit value of 220 m for navigating in the horizontal plane LNAV,
- the lowest accuracy of the horizontal coordinate h in the approach to landing procedure equalled ± 27 m; however the ICAO technical standards do not define the limit of accuracy in the vertical plane, therefore the comparison is not possible in this case.

Therefore, the obtained results in the GPS positioning accuracy with regard to the APV-I procedure meet the ICAO recommendations for navigating in the horizontal plane. The comparison was not possible in the vertical plane due to the lack of the ICAO recommendations [3].

Table 4 presents results of the EGNOS positioning accuracy in the approach to landing procedure with the APV-I vertical guidance in relation to the ICAO recommendations. Based on the comparison, it can be observed that:

- the lowest accuracy of the horizontal coordinate B in the approach to landing procedure equalled ± 3 m and it did not exceed the limit value of 16 m for navigating in the horizontal plane LNAV,
- the lowest accuracy of the horizontal coordinate L in the approach to landing procedure equalled ± 3 m and it did not exceed the limit value of 16 m for navigating in the horizontal plane LNAV,
- the lowest accuracy of the horizontal coordinate h in the approach to landing procedure equalled ± 15 m and it did not exceed the limit value of 20 m for navigating in the vertical plane LNAV.

Therefore, the obtained results in the EGNOS positioning accuracy with regard to the APV-I procedure meet the ICAO recommendations for navigating in the horizontal and vertical planes. It can be concluded that the findings are satisfactory and confirm the ICAO accuracy requirements in the air transport [3].

5 Conclusions

The paper discusses and presents the results of research which focused on determining the GPS and EGNOSS positioning accuracy in air navigation. The paper presents accuracy findings obtained during the operation of the GNSS receiver in an air experiment. The results of the accuracies were determined for the readings of aircraft positions on the receiver Septentrio AsteRx2e. The navigation receiver Septentrio AsteRx2 was fixed in a Cessna aircraft during a flight test carried out in Slovakia, in the village of Bidovce (LZBD). The determined coordinates were referenced to a precise reference position, designated in the differential RTK-OTF technique. The precise aircraft trajectory from the RTK-OTF technique was estimated with standard deviation better than 0.10 m. Based on the conducted investigations, it was found that the accuracy of the GPS positioning in aviation equals ±10 m and of the EGNOS system, it is ±5 m. The obtained results of accuracy of the GPS system does not exceed the limit values of the aircraft positioning according to the ICAO recommendations of. 17 m for lateral navigation and 37 m for vertical navigation. In addition, the paper compares the accuracy findings of the GPS positioning and EGNOS positioning with the ICAO technical requirements with regard to limit values in the NPA procedure and an approach with the AVP-I vertical guidance. The worst accuracy of the GPS positioning in the horizontal plane equals to 3-5 m and it is higher than the ICAO recommendations of 220 m. Moreover, the worst accuracy of the GPS positioning in the vertical plane equals to 27 m. The worst accuracy of the EGNOS positioning in the horizontal plane in the APV-I procedure equals to 3 m and it is higher than the ICAO recommendations of 16 m. In addition, the EGNOS accuracy positioning in the vertical plane in APV-I procedure does not exceed the limit value of the aircraft positioning according to the ICAO recommendations of 20 m. The obtained results of the aircraft positioning show that the GPS system and EGNOS system can be applied in the air navigation.

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Annex

Abbreviation	Full name
GPS	Global Positioning System
EGNOS	European Geostationary Navigation Overlay Service
RTK-OTF	Real Time Kinemtic - On The Fly
ICAO	International Civil Aviation Organization
GLONASS	Global Navigation Satellite System
PBN	Performance-Based Navigation
NPA	Non-Precision Approach
APV	Approach with Vertical Guidance
CORS	Continuously Operating Reference Stations
LNAV	Lateral Navigation
VNAV	Vertical Navigation
SBAS	Satellite Based Augmentation System
ABAS	Aircraft Based Augmentation System
GBAS	Ground Based Augmentation System
GNSS	Global Navigation Satellite System
GPST	GPS Time
VTEC	Vertical TEC
ASG-EUPOS	Aktywna Siec Geodezyjna EUPOS
RTCA-MOPS	Radio Technical Commission for Aeronautics-Minimum Operational Performance Standards