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ACCURACY ANALYSIS OF AIRCRAFT POSITION AT DEPARTURE PHASE USING DGPS METHOD

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Abstract: The aim of this paper is to present the problem of implementation of the Differential Global Positioning System (DGPS) technique in positioning of the aircraft in air navigation. The aircraft coordinates were obtained based on Global Positioning System (GPS) code observations for DGPS method. The DGPS differential corrections were transmitted from reference station REF1 to airborne receiver using Ultra High Frequency (UHF) radio modem. The airborne Thales Mobile Mapper receiver was mounted in the cabin in Cessna 172 aircraft. The research test was conducted around the military aerodrome EPDE in Dęblin in Poland. In paper, the accuracy of aircraft positioning using DGPS technique is better than 1.5 m in geocentric XYZ frame and ellipsoidal BLh frame, respectively. In addition, the obtained accuracy of aircraft positioning is in agreement with International Civil Aviation Organization (ICAO) Required Navigation Performance (RNP) technical standards for departure phase of aircraft. The presented research method can be utilised in Ground-Based Augmentation System (GBAS) in air transport. In paper, also the accuracy results of DGPS method from flight test in Chełm are presented. The mean values of accuracy amount to ±1÷2 m for horizontal plane and ±4÷5 m for vertical plane.

Key words: DGPS Method, Accuracy, GBAS, Reference Station, RTK

1. INTRODUCTION

The International Civil Aviation Organization (ICAO) facilitated the use of GNSS (Global Satellite Navigation System) satellite technique as a modern measurement technique for positioning the aircraft in aviation. At the same time, the GNSS satellite technique is treated as a non-conventional measurement method in relation to the classic system solutions used so far in aviation, e.g. the INS (Inertial Navigation System), DME (Distance Measuring Equipment), VOR (Very High Frequency Omnidirectional Radio Range) systems and others. Within the GNSS satellite technology, the ICAO permits the Global Positioning System (GPS) and GLONASS (Globalnaya Navigacionaya Sputnikovaya Sistema) navigational systems as well as ABAS (Aircraft-Based Augmentation System), SBAS (Satellite-Based Augmentation System) and Ground-Based Augmentation System (GBAS) augmentation systems to be used in aviation (ICAO, 2006). Among the above-mentioned GNSS satellite systems, the GBAS system requires a creation of appropriate technical infrastructure at an aerodrome and appears to be most time consuming and labour intensive. The GBAS system allows precise positioning of an aircraft by means of ground GNSS receivers installed in the vicinity of a given aerodrome. In particular, ground-based satellite receivers (GNSS reference stations) are installed along the approach path for a landing aircraft, so that the mobile receiver mounted on board an aircraft could receive differential correction data in real time. In the navigational aspect, the GBAS system has two fundamental variations exploited in aviation, i.e. the DGNSS (Differential Global Satellite Navigation System): DGPS (Differential Global Positioning System) or DGLONASS (Differential Globalnaya Navigacionaya Sputnikovaya Sistema) positioning technique and the RTK-OTF (Real Time Kinematic – On The Fly) differential technique (Krasuski, 2017). In the DGNSS differential technique, there are the DGPS and DGLONASS positioning methods, on the basis of the ICAO certification for the application of navigation systems – GPS and GLONASS – in aviation. In the DGPS method of positioning, there are differential corrections of the GPS code measurements. On the other hand, the DGLONASS technique uses differential corrections of GLONASS code measurements. The DGPS and DGLONASS measurement techniques can be applied on the basis of ICAO standards, both in real time in order to determine an aircraft position as well as in the post-processing mode to reconstruct the trajectory of the aircraft flight. In addition, in the mathematical DGNSS method, the GNSS observations undergo the process of differentiation in order to eliminate the systematic errors. In case of the RTK-OTF differential technique, in precision aircraft positioning, precise single- or dual-frequency phase observations are used. Therefore, ground-based GNSS satellite receivers and a GNSS on-board receiver must record GPS/GLONASS observations at L1/L2 frequencies. For the DGNSS differential technique, it is possible to determine the aircraft positioning accuracy within several metres, typically less than 3 m (Kim et al., 2017). Due to the differential RTK-OTF technique, it is possible to recover the actual position of an aircraft with an accuracy of approximately 10 cm (Ciećko et al., 2016). In the GNSS satellite measurements in aviation, the RTK-OTF differential technique is used as a precision positioning method, being a reference for the DGNSS code measurements.

In the scientific literature, there are a lot of examples of using the DGNSS differential technique in scientific research concerning aircraft positioning in air navigation. The research concerning the determination of the positioning accuracy of an aircraft by means of the DGNSS differential technique in aviation was conducted in Poland and abroad. The research tests primarily focused on determining the aircraft accuracy of positioning on the basis of the

DGNSS solution. In the study of Krasuski et al. (2018a), the authors determined the accuracy of the DGLONASS positioning for the DGPS solution using dual-frequency GNSS code observations. In the numerical calculations, the recursive forward Kalman filtering was used. A typical accuracy of the DGLONASS positioning in relation to the DGPS solution equalled 10 m. In the study of Ciećko et al. (2014), the authors used the DGPS method in order to determine the accuracy of the aircraft positioning in real time. In the numerical calculations, differential corrections of data from the KODGIS (real time service of DGNSS corrections), being a part of the positioning system ASG-EUPOS (Aktywna Sieć Geodezyjna - European Position Determination System) in Poland, were used. A typical accuracy of the DGLONASS positioning in relation to the RTK-OTF base solution equalled 8 m. In the study of Grzegorzewski (2005), the authors used the DGPS method in order to determine the accuracy of the aircraft positioning in real time and in the post-processing mode. In the numerical calculations, the authors used GPS code observations at L1 frequency. A typical positioning DGPS accuracy in relation to the base RTK-OTF solution amounted up to 2 m in the post-processing mode and up to 18 m in real time. In the work of Grzegorzewski et al. (1999), an integration of the DGPS and DGLONASS methods was used in order to determine the aircraft positioning accuracy in real time. A typical accuracy of the DGPS/DGLONASS positioning in relation to the RTK-OTF base solution equalled 100 m. In the study of Tajima and Asakura (2005), the authors used the DGPS differential method in order to determine the accuracy of the aircraft positioning in real time. In the study, the research tests were conducted for the purposes of installing the GBAS system in air transport. A typical accuracy of the DGPS positioning in relation to the RTK-OTF base solution amounted to 10 m during all flight tests. In the study of Baroni and Kuga (2005), the DGPS differential technique was exploited in order to determine the aircraft positioning accuracy in the local coordinate frame ENU (Earth-North-Up). The mathematical model of designating the position of the aircraft was based on the use of Kalman filtering for the DGPS method. A typical DGPS positioning accuracy in relation to the solution of double-phase DD differences neared 10 m. In the study of Gianniou and Groten (1996), the DGPS differential technique was used to determine the aircraft positioning accuracy in the geocentric XYZ coordinate frame. In the calculations, determining the position of the aircraft at a different elevation angle of the GPS observation was tested. A typical DGPS positioning accuracy in relation to the DD double-phase differences equalled 8 m. In the study Eggleston (2002), the author used the DGPS differential technique in order to determine the accuracy of the aircraft altitude profile during the takeoff phase at the aerodrome. The readings of the aircraft position in the DGPS technique were compared with a laser measurement. The accuracy of calculating the elevation profile of the differential DGPS technique in relation to a laser measurement reached approximately 0.2 m. In the study of Sabatini and Palmerini (2008), the technique of the DGPS differential accuracy in determining the vertical profile of an aircraft was used. The readings of the aircraft position in the DGPS technique were compared with a radar measurement. The accuracy of the designation of the altitude profile of the DGPS differential technique with regard to a radar measurement reached 13 m.

In this article, the author focuses on the use of the DGNSS differential technique for the GPS code measurements (DGPS solution) in a flight test. In particular, the paper specifies the accuracy of aircraft positioning for the DGPS differential technique in the initial phase of the flight. The test flight was conducted by the Cessna 172 aircraft at the EPDE military aerodrome in Dęblin, the region of Lubelskie in Poland. The positioning accuracy of the aircraft Cessna 172 was determined for real-time applications within the DGPS differential technique. Thus, the paper presents a new solution of using the DGPS code measurements in aircraft positioning in the context of the scientific research with regard to implementation of the GBAS system in Polish aviation. The article has been divided into six parts: Introduction, Research Method, Research Test, Findings, Discussion and Conclusions. The article ends with a concise list of research literature.

2. THE RESEARCH METHOD

The mathematical model of the observation equation for the DGPS differential technique for code measurements at frequency L1 in the GPS navigation system, in real time, can be expressed as follows (Ali and Montenegro, 2014; Kim et al., 2017):

$$l = \rho + c \cdot d_{clk} + d_{atm} + PRC + RRC \cdot (t - t_0) \quad (1)$$

where l is the code measurement (pseudorange) registered by the airborne receiver in the GPS system; ρ the geometric distance satellite and the airborne receiver in the GPS system, $\rho = \sqrt{(\mathrm{x}-\mathrm{X_{GPS}})^2 + (\mathrm{y}-\mathrm{Y_{GPS}})^2 + (\mathrm{z}-\mathrm{Z_{GPS}})^2}$; $(\mathrm{X_{GPS}}, \mathrm{Y_{GPS}}, \mathrm{Z_{GPS}})$ are the satellites coordinates in the GPS system; $(\mathrm{x}, \mathrm{y}, \mathrm{z})$ are the aircraft coordinates in the geocentric XYZ frame, unknown parameters in equation (1); c is the speed of light; $\mathrm{d_{clk}}$ the systematic error of the receiver clock delay in the GPS system; $\mathrm{d_{atm}}$ the systematic error of atmosphere delay in the GPS system; PRC the pseudorange correction in the DGPS differential technique; RRC the range rate correction in the DGPS differential technique; t the current measurement epoch and $\mathrm{t_0}$ is the reference time.

The differential corrections PRC and RRC are determined on the basis of the mathematical models as shown below (Kaźmierczak et al., 2011):

$$\begin{cases} PRC = \rho_{ref} - d_{ref} \\ RRC = \frac{\Delta PRC}{\Delta t} \end{cases} \quad (2)$$

where $\mathrm{d_{ref}}$ is pseudorange L1-C/A registered by the GPS reference station, ρ_{ref} the geometric distance between the satellite and the GPS reference station and $\Delta\mathrm{t}$ is the time interval.

In accordance with the technical recommendations of the ICAO for air operations, the airplane position should be determined using the method of least squares in the stochastic process. In case of the DGPS positioning technique, the aircraft coordinates are determined by means of differential corrections data for GPS code observations at L1 frequency. In the first place, the DGPS differential corrections are specified using GPS code observations at the GNSS reference station. The DGPS corrections are calculated on the assumption that precise GPS satellite coordinates and GNSS reference station coordinates are known while taking a measurement. In this way, the DGPS differential corrections are determined in accordance with equation (2). Thus, it is possible to formulate a mathematical equation (1), on the basis of which the aircraft coordinates in the geocentric frame XYZ are determined. The position of the aircraft is calculated in equation (1) in the GPS kinematic measurements in real time. Additionally, some of the systematic errors associated with the satellite clock error, such as satellite clock offset, hardware delay (TGD – Timing Group Delay) and relativistic correction, are eliminated from the observation equation (1) due to the use of the

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difference operator. The remaining systematic errors in the observation equation (1) are divided into parameters which are connected with the receiver clock error d_{clk} and the atmospheric delay d_{atm}. The parameter d_{clk} in the DGPS differential technique is determined along with aircraft coordinates. In turn, the parameter of atmospheric delay d_{atm} is derived from deterministic models.

3. THE RESEARCH TEST AND RESULTS

Within the research test, the author determined the position of the aircraft during the execution of the flight experiment, namely the Cessna 172 had its coordinates designated during a flight test above the military aerodrome EPDE in Dęblin in the region of Lubelskie in Poland (see Fig. 1). Due to the computed coordinates of the Cessna 172, it was possible to evaluate the use of DGPS precision measurement technique in aviation. In particular, the research focused on the determination of the coordinates of the aircraft Cessna 172 in the initial phase of the flight. The aspect of the initial phase of the flight, i.e. take-off and departure, is extremely important to pilots. Besides, the aircraft take-off is one of the most demanding components of pilotage, constituting one of the most important elements of the pilot's work in the cockpit.

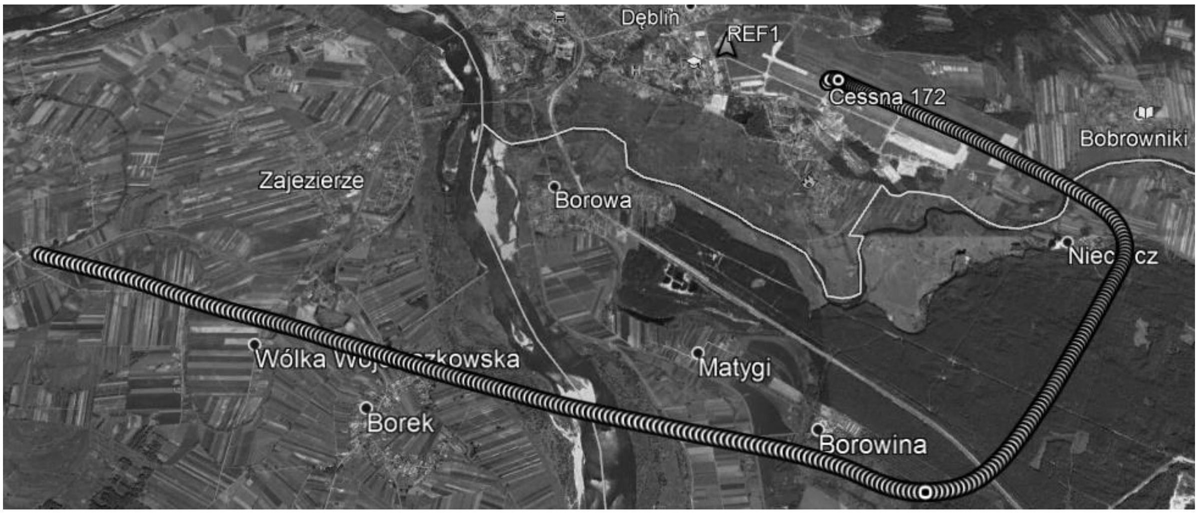

Fig. 1. The horizontal trajecory of the aircraft (https://www.google.pl/maps/)

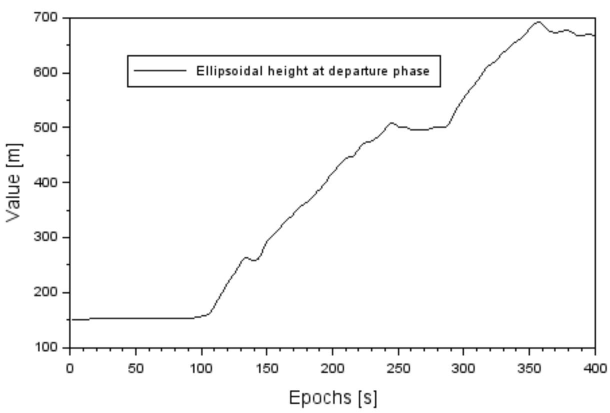

Fig. 2. The vertical trajectory of the aircraft

A portable navigation receiver Thales Mobile Mapper with the function of receiving differential corrections and the work of the DGPS computational module, was installed into airplane Cessna 172. In addition, there was a dual-frequency geodetic receiver Topcon HiperPro, serving as a reference GNSS station (REF1) for the military aerodrome EPDE in Dęblin (see Fig. 1). The DGPS differential corrections were sent from the reference REF1 station to the receiver Thales Mobile Mapper using the Ultra High Frequency (UHF) transmission link (Tsai, 1999). The DGPS differential corrections were sent to the receiver Thales Mobile Mapper in the standard RTCM (Radio Technical Commission for Maritime) format.

The investigations were conducted for the initial phase of the Cessna 172 flight, i.e. take-off and departure from the military aerodrome in Dęblin. The maximum distance of the Cessna 172 from the reference station REF1 was below 10 km. At this time, the aircraft Cessna 172 climbed from approximately 150 m to almost 700 m and levelled off (see Fig. 2). The time of making this operation was close to 400 s, or more than 6.6 minutes. At that time, the aircraft turned right and flew in the direction of the town of Kozienice in Mazowieckie voivodeship in Poland. The target distance to fly over the city of Kozienice against the aerodrome EPDE location in Dęblin was approximately 25–30 km.

Prior to the flight, the test receiver Thales Mobile Mapper was configured and set as below (Hejmanowska et al., 2005):

- internal software of the receiver: Mobile Mapper Field and Mobile Mapper Office;
- export format data: SHP, MIF and DXF;
- the possibility to use base maps: yes; reference frame: global, WGS-84 as a standard;
- mode of computations: DGPS differential;
- final format of coordinates: geocentric XYZ coordinates ellipsoidal BLh frame;
- the maximum number of tracked GPS satellites: 12 GPS satellites;
- manner of tracking GPS satellites: sequential;
- initialisation of calculations: "cold start" <2 minutes, "warm start" <1 minute, "hot start" <15 seconds;
- interval of calculations and recording time of the observation: 1 second as a rule;

- protocol of satellite data transmission: standard RTCM -104;
- receiving antenna: built in the receiver;
- battery life: typically up to 8 hours;
- number of batteries in a set: usually two batteries built into the receiver;
- mode of positioning: real time;
- GPS ephemeris data: on-board broadcast ephemeris;
- weighting of measurement results: applied;
- elevation mask: 5°;
- reference time: GPS time.

Fig. 3 shows the number of GPS satellites being tracked by the Thales Mobile Mapper airborne receiver and reference stations REF1. During the air experiment, the number of GPS satellites ranged from eight to nine; however, eight GPS satellites being tracked were only in 6 measurement epochs, whereas in the remainder of 394 epochs, the number of GPS satellites equalled nine. It needs to be emphasised that during the research test, the number of satellites exceeded four; thus, it was possible to determine the navigational position of the aircraft from equation (1). It can be added, therefore, that during the take-off and climb of the Cessna 172, for approximately 98% of the flight time, the number of GPS satellites equalled 9. Moreover, it can be observed that the number of available GPS satellites translated directly into determining the coordinate values of the aircraft Cessna 172 during the flight.

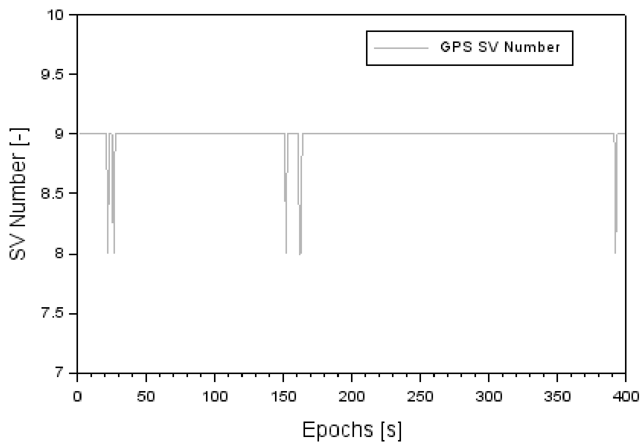

Fig. 3. The number of GPS satellites at the flight test

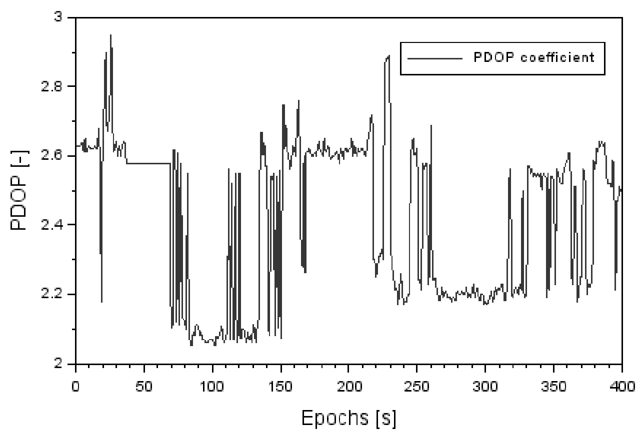

Fig. 4. The value of PDOP (Position Dilution of Precision) coefficients at the flight test

Fig. 4 shows the value of the dilution of precision coefficient PDOP position during the initial phase of the flight. The minimum value of the PDOP coefficient equals 2.1, whereas the maximum value is equal to 2.9. In addition, the median for the PDOP value parameter is equal to 2.5. The average value of the PDOP coefficient equals approximately 2.4 with a mean error of 0.2. It should be noted that at the time of the take-off from the EPDE aerodrome in Dęblin, the value of the PDOP coefficient was below 3. It can, therefore, be concluded that the conditions for making observations to conduct GPS satellite measurements at the time of the air experiment were very good. It was possible to obtain low values of the PDOP coefficient for a high number of tracked GPS satellites during the flight test (see Fig. 3).

In the framework of the conducted air experiment, the key element of the studies was to assess the positioning accuracy of the aircraft Cessna 172 using the DGPS measurement technique. For this reason, the author compared the values of the designated Cessna 172 coordinates from the DGPS solution in relation to the precise position of the aircraft designated by means of the RTK-OTF differential technique. The precise trajectory of the Cessna 172 was recovered by means of the RTK-OTF differential technique for the GPS dual-frequency phase observations. In the RTK-OTF differential technique, the authors used GPS phase observations from the reference station REF1 and additionally from the geodetic receiver Topcon HiperPro, mounted on board the Cessna 172. The Topcon HiperPro receiver was located at a distance of less than 0.1 m against the navigation receiver Thales Mobile Mapper. The computations of the Cessna 172 aircraft base position for the RTK-OTF differential technique were performed in the AOSS v.2.0 programme (Krasuski et al., 2018b). Therefore, it was possible to compare the designated coordinates of the Cessna 172 from the DGPS solution with the reference position from the RTK-OTF solution. Comparison of the Cessna 172 position was done in the frame of geocentric XYZ coordinates and ellipsoidal BLh coordinates in the framework of implementation of the reference frame ETRF'89.

Therefore, in the first place, a comparison was made between the designated coordinates of the Cessna 172 from the navigational receiver Thales Mobile Mapper and the base RTK-OTF solution. On this basis, it was possible to determine the difference in the coordinate values of the aircraft Cessna in the geodetic XYZ frame for the code DGPS method as below (Gianniou and Groten 1996):

$$\begin{cases} DX = x_{DGPS} - x_{RTK} \\ DY = y_{DGPS} - y_{RTK} \\ DZ = z_{DGPS} - z_{RTK} \end{cases} \tag{3}$$

where x_{DGPS} is the designated aircraft coordinate along the X axis, on the basis of the DGPS solution, in accordance with equation (1); y_{DGPS} the designated aircraft coordinate along the Y axis, on the basis of the DGPS solution, in accordance with equation (1); z_{DGPS} the designated aircraft coordinate along the Z axis, on the basis of the DGPS solution, in accordance with equation (1); x_{RTK} the reference coordinate of the aircraft along the X axis on the basis of the RTK-OTF differential technique; y_{RTK} the reference coordinate of the aircraft along the Y axis on the basis of the RTK-OTF differential technique and z_{RTK} is the reference coordinate of the aircraft along the Z axis on the basis of the RTK-OTF differential technique.

Fig. 5 shows the results of a comparison of XYZ coordinates of the aircraft Cessna 172 on the basis of the DGPS code solution and the RTK-OTF phase solution. The positioning accuracy of the aircraft Cessna 172 along the X axis ranges from −0.25 to +0.18 m. In addition, the average value of DX parameter equals −0.02 m, with the RMS (Root Mean Square) error being approximately 0.08 m. The mean value of positioning of the Cessna 172 along the Y axis is equal to +0.09 m and the RMS error is 0.07 m. Moreover, the amplitude of the obtained findings for the difference in the coordinate along the Y axis ranges from −0.08 to +0.21 m. The mean value of positioning accuracy of the aircraft Cessna 172 along the axis Z is equal to −0.34 m, whereas the RMS error is equal to 0.35 m. Besides, the amplitude of the obtained results for the difference in the coordinate along the Z axis is between −1.16 and +0.28 m. It is worth adding that the maximum value of the parameters (DX, DY) reaches the range of ±0.25 m. At the same time, the RMS error for the parameter values (DX, DY) reaches the maximum results to the level of 0.1 m. The dispersion of results for the parameter DZ, compared to the results of the accuracy along the X axis and Z axis, is quite significant, exceeding the level of ±1 m. Nevertheless, the RMS error along the Z axis is under 0.4 m.

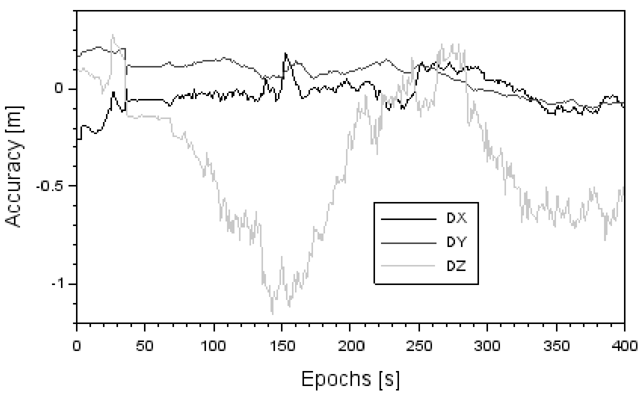

Fig. 5. The accuracy of aircraft positioning in the geocentric XYZ coordinates

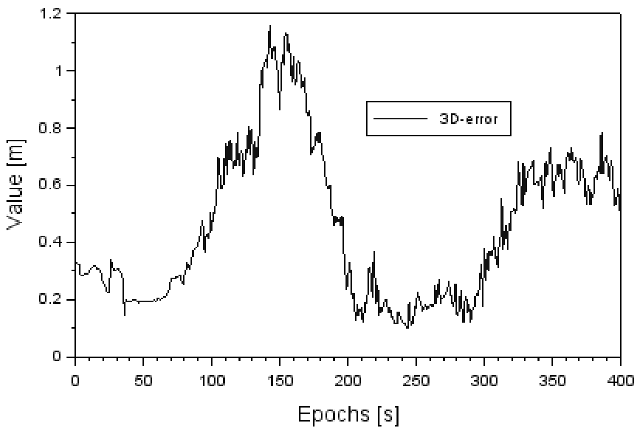

Fig. 6. The results of 3D-error in the geocentric XYZ coordinates

In the next stage, Fig. 6 shows the resultant shift error (3D-error) of geocentric XYZ coordinates of the Cessna 172 from the DGPS solution with regard to the reference coordinates of the RTK-OTF differential technique. The 3D-error parameter was determined from the dependence as below (Rodríguez-Bilbao et al., 2015):

$$3D - \text{error} = \sqrt{DX^2 + DY^2 + DZ^2} \tag{4}$$

The mean value of the 3D-error parameter equalled 0.45 m for the range between 0.10 and 1.17 m. It is worth stressing that the value of the 3D-error exceeds 1 m for 23 measurement epochs. To conclude, in approximately 95% of the measurement epochs, the value of the 3D-error does not exceed the level of 1 m.

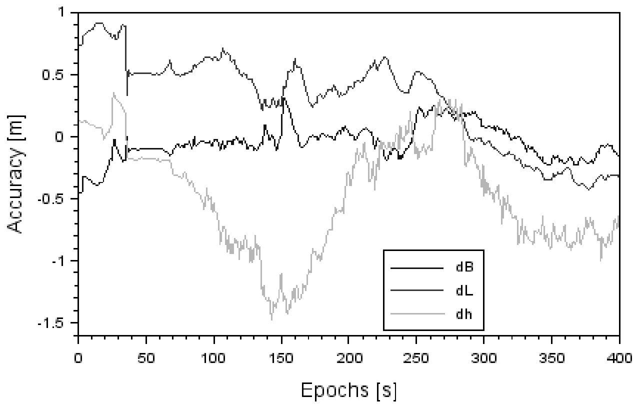

Fig. 7. The accuracy of aircraft positioning in the ellipsoidal BLh coordinates

In the next stage, the positioning accuracy of the aircraft Cessna 172 from the DGPS solution in the ellipsoidal BLh frame was determined. In order to determine the position of the aircraft Cessna 172 in the ellipsoidal frame, the Helmert transformation from the geocentric XYZ coordinates to the ellipsoidal BLh coordinates was used. The positioning accuracy values of the aircraft Cessna 172 in the ellipsoidal BLh frame were defined as below (Grzegorzewski et al., 2008):

$$\begin{cases} \mathrm{dB} = \mathrm{B_{DGPS}} - \mathrm{B_{RTK}} \\ \mathrm{dL} = \mathrm{L_{DGPS}} - \mathrm{L_{RTK}} \\ \mathrm{dh} = \mathrm{h_{DGPS}} - \mathrm{h_{RTK}} \end{cases} \tag{5}$$

where $\mathrm{B_{DGPS}}$ is the designated coordinate of the aircraft for B geodetic latitude on the basis of the DGPS solution, $\mathrm{L_{DGPS}}$ the designated coordinate of the aircraft for L geodetic longitude on the basis of the DGPS solution, $\mathrm{h_{DGPS}}$ the designated coordinate of the aircraft for h ellipsoidal height on the basis of the DGPS solution, $\mathrm{B_{RTK}}$ the reference coordinate of the aircraft for B geodetic latitude on the basis of the RTK-OTF differential technique, $\mathrm{L_{RTK}}$ the reference coordinate of the aircraft for L geodetic latitude on the basis of the RTK-OTF differential technique and $\mathrm{h_{RTK}}$ is the reference coordinate of the aircraft for h ellipsoidal height on the basis of the RTK-OTF differential technique.

The results of the positioning accuracy of the aircraft Cessna 172 from the DGPS solution in the ellipsoidal BLh frame is shown in Fig. 7. The positioning accuracy of the aircraft Cessna 172 along the axis B ranges from −0.45 to +0.32 m. In addition, the mean value of dB parameter equals −0.05 m, with the RMS error being approximately 0.14 m. The mean value of the positioning accuracy of the Cessna 172 along the axis L is equal to +0.29 m and the RMS error is 0.37 m. Furthermore, the amplitude of the results obtained for the difference in the coordinate along the axis L ranges from −0.43 to +0.92 m. The mean value of the positioning accuracy of the aircraft Cessna 172 along the axis h is equal to −0.48 m, whereas the RMS error is equal to 0.44 m. Besides, the amplitude of the obtained results for the difference along the axis h ranges from −1.48 to +0.36 m. The smallest positioning accuracy of the aircraft Cessna 172 is noticeable along the axis h and the highest accuracy is found for the coordinate B. In addition, the RMS error is the biggest for the coordinate h and the smallest for the coordinate B.

4. DISCUSSION

The findings obtained in the study, with regard to the positioning accuracy of Cessna 172 in the initial phase of the flight, proved the usefulness of using the DGPS differential technique in aviation. In particular, the high accuracy of positioning using the DGPS differential technique in relation to the real position of the aircraft Cessna 172 is extremely important in the context of the development of infrastructure of the GBAS system in aviation. The values of the positioning accuracy of the Cessna 172, found using the DGPS differential technique, did not exceed the level of ±1.5 m. The results of the positioning accuracy of the Cessna 172 are very interesting in terms of comparison of the scientific research findings with other studies (Baroni and Kuga, 2005; Ciećko et al., 2014; Gianniou and Groten, 1996; Grzegorzewski et al., 1999; Grzegorzewski, 2005; Krasusky et al., 2018; Tajima and Asakura, 2002). It should be observed that the obtained positioning accuracy of the Cessna 172 aircraft is much higher than the results published in other studies (Baroni and Kuga, 2005; Ciećko et al., 2014; Gianniou and Groten, 1996; Grzegorzewski et al., 1999; Grzegorzewski, 2005; Krasuski et al., 2018a; Tajima and Asakura, 2002). Therefore, the use of DGPS differential measurements in aviation is justifiable and efficient. However, the problem of the DGPS differential technique is the construction and maintenance of expensive technical infrastructure at an aerodrome in the form of GNSS reference stations, enabling transmission of differential corrections. Such a GNSS reference station must be equipped with a dual-frequency receiver, resistant to the effect of multipath and allowing tracking of GPS, GLONASS, BeiDou and Galileo satellite constellations. The need to build technical infrastructure for a GNSS reference station leads to additional expenses for the Airport Area Manager. On the other hand, however, the construction of a GNSS reference station at an aerodrome will ensure creation of the GBAS augmentation system, which will significantly increase the precision and accuracy of performed air operations. The basic navigation features for the operation of the GBAS system at the airport should allow distribution of the DGPS differential corrections, provision of data associated with the GBAS, provision of data with regard to the final approach in case of precision approaches and provision of data on the precise distance of an aircraft to a runway. It should also provide monitoring of credibility and integrity for the determination of the distance parameter of the aircraft to the airport and improve the aircraft position and reference time.

Lastly, the problem of accuracy of an aircraft operation, in the context of ICAO provisions and recommendations, is worth discussing. In accordance with the provisions of ICAO Required Navigation Performance (RNP), the accuracy of positioning for the conduct of navigation in the horizontal plane LNAV in a departure phase from the airport must not exceed 220 m. On the other hand, for the conduct of navigation in the vertical plane VNAV, the ICAO has not introduced any technical recommendations or indications for the use of the GNSS sensor in aircraft positioning (ICAO, 2006). Thus, the accuracy results with regard to the Cessna 172 positioning, using the DGPS method, can be compared only for horizontal coordinates. The technical recommendations of the ICAO Annex 10 to the Chicago Convention refer to aircraft positioning accuracy with the use of the GNSS sensor, expressed in ellipsoidal BLh coordinates. The resulting positioning accuracy of the horizontal coordinates (B and L) for the Cessna 172 does not exceed 1 m. Thus, the technical standards and recommendations made by the ICAO for aircraft positioning accuracy in the phase of a departure from an aerodrome were satisfied. However, it is essential to conduct further testing using the DGPS technique in order to evaluate the aircraft positioning accuracy, also in the phase of a flight and a landing approach.

Further, the accuracy parameters of DGPS method were verified and calculated for GPS data in a flight experiment in Chełm in southeastern Poland. Fig. 8 presents the accuracy of aircraft position in BLh ellipsoidal coordinates. The typical accuracy of latitude ranges between −2.92 and −0.46 m. In addition, the arithmetic mean of latitude accuracy is about −1.95 m. The typical accuracy of longitude ranges between −0.85 and −0.28 m. In addition, the arithmetic mean of longitude accuracy is about −0.61 m. The typical accuracy of ellipsoidal height ranges between +1.57 and +8.42 m. In addition, the arithmetic mean of ellipsoidal height accuracy is about +4.65 m.

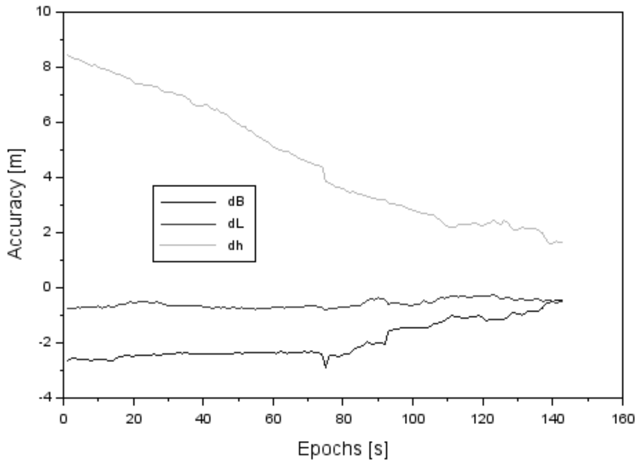

Fig. 8. The accuracy of aircraft positioning in the ellipsoidal BLh coordinates in Chełm experiment

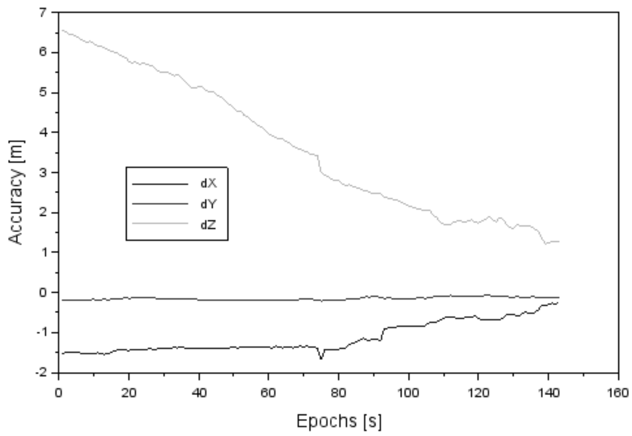

Fig. 9. The accuracy of aircraft positioning in the geocentric XYZ coordinates in Chełm experiment

Fig. 9 presents the accuracy of aircraft position in XYZ coordinates. The typical accuracy along X axis ranges between −1.68 and −0.26 m. In addition, the arithmetic mean of X coordinate

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accuracy is about −1.13 m. The typical accuracy along the Y axis ranges between −0.21 and −0.08 m. In addition, the arithmetic mean of Y coordinate accuracy is about −0.15 m. The typical accuracy along the Z axis ranges between +1.22 and +6.55 m. In addition, the arithmetic mean of Z coordinate accuracy is about +3.62 m.

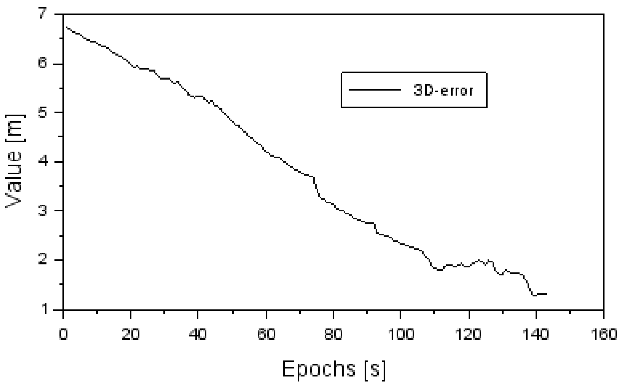

Fig. 10. The results of 3D-error in the geocentric XYZ coordinates in Chełm experiment

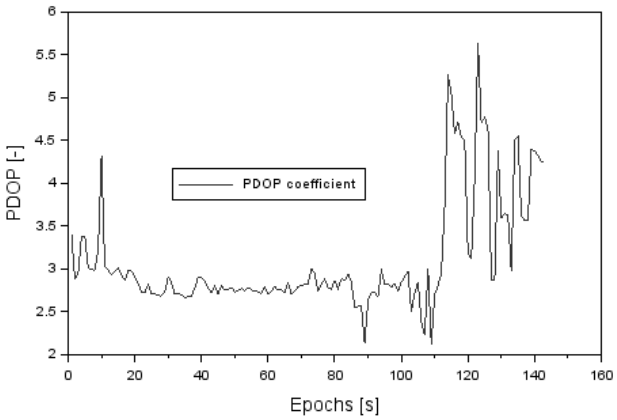

Fig. 11. The value of PDOP coefficients at the flight test in Chełm experiment

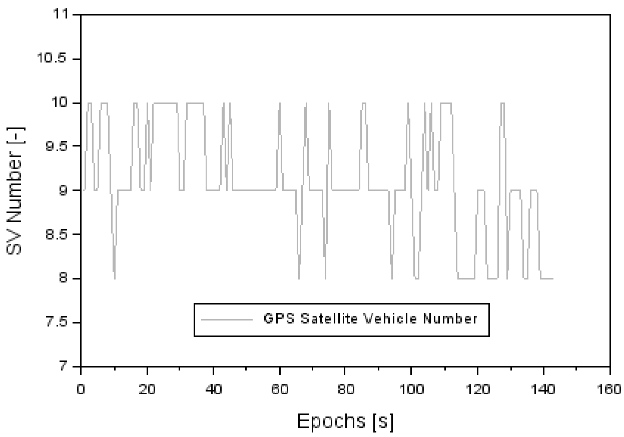

Fig. 12. The number of GPS satellites at the flight test

Fig. 10 shows the results of 3D-error for the accuracy of XYZ coordinates. The mean value of the 3D-error parameter equalled 3.80 m for the range between 1.26 m and 6.73 m obtained in the results. The highest results of 3D-error are obtained at the first phase of flight and it decreases with the observation time.

Fig. 11 shows the value of the dilution of precision coefficient PDOP position during the initial phase of the flight in Chełm experiment. The minimum value of the PDOP coefficient equals 2.1, whereas the maximum value is equal to 5.6. In addition, the median for the PDOP value parameter is equal to 2.8. The average value of the PDOP coefficient equals approximately 3.1. It should be noted that at the time of the take-off from the EPCD aerodrome in Chełm, the value of the PDOP coefficient was below 6.

Fig. 12 shows the number of GPS satellites being tracked by the airborne receiver and GNSS reference station in Chełm experiment. During the air experiment, the number of GPS satellites ranged from 8 to 10; however, the average value of the number of GPS satellites being tracked equalled 9 in the flight test in Chełm.

5. CONCLUSIONS

The paper publishes the results of scientific research concerning the use of the DGPS differential technique in positioning the aircraft in air navigation. In particular, the paper presents the results of the positioning accuracy of the aircraft using the DGPS techniques during the phase of a departure from the airport. In the air experiment, the author used the Cessna 172 aircraft, which performed a test flight over the military aerodrome EPDE in Dęblin. On board the aircraft, the navigation receiver Thales Mobile Mapper was mounted, which determined the aircraft position in a differential mode DGPS. Besides, at the airport in Dęblin, a geodetic receiver Topcon HiperPro was mounted. Its aim was to transmit differential corrections through the UHF Link to the on-board receiver Thales Mobile Mapper. The test flight was conducted for the first 400 seconds of the flight of the Cessna 172 from the military aerodrome EPDE in Dęblin. During the test flight, the Cessna 172 changed its altitude from approximately 150 m to nearly 700 m. In addition, during the flight test, the number of GPS satellites used in the solution of the aircraft position in the DGPS technique ranged from eight to nine. Additionally, the PDOP coefficient during the tests was less than 3. In order to determine the positioning accuracy of the Cessna 172, the authors verified the designated coordinates from the DGPS solution in relation to a precise flight trajectory obtained from the RTK-OTF differential technique. The positioning accuracy of the aircraft Cessna 172 in the geocentric XYZ coordinates was higher than 1.2 m, whereas in the ellipsoidal BLh coordinates, it exceeded 1.5 m. The findings on Cessna 172 positioning accuracy emphasise the fact that the DGPS technique can be used in the GBAS system in aviation. Furthermore, the obtained results of aircraft positioning accuracy of the Cessna 172 by means of the DGPS technique comply with the ICAO recommendations and instructions within executed departures from an aerodrome. The accuracy results of DGPS method from a flight test in Chełm are also presented in the paper. The mean values of accuracy amounts to ±1÷2 m for horizontal plane and ±4÷5 m for vertical plane. In addition, the PDOP coefficient amounts between 2.1 and 5.6. Moreover, the number of GPS satellites used in the solution of the aircraft position in the DGPS technique ranged from 8 to 10. Accuracy results from the flight test in Dęblin and Chełm are suitable for DGPS solution in air navigation.

In the future, the authors plan to perform tests for other phases of flight, e.g. landing.

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REFERENCES

1. **Ali, Q., Montenegro, S.** (2014), A Matlab Implementation of Differential GPS for Low-cost GPS Receivers, *TransNav*, 8(3), 343-350.
2. **Baroni, L., Kuga H. K.** (2005), Analysis of navigational algorithms for a real time differential GPS system, *18th International Congress of Mechanical Engineering*, November 6-11, 2005, Ouro Preto, Brazil.
3. **Ciećko, A., Grunwald, G., Kaźmierczak, R., Grzegorzewski, M., Ćwiklak, J., Oszczak, S., Bakuła M.** (2014), Analysis of the accuracy and availability of ASG-EUPOS services in air navigation and transport, *Logistyka*, 3, 1091-1100. (in Polish)
4. **Ciećko, A., Grzegorzewski, M., Oszczak, S., Ćwiklak, J., Grunwald, G., Balint, J., Szabo, S.** (2016), Examination of EGNOS Safety-Of-Life service in Eastern Slovakia, *Annual of Navigation*, 22/2015, 65-67.
5. **Eggleston, B., McKinney, W. D., Choi, N. S., Min D.** (2002), A low cost flight test instrumentation package for flight airplanes, *23rd Congress of International Council of the Aeronautical Sciences*, 8-13 September, 2002, Toronto, Canada, Paper ICAS 2002-5.2.2.
6. **Gianniou, M., Groten E.** (1996), An advanced real-time algorithm for code and phase DGPS, *Paper presented at DSNS'96 Conference*, St. Petersburg, Russia, May 20-24.
7. **Grzegorzewski, M.** (2005), Navigating an aircraft by means of a position potential in three dimensional space, *Annual of Navigation*, 9, 26-27.
8. **Grzegorzewski, M., Ciećko, A., Oszczak, S., Popielarczyk, D.** (2008), Autonomous and EGNOS Positioning Accuracy Determination of Cessna Aircraft on the Edge of EGNOS Coverage, *Proceedings of the 2008 National Technical Meeting of The Institute of Navigation,* San Diego, CA, January 2008, 407-410.
9. **Grzegorzewski, M., Jaruszewski, W., Fellner, A., Oszczak, S., Wasilewski, A., Rzepecka, Z., Kapcia, J., Popławski T.** (1999), Preliminary results of DGPS/DGLONASS aircraft positioning in flight approaches and landings, *Annual of Navigation*, 1, 41-53.
10. **Hejmanowska, B., Rodolphe, P., Oszczak, S., Ciećko A.** (2005), *Validation of methods for measurement of land parcel areas*, Draft final report, AGH University of Science and Technology.
11. **ICAO** (2006), "ICAO standards and recommended practices (SARPS), annex 10 volume I (radio navigation aids)", available at: www.ulc.gov.pl/pl/prawo/prawo-mi%C4%99dzynarodowe/206-konwencje, current version on date: 15 October 2018, (in Polish).
12. **Kaźmierczak, R., Grunwald, G., Bakuła, M**. (2011), The use of RTCM 2.X Dekoder Software for Analyses of KODGIS and NAWGIS Services of the ASG-EUPOS System, *Technical Sciences*, 14(2), 229-243.
13. **Kim, J., Song, J., No, H., Han, D., Kim, D., Park, B., Kee, C.** (2017), Accuracy Improvement of DGPS for Low-Cost Single-Frequency Receiver Using Modified Flächen Korrektur parameter Correction, *ISPRS Int. J. Geo-Inf.*, 6*,* 222.
14. **Krasuski, K.** (2017), Application the GPS code observations in BSSD method for recovery the position of the aircraft, *Journal of Automation, Mobile Robotics & Inteligent Systems*, 11(3), 45-52.
15. **Krasuski, K., Ćwiklak, J., Grzesik, N.** (2018), Accuracy assessment of aircraft positioning by using the DGLONASS method in GBAS system, *Journal of KONBIN*, 45, 97-124.
16. **Krasuski, K., Wierzbicki, D., Jafernik H.** (2018), Utilization PPP method in aircraft positioning in post-processing mode, *Aircraft Engineering and Aerospace Technology*, 90(1), 202-209.
17. **Rodríguez-Bilbao, I., Radicella, S. M., Rodríguez-Caderot, G., Herraiz M.** (2015), Precise point positioning performance in the presence of the 28 October 2003 sudden increase in total electron content, *Space Weather*, 13, 698–708.
18. **Sabatini, R., Palmerini, G. B.** (2008), *Differential Global Positioning System (DGPS) for Flight Testing*, ISBN 978-92-837-0041-8, RTO AGARDograph 160 Flight Test Instrumentation Series – Volume 21, Chapter 6 – DGPS PERFORMANCE ANALYSIS.
19. **Tajima, H., Asakura, M.** (2002), Flight Experiments of DGPS Approaches and Landings on a Megafloat Airport Model, *Transactions Of The Japan Society For Aeronautical And Space Sciences*, 45 (147), 66-68.
20. **Tsai, Y-J.** (1999), *Wide Area Differential operation of the Global Positioning System: ephemeris and clock algorithms*, PhD thesis, Stanford University, 110-112.
21. **URL1.** (2019), https://www.google.pl/maps/, current on 2019.

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