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APPLICATION OF THE GLONASS CODE OBSERVATIONS FOR THE DESIGNATION OF COORDINATES OF AN AIRCRAFT IN FLIGHT TEST MODE: A CASE STUDY

Summary. The aim of this article is to present the results of GLONASS positioning in kinematic mode in air navigation. The flight experiment was conducted at Dęblin Airfield on a Cessna 172 aircraft. The aircraft position was recovered on the basis of the single-point positioning (SPP) method of the GLONASS code observations. The numerical computations of aircraft coordinates were executed in the RTKPOST library of the RTKLIB software. The standard deviations in aircraft position in a BLh geodetic frame were checked with the ICAO standards on civil aviation for the GLONASS system. The typical accuracy of aircraft positioning on the horizontal plane is better than 12 m, whereas, on a vertical plane, it is better than 17 m. In this paper, standard deviations in aircraft position were also compared with the theoretical accuracy of the non-precision approach (NPA) landing procedure for the GNSS system. In this paper, the MRSE parameter was also calculated during the flight test.

Keywords: GLONASS; ICAO; air transport; accuracy; SPP method

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1. INTRODUCTION

The GLONASS system is part of the GNSS systems, along with the GPS, Galileo and BeiDou systems [7]. Moreover, the GLONASS system can be applied to a number of scientific areas as another navigation system, e.g., in geodesy and cartography, mobile mapping, geodynamics, geophysics, atmosphere monitoring, cosmic weather, meteorology, telecommunication and radio communications, logistics and transport, precise agriculture, civil engineering, GIS, time transfer and navigation. In the navigation area, the GLONASS system is still implemented in automobiles, as well as in marine and air navigation. Unfortunately, it is very hard to obtain official data about standard positioning services for civil users in the GLONASS system. In addition, the typical accuracy of the user's position should be higher than 100 m on the horizontal plane and 156 m on the vertical plane [5]. In [9], the horizontal accuracy equals 28 m, and 60 m for the vertical coordinate, whereas, on [14], the horizontal accuracy exceeds 55 m, and 70 m in the vertical plane. The ICAO suggests that the accuracy of the user's position in the GLONASS system ranges between 5 and 12 m on the horizontal plane and between 9 and 25 m on the vertical plane [6]. These values are referenced to satellites of the GLONASS-M generation and currently being implemented in civil aviation. The accuracy of the user's position in the GLONASS system, in accordance with the ICAO standards, is estimated with a probability of 95%; however, the ionosphere and receiver errors are not included in this criterion. In civil aviation, availability and integrity terms are also recommended to be used in the GLONASS system. The average value of the availability parameter is over 99%, while the integrity parameter should exceed 99.7% for the GLONASS satellites' constellation.

The authors also present the results of GLONASS positioning in a kinematic test in civil aviation. The kinematic test was conducted using a Cessna 172 aircraft at the military airfield in Dęblin on 1 June 2010. The aircraft's trajectory was recovered based on the GLONASS code observations for the SPP method. The raw GLONASS observations were collected via a Topcon Hiper Pro receiver, which was installed in the pilot's cabin. The aircraft's coordinates and their accuracy were calculated in the RTKPOST library of the RTKLIB software. The least-squares estimation was applied in the adjustment processing of the GLONASS code observations at an interval of 1 s. The article is divided into five sections: Introduction, Methodology of Research, Research Experiment and Results, Discussion and Conclusions.

2. METHODOLOGY OF RESEARCH

In this section, the mathematical formulations for a recovery of the aircraft position are presented. The mathematical formulation is focused on the undifferenced positioning method, i.e., the SPP method. The basic equations for the presented method are expressed below [1]:

$$l = d + c \cdot (dtr - dts) + Ion + Trop + \mathrm{Re}\,l + SIFCB_{L1} + RIFCB_{L1} + \varepsilon_l \tag{1}$$

where:

l - pseudorange value (C/A or P code) at the first frequency in the GLONASS system, with the precise P code recovered using the following equation: $P1 = C1 + DCB_{P1C1}$ [3],

DCB_{P1C1} - DCB instrumental biases between P and C/A code at the first frequency in the GLONASS system (the DCB values are distributed in the CODE Analysis Center in Switzerland [12]),
d - geometric distance between the satellite and the receiver,
$d = \sqrt{(x - X_{GLO})^2 + (y - Y_{GLO})^2 + (z - Z_{GLO})^2}$,
(x, y, z) - aircraft's coordinates in the ECEF frame,
$(X_{GLO}, Y_{GLO}, Z_{GLO})$ - GLONASS satellite coordinates,
c - speed of light,
dtr - receiver clock bias,
dts - satellite clock bias,
Ion - ionosphere delay,
$Trop$ - troposphere delay,
$\mathrm{Re}\,l$ - relativistic effect,
$SIFCB_{L1}$ - satellite inter-frequency code bias (IFCB), referenced to the first frequency in the GLONASS system,
$RIFCB_{L1}$ - receiver ICFB, referenced to the first frequency in GLONASS system,
ε_l - measurement noise and multipath effect in the SPP method.

In Equation (1), the number of unknown parameters equals four (e.g., the aircraft's coordinates = three parameters and the receiver clock bias = one parameter). The remaining terms in Equation (1) are modelled as follows:
- The GLONASS satellite coordinates are calculated using the Lagrange polynomial based on the precise ephemeris file or the applied fourth-order Runge-Kutta method based on the broadcast ephemeris file.
- The satellite coordinates must be referenced to the emission time of the pseudorange (e.g., the time of the pseudorange travelling through the atmosphere and the Sagnac effect are applied in this algorithm).
- The satellite clock bias is calculated using the Lagrange polynomial based on the precise ephemeris file or the applied data from the broadcast message.
- The satellite clock bias is also corrected using information about the relativistic effect.
- The relativistic effect in the GLONASS system can be obtained using data about the satellite position and velocity from the precise ephemeris file or the broadcast message.
- The ionosphere delay is evaluated using the Klobuchar model.
- The troposphere delay is estimated using the deterministic model (e.g., Hopfield, simple or Saastamoinen).
- The measurement noise in Equation (1) is neglected.
- The multipath effect in Equation (1) is neglected.
- The GLONASS navigation message does not include any information about IFCBs; the IFCB parameters are estimated for satellites and receivers using a geometry-free linear combination; currently the IFCB parameters are published at the website of the CODE Analysis Center.

The unknown parameters in Equation (1) are solved based on the least-squares estimation in adjustment processing of the GLONASS code observations for each measurement epoch, as per below [5]:

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

where:
$\mathbf{Qx}$ - vector with unknown parameters,
$\mathbf{Qx} = [x; y; z; c \cdot dtr]^T$,
$(x; y; z)$ - unknown aircraft's coordinates,
$\mathbf{N} = \mathbf{A}^{\mathbf{T}} \cdot \mathbf{p} \cdot \mathbf{A}$ - 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 that includes the difference between observations and modelled parameters,
$m0$ - standard error of unit weight a posteriori,
n - number of observations,
k - number of unknown parameters,
$\mathbf{v}$ - vector of residuals,
$\mathbf{m_{Qx}}$ - standard deviations for unknown parameters, with parameter $\mathbf{m_{Qx}}$ referenced to the ECEF frame.

The standard deviations $\mathbf{m_{Qx}}$ can also be expressed in the BLh geodetic frame BLh, as per below [8]:

$$\begin{cases} mB = \sqrt{\mathbf{m_{BLh}}(1,1)} \\ mL = \sqrt{\mathbf{m_{BLh}}(2,2)} \\ mh = \sqrt{\mathbf{m_{BLh}}(3,3)} \end{cases} \tag{3}$$

where:
$\mathbf{m_{BLh}}$ - covariance matrix of the aircraft's coordinates in the geodetic frame (BLh),
$\mathbf{m_{BLh}} = \mathbf{R} \cdot \mathbf{m_{Qx}} \cdot \mathbf{R}^{\mathbf{T}}$,
$\mathbf{R}$ - transition matrix from geocentric (XYZ) to geodetic frame (BLh),
mB - standard deviation for latitude,
mL - standard deviation for longitude,
mh - standard deviation for ellipsoidal height.

3. RESEARCH EXPERIMENT AND RESULTS

In this section, the research experiment is described and the results of GLONASS positioning in the kinematic test are presented. The flight experiment was conducted on a Cessna 172 aircraft at the military airfield in Dęblin on 1 June 2010 (see Fig. 1). The flight experiment was planned between 09:39:04 and 10:35:03 GPS time.

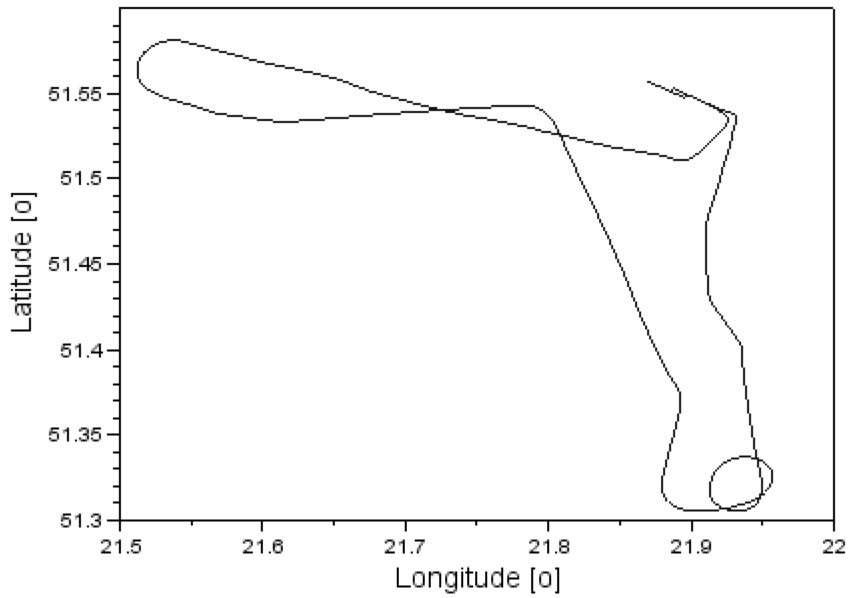

Fig. 1. The horizontal trajectory of the Cessna 172 aircraft

The aircraft position was recovered based on the GLONASS code observations with a time interval of 1 s. The raw GLONASS observations were collected using a Topcon Hiper Pro receiver, which was installed in the pilot’s cabin. The Topcon Hiper Pro receiver also saved the GPS observations, although they were not used in the computations. The raw GPS data were removed from RINEX file using the teqc program [2].

Data available on 01-06-2010

Total satellites in constellation:	23 SC
Operational:	21 SC
In commissioning phase:	0 SC
In maintenance:	0 SC
Spares:	2 SC
In decommissioning phase:	0 SC
Changes in spacecrafts status detected:	No
Integral availability global:	98.6%
Integral availability on Russian territory:	100.0%

Fig. 2. Status of the GLONASS satellites’ constellation on 01.06.2010 [13]

Fig. 2 presents the status of the GLONASS satellites' constellation on 1 June 2010. The number of available satellites equals 21, all of which belong to the GLONASS-M generation. In addition, two GLONASS-M satellites were in a spare phase. The marker of the operational GLONASS satellites is presented in Fig. 3. None of the GLONASS satellites experienced any temporary breaks on that day [13].

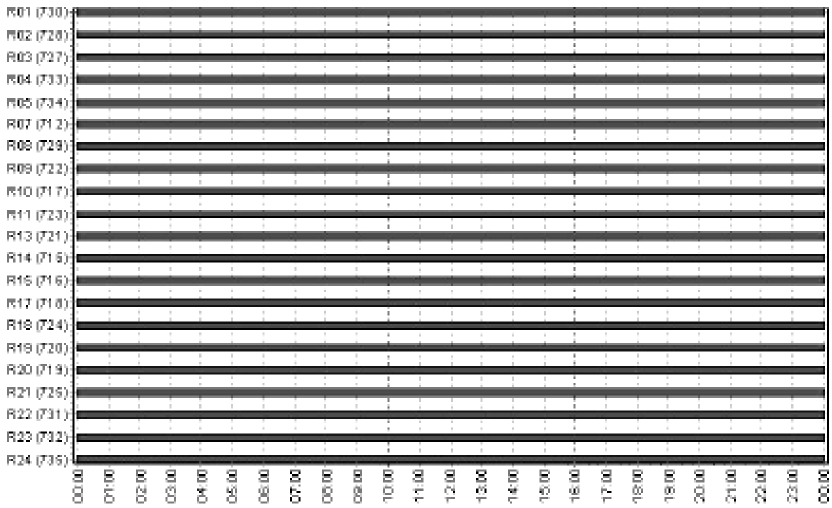

Fig. 3. Number of GLONASS satellites [13]

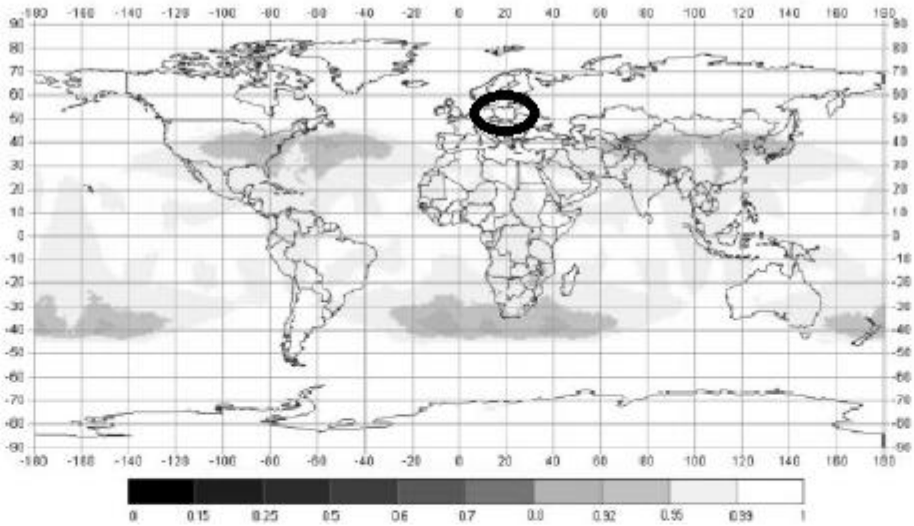

Fig. 4. Availability of the GLONASS satellites [13]

Fig. 4 presents the status of the GLONASS satellites' constellation. Across Poland, the availability parameter of the GLONASS system is over 99%, similar to ICAO standards. The number of visible GLONASS satellites equals nine for this experiment, i.e., R01, R02, R03, R10, R11, R13, R18, R19 and R20.

In the research experiment, only the GLONASS code observations were applied to the aircraft position determination process. The aircraft's coordinates were determined based on the SPP method in the RTKPOST module in the RTKLIB software. The RTKLIB software is an "open-source" programme, for which the source code was written in Borland C++ language. Currently, the RTKLIB package can apply GPS, GLONASS, Galileo, BeiDou and SBAS observations to the adjustment processing of GNSS data. The initial parameters and models of the SPP method in the RTKLIB software were configured as per below [11]:

- Positioning mode: single
- Elevation mask: 5°
- Source of ionosphere delay: Klobuchar model
- Source of troposphere delay: Saastamoinen model
- Source of satellite coordinates and clocks: broadcast ephemeris
- Methods of estimation of the GLONASS satellites' position: Runge-Kutta fourth-order method
- IFCBs: based on the product from CODE
- Relativistic effect: applied
- Phase centre offset/variation: based on the ANTEX file
- Earth rotation correction, Sagnac effect: applied
- Reference frame: WGS-84 (a seven-parameter transformation between PZ-90.02 and WGS-84 was applied)
- Computation mode: postprocessing
- Computation solution: least-squares estimation
- GNSS system: GLONASS
- GNSS observations: L1-C/A GLONASS code observations
- Adjustment processing: applied
- Interval of computation: 1 s
- GNSS time: GPS time, based on the RINEX file

Figs. 5, 6 and 7 present the standard deviations of the aircraft's coordinates in the BLh geodetic frame. The accuracy of the latitude in the SPP method equals 4.1 m, ranging from 0.3 to 8.1 m. Furthermore, the median parameter for the accuracy of the geodetic latitude coordinate is over 3.8 m. It should be pointed out that over 85% of the results of the accuracy coordinate (B) are higher than 4 m. On the other hand, over 91% of the accuracy coordinate (B) results do not exceed 5 m.

In the case of longitude, the accuracy amounts to 5.4 m within a range between 4.7 and 11.3 m. The statistical value of the median for the accuracy results of the geodesic longitude coordinate is nearly 5 m. Approximately 57% of the results of the accuracy of the coordinate of geodetic longitude L are greater than 5 m. Approximately 81% of the results with regard to the accuracy of the geodetic longitude L coordinate are greater than 6 m. In addition, approximately 96% of the results of the accuracy of the geodetic longitude L coordinate do not exceed 7 m. The average value of the standard deviation for latitude and longitude in the SPP method exceeds 12 m, which is the official level of accuracy in civil aviation for the GLONASS system in the ICAO.

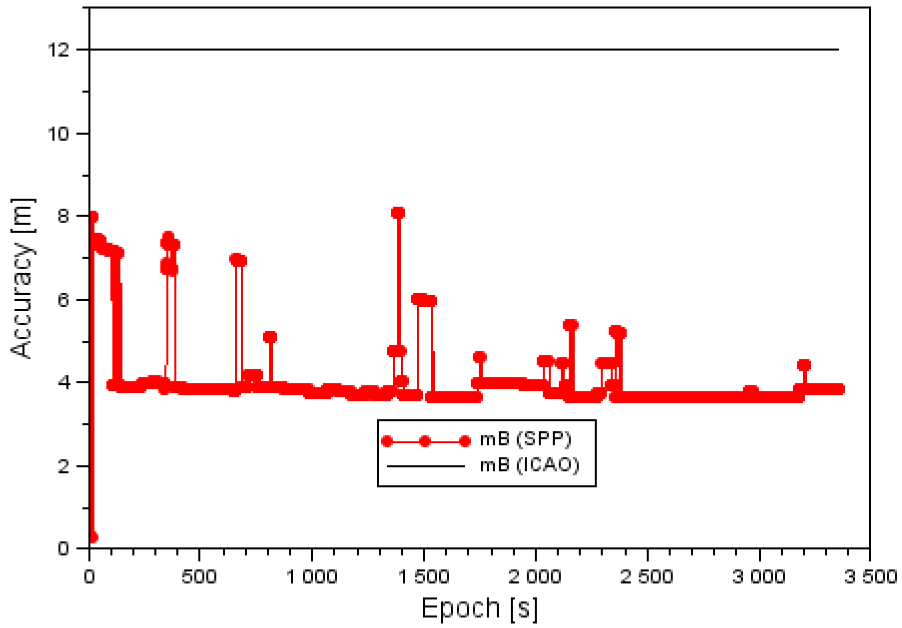

Fig. 5. Latitude accuracy of the Cessna 172 aircraft

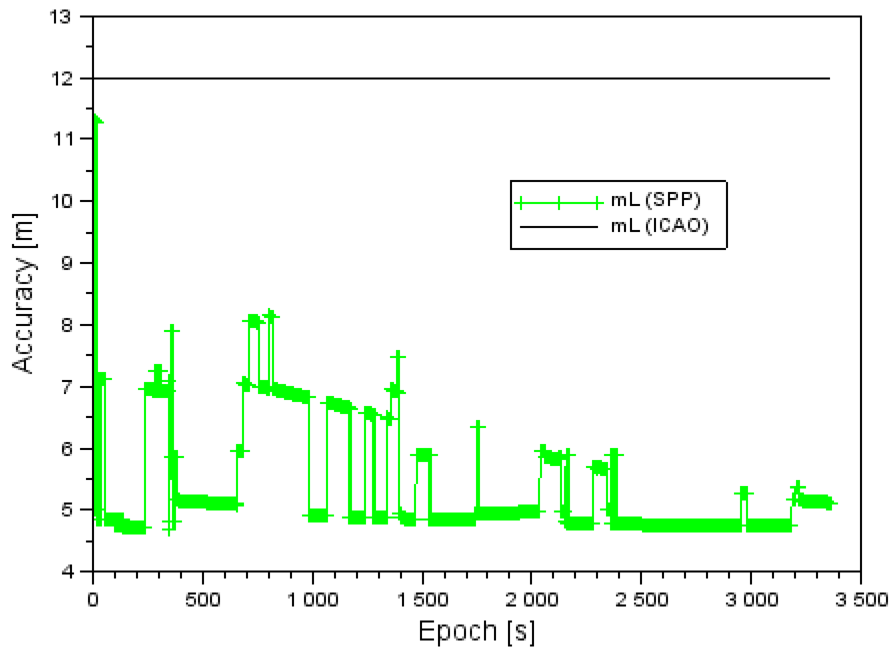

Fig. 6. Longitude accuracy for the Cessna 172 aircraft

The accuracy of ellipsoidal height in the SPP method is about 8.8 m, with the magnitude order being between 6.8 and 16.5 m. Furthermore, the median parameter for the accuracy of ellipsoidal height h is equal to approximately 8.7 m. It should be pointed out that only 26% of the accuracy results of ellipsoidal height h are higher than 8 m. On the other hand, over 94% of the accuracy results of ellipsoidal height h do not exceed the level of 10 m. In each measurement epoch, the accuracy of ellipsoidal height does not exceed the ICAO aircraft position standard on the vertical plane (i.e., 25 m). Based on the values in Figs. 5, 6 and 7, the accuracy of the aircraft position is in accordance with the ICAO standards for GLONASS-M satellites.

The obtained results of the accuracy of aircraft positioning by means of the SPP method are of paramount importance when it comes to the certification and handover to operation of the GLONASS system in civil aviation. The technical standards, which have been implemented by the ICAO, are designed to determine the possible use of the GLONASS system for civil aviation. The ICAO recommendations published in Appendix 10, Volume I, entitled "Radionavigation aids", are designed to use satellite signals from satellites of the GLONASS-M generation for the precise positioning of aircraft in air navigation. It needs to be observed that, in civil aviation, the ICAO recommendations permit the generally available L1-C/A signal for the GLONASS system. This signal is modulated by using the frequency division multiple access technique for the 1.6-GHz frequency band. The limits of the accuracy of the set aircraft position by means of the GLONASS system are specified in the technical standards of the ICAO through the parameters of the navigation error position on the vertical and horizontal planes. For navigation on the horizontal plane, the limit of accuracy ranges from 5 to 12 m, with a confidence level of 95%. On the other hand, for navigation on the vertical plane, the limit of accuracy ranges from 9 to 25 m, with a confidence level of 95%. Furthermore, the accuracy of the precise time transfer in the GLONASS system equals 700 ns for a confidence level of 95%. The limit of accuracy for determining the pseudorange measurement error in the GLONASS system even reaches 18 m. On the other hand, the availability of the GLONASS system across the globe should be 99% for navigation on both the horizontal and the vertical planes. However, the reliability of the GLONASS system in civil aviation must not be lower than 99.7% [6].

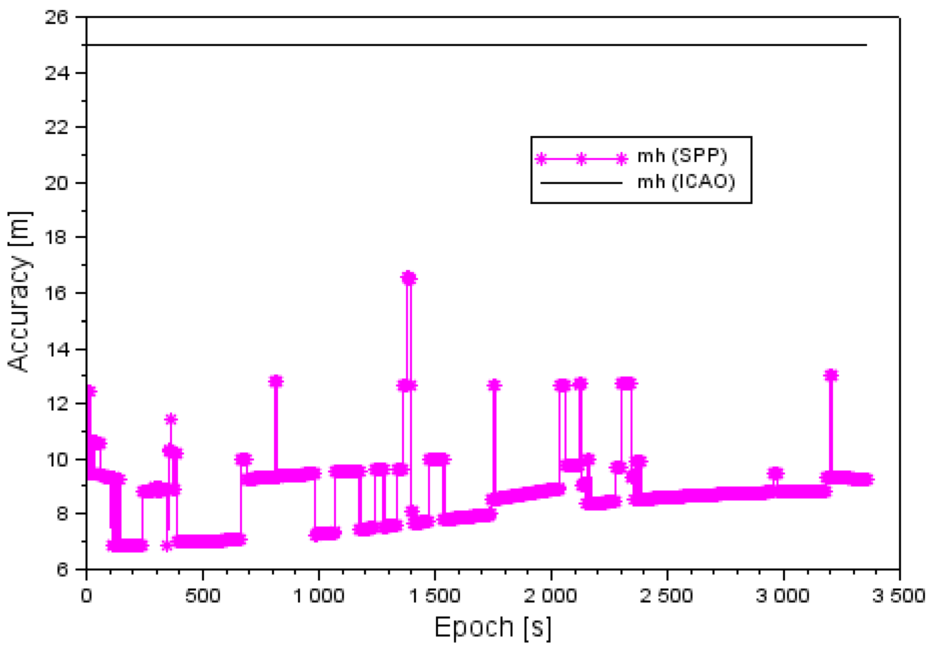

Fig. 7. The accuracy of ellipsoidal height of the Cessna 172 aircraft

Fig. 8 presents the values of the mean radial spherical error (MRSE) parameter in 3D space, based on the SPP solution. The MRSE parameter in Fig. 8 is estimated as per below [10]:

$$MRSE = \sqrt{mB^2 + mL^2 + mh^2} \tag{4}$$

The average value of the MRSE term equals 11.1 m, with the range of 9.1 to 19.9 m. In addition, the average value of the median for the MRSE parameter is 10.6 m. Approximately 26% of the results for MRSE parameter accuracy are higher than 10 m. On the other hand, approximately 74% of the results for MRSE parameter accuracy exceed 12 m. Furthermore, approximately 95% of the results of the measurement of MRSE position error accuracy do not exceed the level of 14 m. In the approach to landing phase, the values of the MRSE term are much higher than 8 m and continue rise until the last measurement epoch.

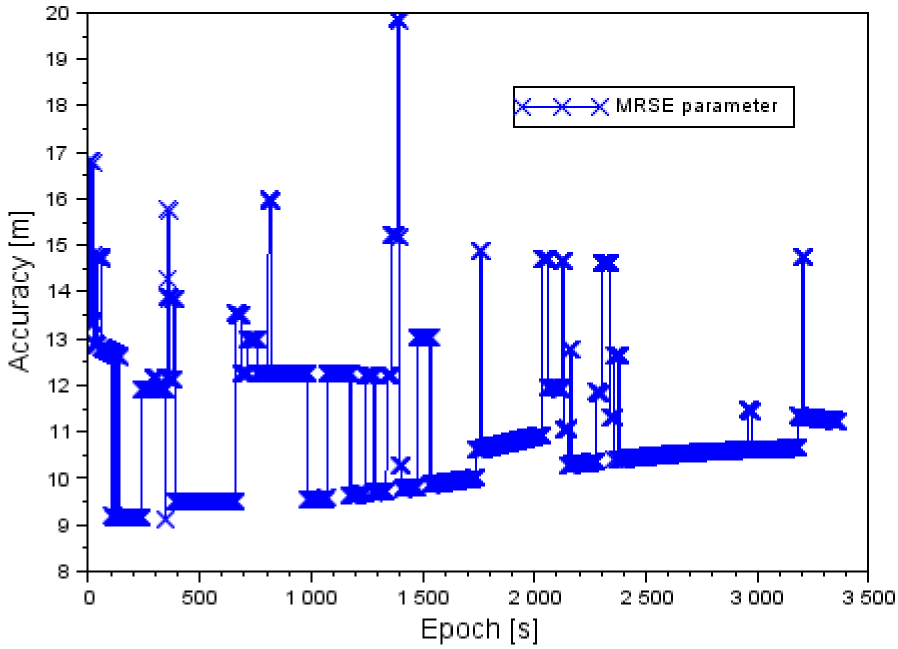

Fig. 8. The values of the MRSE parameter

4. DISCUSSION

In this section, the accuracy of the aircraft position, based on the GLONASS solution in a flight experiment, is compared with NPA standards for the GNSS system. In Table 1, the accuracy of the aircraft position is referenced to the official data of the NPA GNSS procedure in the landing phase. The ICAO recommends that the accuracy of the aircraft position on the horizontal plane should be equal to approximately 220 m, while the accuracy in the vertical plane is not active for users [4,6]. In the flight experiment, the average accuracy of the aircraft position in the horizontal plane equals 4.1 m for latitude and 5.4 m for longitude. The maximum value for aircraft positioning on the horizontal plane in flight test mode is about 8.1 m for latitude and 11.3 m for longitude. The accuracy of the horizontal coordinates for a Cessna 172 aircraft is over 220 m for the SPP solution. Official data on accuracy on the vertical plane for the NPA GNSS procedure are unavailable and thus cannot be compared with the results obtained from the RTKLIB software. It should be noted that the typical accuracy for ellipsoidal height exceeds 16.5 m in the SPP method.

Tab. 1

The accuracy of the aircraft position in relation to official data for the NPA GNSS procedure

Parameter	Obtained accuracy of the aircraft from the SPP solution	Technical ICAO standard
Accuracy of latitude	The average value of standard deviation for latitude in the flight test is higher than 8.1 m	The theoretical value of accuracy of the aircraft position on the horizontal plane equals 220 m in the NPA GNSS procedure
Accuracy of longitude	The average value of standard deviation for longitude in the flight test is higher than 11.3 m	The theoretical value of accuracy for the aircraft's position on the horizontal plane equals 220 m in the NPA GNSS procedure
Accuracy of ellipsoidal height	The average value of standard deviation in ellipsoidal height in the flight test is higher than 16.5 m	The NPA GNSS procedure does not include the official data on aircraft position accuracy in the vertical plane

5. CONCLUSIONS

In this article, the results of GLONASS positioning in the kinematic test in civil aviation were presented and described. The kinematic experiment was conducted using a Cessna 172 aircraft at the military airfield in Dęblin on 1 June 2010. The aircraft's trajectory was recovered based on the SPP method, using the GLONASS code observations. The raw GLONASS observations were collected using a Topcon Hiper Pro receiver, which was mounted in the pilot's cabin. The aircraft's coordinates and their accuracy were calculated in the RTKPOST module in the RTKLIB software. The least-squares estimation was applied to the adjustment processing of the GLONASS code observations for each measurement epoch. The accuracy of the aircraft's position from the SPP method was compared in this paper with the official release of the ICAO standards in civil aviation. The aircraft position accuracy on the horizontal plane exceeded 12 m, and 25 m with regard to the vertical plane. Standard deviations in the aircraft position were also compared with the accuracy of the NPA GNSS landing procedure.

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