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IMPLEMENTATION THE GLONASS SYSTEM IN AERONAUTICAL APPLICATION

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Abstract

The article determines the accuracy of positioning of the aircraft with the use of a satellite system GLONASS. In addition, the SPP (Single Point Positioning) absolute positioning method was utilized in research test in article. Research test was carried out in the new software APS (Aircraft Positioning Software), used for precise GPS/GLONASS satellite positioning in air navigation. The article describes the research method and presents mathematical formulas of the SPP positioning method. In the research test, the positioning accuracy of the Cessna 172 aircraft was obtained based on comparison of results between APS and RTKLIB software. The difference of Cessna 172 aircraft coordinates in the XYZ geocentric frame between the APS and RTKLIB solution is between -7 m to +6 m. The research material developed in the article comes from an aeronautical experiment carried out with the Cessna 172 aircraft for the EPDE military airport in Deblin.

Keywords: *Remote Maintenance System, air navigation, GLONASS, accuracy, Single Point Positioning method*

1. Introduction

Satellite system GLONASS, similar to the GPS navigation system has certification for use in aviation on the basis of ICAO recommendations. According to ICAO recommendations, satellite system GLONASS must provide basic parameters of satellite positioning in aviation i.e.: accuracy, availability, reliability, continuity of navigating the position of the aircraft [1]. Navigation system GLONASS is increasingly used in the operation of aircraft for the implementation of satellite GNSS. In particular, when performing airborne tests, the GLONASS sensor is a piece of navigational equipment on board the aircraft. Since the early 1990s, the GLONASS system has been used in navigation applications in aviation experiments. Typically, in these types of solutions, the GLONASS system has been tested for use in aviation together with a GPS system as described below:

– in paper [2], the GLONASS and GPS satellite system is described in detail. The work compares GPS and GLONASS navigation systems in the aspect of reference frame and time system. In addition, the article specifies the basic parameters of satellite positioning quality using GPS/GLONASS observation, i.e.: accuracy parameters, continuity and reliability. The article also presents the characteristics of the accuracy and reliability of the GLONASS and GPS systems used during air operations. For air operations of the “En-route” type, the accuracy of the horizontal positioning of the aircraft is up to 1000 m, and the reliability up to 3700 m. In the case of “Terminal” type operations, the accuracy of the horizontal positioning of the aircraft is up to 500 m, and credibility up to 1850 m. In the case of “Non-precision approach” aircraft, the horizontal positioning accuracy of the aircraft is up to 100 m, and reliability up to 550 m. And finally for flight operations such as “Precision approach cat. I” the accuracy of the horizontal positioning of the aircraft is up to 15 m and vertically up to 7 m, and the level of reliability in the level is up to 50 m and vertically up to 15 m,
– work [3] specifies the parameters of the accuracy of satellite positioning in aviation using GPS/GLONASS code observations. In particular, the work defined the parameter for the

availability of the GPS/GLONASS constellation and the value of DOP coefficients from the GPS/GLONASS solution. The average number of observed satellites in the GPS/GLONASS constellation was about 12-13 satellites, with a probability of over 20%. On the other hand, the DOP coefficients in the form of HDOP, VDOP and PDOP parameters ranged from 1 to 3. In addition, the maximum values of DOP coefficients were lower than 10 with the 99.99% probability level. The article discusses the problem of a reference frame, time system, GPS/GLONASS data integration and RAIM navigation,

– paper [4] discussed the problem of GLONASS and GPS implementation for navigational operation with the WAAS support system as part of the precise approach category I. The study states that the use of the GLONASS system for precision approach operations with category I increases the availability of the navigation solution aircraft position. In addition, GPS/ GLONASS/WAAS positioning cause fewer erroneous determinations of aircraft positions in the RAIM module operating mode. It is particularly important in the case of high values of systematic errors such as: tropospheric and ionosphere delay and the effect of multipath,
– paper [5] presents the possibilities of implementing the GLONASS satellite system as part of the LAAS ground support system operation. The work highlights the differences between GPS and GLONASS systems at the level of various reference frames, different time systems, different ways of multiple viewing access, different signal transmission frequencies. In addition, the paper presents the diagrams of the availability of the position navigation solution using different classes (A, B, C) of GPS/GLONASS receivers,
– in project [6], the navigation solution of the GPS/GLONASS position was tested in absolute mode on the background of the dual-frequency differential solution in the GPS system. In the case of a differential solution, the positioning accuracy of the aircraft ranged from 2 cm to 4 cm horizontally and respectively from 3 cm to 6 cm in vertical plane. The average accuracy of the GPS/GLONASS absolute solution was 1 m to 5 m in the horizontal plane and respectively up to 10 m in the vertical. The aircraft position recovery calculations were carried out in the post processing mode in the PNAV software,
– project [7] presents combined results of aircraft position using GPS/GLONASS navigation systems. In the experiment was used the aircraft Northwest Airline 747-200. In the project determine the positioning accuracy of the aircraft against the background of transformation between WGS-84 and SGS-85 reference frames. In the article also presents the parameters of the constellation availability of GLONASS constellation of satellites and the parameter for the RAIM module with the GPS/GLONASS solution,
– project [8] presents initial results of aircraft positioning accuracy using the DGNSS differential technique in almost real time. In the experiment used a dual-system GPS/ GLONASS receiver for aircraft positioning. The article describes the RTCM format for differential corrections for the GPS/GLONASS system. In the research experiment, it was found that the increase in the number of available satellites in the GPS/GLONASS constellation allowed to improve the determination of aircraft position in real time.

Also in Poland in the 90s of the twentieth century, the GLONASS reloading system was used in aerial experiments. Research experiments using the GLONASS system were conducted as part of air tests:

– aerial test in Deblin in 1999 with the use of TS11 Iskra. The experiment compares the ellipsoidal coordinates of the TS11 Iskra aircraft on the basis of the DGPS/DGLONASS solution in the near real time and RTK-OTF in the post-processing. Horizontal difference between the DGPS/DGLONASS solution and RTK-OTF amounted to +/-100 m, and the ellipsoidal height to +/-70 m respectively [9],
– aerial test in Powidz in 1999 using the Su-22M aircraft. In the aviation experiment, a dual-system GPS/GLONASS on-board GG24 receiver and a single-system GPS Z-12 receiver were used to reconstruct the position of the Su-22M4 aircraft during the test flight period. The GLONASS receiver in the positioning of navigation in aviation. During the experiment the

problems appeared with recording of raw GLONASS data in the GG24 geodetic receiver. The consequence of this was the inability to use the DGLONASS differential technique to reconstruct the Su-224 flight route. In addition, a GG 24 receiver with the GPS/GLONASS tracking and recording option was also installed at the REF0 reference station. The REF0 reference station was used to reproduce the reliable position of the Su-224 aircraft in the post-processing mode for the RTK-OTF differential technique [10].

Currently, globally, the GLONASS system is used in aviation to carry out tasks in the following research areas:

- precise GPS/GLONASS positioning using phase observations for the RTK-OTF differential technique [11],
- monitoring HPL/VPL security levels in air navigation [12],
- RAIM controller module test in the positioning process based on the GPS/GLONASS/ Galileo/BeiDou solution [13],
- absolute positioning in air transport using GLONASS L1-C/A code observations [14],
- positioning GPS/GLONASS/SBAS in aeronautical applications [15],
- positioning satellite GPS/GLONASS/BeiDou connected to the system INS in aeronautical applications [16],
- observation application GPS/GLONASS/BeiDou in technology UAV [17],
- determining the speed of the aircraft's movement based on the Doppler effect for observations GPS/GLONASS [18].

The primary purpose of a scientific article is to determine accuracy of satellite positioning in air navigation based on GLONASS solution. As part of the research, the system GLONASS was implemented in the precise positioning of the Cessna 172 aircraft during a trial flight around the military airport EPDE in Deblin. Calculating the position of the Cessna 172 aircraft were made in proprietary navigation software APS (Aircraft Positioning Software). In article presents the new possibilities of the APS program for practical application in aviation. The article has been divided into 4 parts: 1 – introduction, 2 – the research method, 3 – results and discussions, 4 – final conclusions. The scientific article concludes the list of research literature.

2. The research method

The article uses the absolute SPP positioning method to reconstruct the position of the Cessna 172 aircraft based on the solution in the GLONASS system. The basic observational equation of the SPP method in the GLONASS system can be written as follows [19]:

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

where:

l – the pseudorange value (C/A or P code) at 1st frequency in the GLONASS system, the precise P code is recovered using the following equation: $P1 = C1 + DCB_{P1C1}$,

DCB_{P1C1} – instrumental biases DCB between P and C/A code at 1st frequency in the GLONASS system, the DCB values are distributed in the CODE Analysis Centre in Switzerland,

d – the geometric distance between the satellite and the receiver,

$d = \sqrt{\left(x - X_{GLO}\right)^2 + \left(y - Y_{GLO}\right)^2 + \left(z - Z_{GLO}\right)^2}$,

(x, y, z) – the 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,
Rel – relativistic effect,
$SIFCB_{L1}$ – Satellite Inter-Frequency Code Bias, referenced to 1st frequency in GLONASS system,
$RIFCB_{L1}$ – Receiver Inter-Frequency Code Bias, referenced to 1st frequency in GLONASS system,
ε_1 – measurement noise and multipath effect in the SPP method.

The coordinates of the aircraft and the improvement of the clock bias of the receiver are determined in a stochastic process using a weight and covariance matrix. In addition, in the stochastic process of developing GLONASS observations, standard deviations of the determined parameters are estimated. The stochastic model for the development of GLONASS code observations in the smallest squares method can be written as follows [20]:

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

where:
$\mathbf{Qx}$ – vector with unknown parameters, $\mathbf{Qx} = [x; y; z; c \cdot dtr]^T$,
$\mathbf{N} = \mathbf{A}^\mathbf{T} \cdot \mathbf{p} \cdot \mathbf{A}$ – 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 includes 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, parameter $\mathbf{m_{Qx}}$ are referenced to ECEF frame.

The mathematical mode from equation (1) and stochastic model from equation (2) was implemented in APS (Aircraft Positioning System) software package under Windows system. The APS program was developed for the implementation of GPS satellite systems and GLONASS in precise air navigation. The APS program has 4 calculation modules:

– SPP (single point positioning) module: absolute positioning using code observations L1-C/A in the GPS satellite system and GLONASS,
– BSSD SPP (Between Satellite Single Difference of SPP) module: technique of single difference of L1-C/A code observations in the GPS and GLONASS navigation system as part of the SPP positioning method,
– IF LC (Ionosphere- Free linear combination) module ”Ionosphere-Free” linear combination for code observation P1/P2 in GPS satellite system and GLONASS,
– BSSD IF LC (Between Satellite Single Difference of IF LC) module: the technique of a single ”Ionosphere- Free” linear combination difference for code observation P1/P2 in GPS satellite system and GLONASS.

For using calculations in SPP module in APS program, following configuration of GLONASS module in method SPP was set:

– GNSS system: GLONASS,
– positioning mode: SPP method,

– precise ephemeris: SP3 or EPH data,
– broadcast ephemeris: NAV GPS and NAV GLONASS,
– Lagrange polynomial order: 9,
– Earth rotation correction: applied,
– relativistic effect: applied,
– ionosphere model: Klobucher model,
– troposphere model: Simple model,
– ZHD value a priori: 2.3 m,
– ZWD value a priori: 0.1 m,
– satellite phase centre offset: applied, based on IGS ANTEX file,
– receiver phase centre offset: applied, based on RINEX file,
– DCB correction: applied,
– adjustment processing: applied,
– cut-off elevation: 5 degree,
– pseudorange error a priori: 1 m,
– approximate user position: based on RINEX file,
– reference frame: IGS,
– output coordinates: XYZ geocentric and BLh ellipsoidal coordinates,
– receiver clock: estimated,
– number of unknown parameters in single epoch: 4,
– statistical test: Chi-square
– standard deviation of the weight unit error a priori: 1,
– significance level: 0.95,
– number of iterations: 10,
– speed of light [m/s]: 299792458,
– Earth rotation velocity [rad/s]: 7.2921151467d-5,
– basic frequency L1 in GLONASSS system [MHz]: 1602e06,
– basic frequency L2 in GLONASSS system [MHz]: 1246e06,
– frequency rate dL1 in GLONASSS system [MHz]: 0.5625e06,
– frequency rate dL2 in GLONASSS system [MHz]: 0.4375e06,
– major axis of GRS-80 ellipsoid [m]: 6378137,
– minor axis of GRS-80 ellipsoid [m]: 6356752.314,
– gravitational constant GM [m3/s2]: 3.986004418*1d14,
– height of electron content [km]: 350,
– coefficient KH for HPL protection level: 6.18
– coefficient KV for VPL protection level: 5.33,
– DOP max: 6.

3. The results and discussion

In the major part of the research, the accuracy of the obtained aircraft coordinate results from the APS program was assessed against the background of the RTKLIB program solution. In order to compare the designated coordinates (x, y, z) of the aircraft from both programs, the difference was determined as below [21]:

$$\begin{cases} dx = x_{APS} - x_{RTKLIB}, \\ dy = y_{APS} - y_{RTKLIB}, \\ dz = z_{APS} - z_{RTKLIB}, \end{cases} \tag{3}$$

where:

x_{APS} – x coordinate of aircraft from APS solution,

x_{RTKLIB} – x coordinate of aircraft from RTKLIB solution,
y_{APS} – y coordinate of aircraft from APS solution,
y_{RTKLIB} – y coordinate of aircraft from RTKLIB solution,
z_{APS} – z coordinate of aircraft from APS solution,
z_{RTKLIB} – z coordinate of aircraft from RTKLIB solution.

The position of the aircraft in the RTKLIB program was also determined using the SPP method for GLONASS code observations. In addition, precise ephemeris and RINEX navigation and observation files in the GLONASS system were used in the calculations. The elevation angle was above 5 degrees in calculations, and the average error of GLONASS code observations a priori is 1 m. The RTKLIB program uses the Klobuchar ionosphere model and the Saastamoinen troposphere model [22].

Figure 1 presents the results of difference of Cessna 172 aircraft coordinates based on APS and RTKLIB solution. The average value of parameter *dx* is +1.36 m, while the RMS error is equal to 1.29 m. In addition, the dispersion of the results of the *dx* parameter is between -3.89 m to +5.84 m. The average value of the *dy* parameter is +2.24 m, while the RMS error is 0.71 m. In addition, the spread of the results of the *dy* parameter ranges between -1.08 m to +5.44 m. The average value of the *dz* parameter is -2.07 m, while the RMS error is 1.18 m. In addition, the distribution of the results of the *dz* parameter is from -6.83 m to +2.10 m. It is worth noting that the best consistency of the results is along the Y-axis, and the worst convergence along the Z-axis.

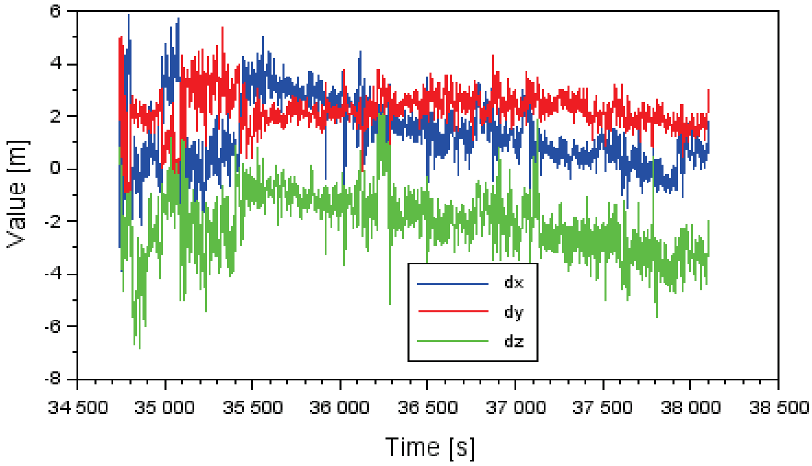

Fig. 1. The difference of aircraft coordinates in XYZ geocentric frame based on APS and RTKLIB solution

In Fig. 2, the parameter 3D-error was determined, determining the resultant shift between the position of the aircraft in 3D space based on the results from the APS and RTKLIB programs. The 3D-error parameter has been set as below [23]:

$$3D - error = \sqrt{dx^2 + dy^2 + dz^2}\ . \tag{4}$$

The average value of the 3D-error parameter is 3.80 m, and the median for this parameter equals 3.72 m. In addition, the dispersion of 3D-error results is from 1.53 m to 7.19 m. Over 72% of all 3D-error results are less than 4 m, and more than 96% of 3D-error results are less than 5 m.

4. Conclusions

In the article, the position of the Cessna 172 aircraft was determined using GLONASS code observations in the APS program. The article uses research material from an aviation experiment made for the EPDE military airport in Deblin. A geodetic receiver Topon HiperPro was installed on the desk of Cessna 172 during the air test. The set had been recording the raw code

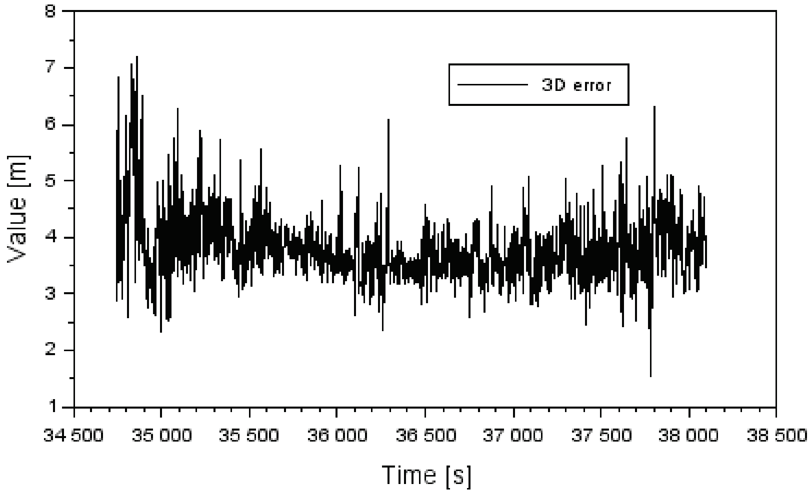

Fig. 2. The results of 3D-error

observations and GLONASS navigational data. Collected satellite data was used to recreate coordinates of Cessna 172 aircraft in XYZ geocentric frame. The article has been determined the accuracy of aircraft Cessna 172 positioning on the grounds of solutions from APS program. Therefore, aircraft coordinates (x, y, z) has been compared between APS program and RTKLIB. The difference of (x, y, z) coordinates totals from -7 to +6 meters. What is important, APS program is a new application vehicle using to accurate positioning of aircraft in air navigation. APS program will be employed in further air test with using GPS and GLONASS satellite systems.

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