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MONITORING THE VECTOR ERROR BETWEEN A REFERENCE STATION AND A GNSS ON-BOARD RECEIVER IN THE GBAS SYSTEM IN THE POLISH AIR TRANSPORT

Monitoring błędu wektora pomiędzy stacją referencyjną a pokładowym odbiornikiem GNSS w systemie GBAS w transporcie lotniczym w Polsce

Abstract: The article presents research results concerning the determination of the vector error between a reference station and the GNSS on-board receiver in the GPS satellite measurements for GBAS system, taking into account the ZTD troposphere delay parameter. Based on the conducted studies, it was found that the highest value of the vector error between a reference station and the GNSS on-board receiver can exceed 0.18 m, for a distance of over 40 km and the ZTD value equalling to 2428.1 mm. The error results of vector measurement can be used in the RTK-OFT differential technique in the GBAS system.

Keywords: GPS, GBAS system, flight test, vector (baseline) error, ZTD parameter

Streszczenie: Artykuł przedstawia wyniki badań dotyczących określenia błędu wektora pomiędzy stacją referencyjną a pokładowym odbiornikiem GNSS w pomiarach satelitarnych GPS dla systemu wspomagania GBAS, przy uwzględnieniu parametru opóźnienia troposferycznego ZTD. Na podstawie przeprowadzonych badań stwierdzono, że najwyższa wartość błędu wektora pomiędzy stacją referencyjną a pokładowym odbiornikiem GNSS wynosić może ponad 0,18 m, przy odległości ponad 40 km i wartości ZTD równej 2428,1 mm. Wyniki błędu pomiaru wektora mogą zostać wykorzystane w zastosowaniu techniki różnicowej RTK-OTF w systemie GBAS.

Slowa kluczowe: GPS, system GBAS, test lotniczy, bład wektora, parametr ZTD

1. Introduction

The future of aviation, including Polish aviation, is to develop and implement the GBAS system, particularly an approach procedure [2]. A solution for the GBAS system in aviation entails the development of a specialized technical infrastructure at airports. This involves the installation of a network of reference stations with satellite GNSS receivers [4, 6]. GNSS reference stations must be dual-frequency and at least two-system, for example, GPS/GLONASS. This is to control the obtained satellite data in the event of a shutdown of one of the GNSS navigation systems. In Poland, a solution for a reference station network is the ASG-EUPOS system, which was originally designed for geodesic purposes [3]. However, in accordance with the agreement between the Surveyor General of Poland and the Polish Air Navigation Services Agency, the GNSS sensor was to be available and exploited in air navigation [14]. As long as the GNSS sensor is used for positioning in Poland within the framework of the GPS, GLONASS and SBAS (EGNOS) satellite navigation, until the present moment, no scheme of the implementation of the GNSS sensor for the GBAS augmentation in Polish aviation has been developed [15, 16]. The GBAS system performs numerous functions. For geodesy needs, the GBAS allows [10]: a designation of coordinates of a GNSS reference station with high precision and accuracy, permanent monitoring of GNSS reference station coordinates, monitoring of the multi-path effect, monitoring signal noise to ratio, determining the elevation and azimuth of the GNSS satellites, monitoring the ephemeris data and GNSS satellite clock, monitoring the transfer of time. For the needs of aviation, the GBAS system allows [8]: continuous monitoring of the atmosphere (ionosphere and troposphere), verification of data quality of the GNSS positioning, determining continuity, integrity, availability and accuracy of the GNSS sensor in aviation, transferring differential corrections from the reference station to an on-board GNSS receiver, accurate time references in GNSS, determination of velocity and of acceleration of moving objects against ground stations.

In the framework of the GBAS system, the parameters of the ionospheric delay are designed in the form of the VTEC parameter - Vertical TEC [9] and of the tropospheric delay in the form of the ZTD parameter - Zenith Troposphere Delay [12]. This paper presents research findings with regard to the measurement of the impact of the ZTD value upon designating vector values (baseline) in the GBAS system, between a reference station and an on-board GNSS receiver. The work exploits real observation and GPS navigation data derived from an experimental flight over the aerodrome in Dęblin. The value of the ZTD tropospheric delay will be designated for the baseline: reference station-on-board GNSS receiver. The work is experimental in its nature and may prove crucial for the implementation of the GBAS system in Polish aviation. Therefore, the presented research methodology can be used for monitoring the condition of the troposphere over a selected aerodrome in Poland. Thus, the concept of the research work is of key importance for civil and military aviation.

2. Research method

The mathematical model of the dependence of the ZTD tropospheric correction on determining the reference station-aircraft position is defined in the GBAS augmentation system in air transport. This mathematical dependence can be described as follows [1]:

$$\frac{dr}{r} = \frac{ZTD}{R \cdot \cos z} \tag{1}$$

where:

dr – vector error (baseline): accuracy of vector measurement in differential GNSS positioning (expressed in meters), r – baseline between a reference station and a GNSS onboard receiver (expressed in meters), ZTD – Zenith Troposphere Delay (expressed in millimetres), R – Earth radius, R = 6371 km, z – zenith angle (expressed in degrees). After a transformation, we ultimately receive:

$$dr = \frac{ZTD \cdot r}{R \cdot \cos z} \tag{2}$$

The formula of equation (1) is used to determine the accuracy of the vector measurement of the reference station-aircraft, hence determining the aircraft positioning accuracy in the GBAS augmentation system. It should be noted that dependence (1) determines aircraft positioning accuracy in the horizontal plane for LNAV navigation. In equation (1), the variable parameters are: baseline (vector) r, tropospheric delay parameter ZTD, parameter of the zenith angle z.

The dependence of equation (1) must be determined for a given GNSS observation interval in the GBAS system, e.g. every 1 sec.

3. Research experiment

In the research test, the authors performed a number of practical experiments to determine the effect of the *ZTD* parameter upon the baseline length: reference station – GNSS onboard receiver. In the research, the authors applied real source materials from the air experiment of a Cessna 172 flight above Dęblin aerodrome. In addition, on the flight route, three reference stations were assembled: Base, VirA and VirB. On this basis, it was possible to determine a baseline between particular reference stations and the GNSS on-board receiver. Moreover, for each reference station, the authors designed the *ZTD* tropospheric delay parameter, exploiting the dual-frequency PPP accurate positioning method. The position of the Cessna 172 and the reference stations was determined by means of the PPP method, using GPS code-phase observations. The calculations were performed for a one-second interval. A trajectory of the Cessna 172 against the location of reference stations is shown in fig. 1. Ultimately, the flight trajectory and the position of the reference stations

were determined in fig. 1 in the ellipsoidal BLh coordinates (B – Latitude, L – Longitude, h – ellipsoidal height). Coordinates B and L in fig. 1 are expressed in degrees.

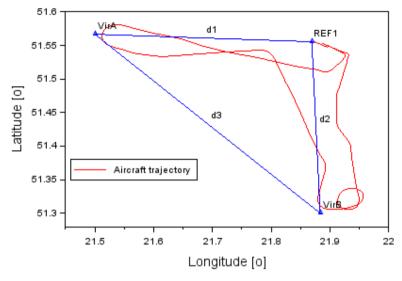


Fig. 1. The aircraft trajectory with the background of reference stations location [based on Scilab software]

In the case of the *ZTD* tropospheric delay parameter, the calculations were made by independent geodetic software: APPS, developed by JPL LAC Analysis Centre [7]. The software is available as a computation interface on the website: https://apps.gdgps.net/apps/apps_file_upload.php [17]. In the above-mentioned geodetic programme, the *ZTD* parameter is determined from the PPP method in the stochastic process. The computation interval was set at 1 s. Moreover, when determining the *ZTD* parameter in a stochastic process, it is modelled by means of the random walk hypothesis, in the least-squares method, in a sequential solution [11]. Finally, the *ZTD* parameter is defined as a sum of the following factors [13]:

$$ZTD = ZHD + ZWD \tag{3}$$

where: ZHD – Zenith Hydrostatic Delay (expressed in millimetres), ZWD – Zenith Wet Delay (expressed in millimetres).

In the PPP method, the ZHD parameter is modelled as a deterministic part, while the ZWD parameter as a stochastic part. The sum of parameters ZHD and ZWD leads to the final ZTD tropospheric product.

4. Results

The research was started with a determination of the baseline (vector) between each reference station and a GNSS on-board receiver as follows:

$$r = \begin{cases} r_{Cessna-Base} \\ r_{Cessna-VirA} \\ r_{Cessna-VirB} \end{cases}$$
(4)

where:

 $r_{Cessna-Base}$ – baseline Base-Cessna reference station, $r_{Cessna-VirA}$ – baseline reference station-VirA-Cessna, $r_{Cessna-VirB}$ – baseline reference station-VirB Cessna.

Next, the *ZTD* parameter values, for each reference station, were determined individually, using the PPP method. Hence, the *ZTD* parameter was defined as:

$$ZTD = \begin{cases} ZTD_{Base} \\ ZTD_{VirA} \\ ZTD_{VirB} \end{cases}$$
 (5)

where:

 ZTD_{Base} – determined ZTD value for base reference station, ZTD_{VirA} – determined ZTD value for VirA reference station, ZTD_{VirB} – determined ZTD value for VirB reference station.

In the next stage, the authors determined the maximum values of the zenith angle z, as:

$$z = \begin{cases} 85^{o} \\ 80^{o} \\ 75^{o} \end{cases}$$
 (6)

where:

 85° – value of zenith angle, 80° – value of zenith angle, 75° – value of zenith angle.

The obtained results are presented in figs. 2-7, developed in Scilab v.6.0.0 software [18].

Figure 2 shows the results of determining the measurement error of the baseline between the base reference station and a GNSS on-board receiver. The measurement vector values are presented in the function of the ZTD parameter. It can be concluded that the biggest measurement error of vector $r_{Cessna-Base}$ arises when the ZTD is equal to 2436.7 mm. Then, for the zenith angle $z = 85^{\circ}$, the parameter dr exceeds 0.124 m. Moreover, at $z = 80^{\circ}$, the dr is equal to 0.062 m. In addition, at $z = 75^{\circ}$, the vector error dr equals 0.042 m. It is worth

adding that the average value of the error of vector dr for the zenith angle $z = 85^{\circ}$ equals 0.044 m, and for the angle $z = 80^{\circ}$ it is equal to 0.022 m, whereas for the zenith angle $z = 75^{\circ}$, it is 0.015 m.

Figure 3 shows the results of designating the measurement error of vector $r_{Cessna-Base}$ in the function of distance: reference station – GNSS on-board receiver. The greatest vector error for the baseline $r_{Cessna-Base}$ is visible when the value $r_{Cessna-Base}$ exceeds 28 km. The dependence of the vector error dr on its length $r_{Cessna-Base}$ is a linear dependence, as shown in fig. 3. The minimum error value of the vector dr is visible when the distance $r_{Cessna-Base}$ is equal to approximately 0.1 km. In fig. 3, it is possible to observe that an increase in the zenith angle for large distances $r_{Cessna-Base}$ has a direct impact on the results of the parameter dr.

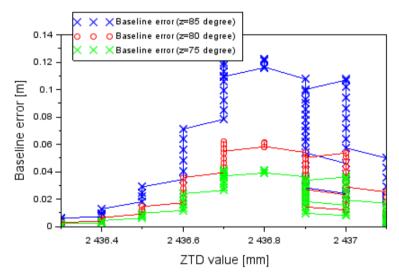


Fig. 2. The baseline error as a function of *ZTD* parameter for vector of base reference station-Cessna aircraft [based on Scilab software]

Figure 4 shows the results of determining the baseline measurement error between the reference station VirA and the GNSS on-board receiver. The values of the measurement error of vector are presented in the function of the ZTD parameter. It can be concluded that the biggest measurement error of vector $r_{Cessna-VirA}$ arises when the ZTD is equal to 2428.1 mm. Then, for the zenith angle $z=85^{\circ}$, the parameter dr exceeds 0.183 m. Moreover, at $z=80^{\circ}$, the dr is equal to 0.092 m. In addition, at $z=75^{\circ}$ the vector error dr is equal to 0.062 m. It is worth adding that the average value of the error vector dr for the zenith angle $z=85^{\circ}$ equals 0.112 m, and for the angle $z=80^{\circ}$ it is equal to 0.056 m, whereas for the zenith angle $z=75^{\circ}$, it is 0.038 m.

Figure 5 shows the results of determining the measurement error of vector $r_{Cessna-VirA}$ in the distance function: reference station – GNSS on-board receiver. The biggest

measurement error of the vector for the baseline $r_{Cessna-VirA}$ is visible when the value $r_{Cessna-VirA}$ exceeds 42 km. The dependence of the vector error dr on its length $r_{Cessna-VirA}$ is a linear relationship, as shown in fig. 5. The minimum value of the error of vector dr is visible when the distance $r_{Cessna-VirA}$ is equal to approximately 1.3 km. In fig. 5, it can be observed that an increase in the zenith angle for large distances $r_{Cessna-VirA}$ has a direct impact on the results of the parameter dr.

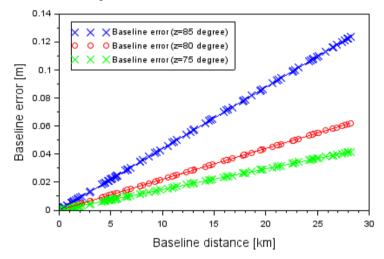


Fig. 3. The baseline error as a distance function for vector of base reference station-Cessna aircraft [based on Scilab software]

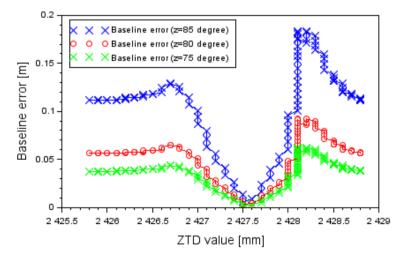


Fig. 4. The baseline error as a function of *ZTD* parameter for vector of VirA reference station-Cessna aircraft [based on Scilab software]

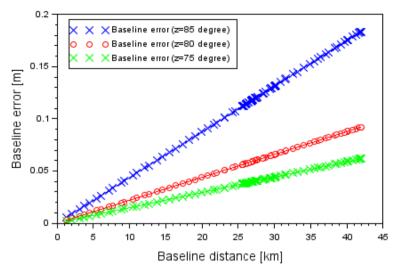


Fig. 5. The baseline error as a distance function for vector of VirA reference station-Cessna aircraft [based on Scilab software]

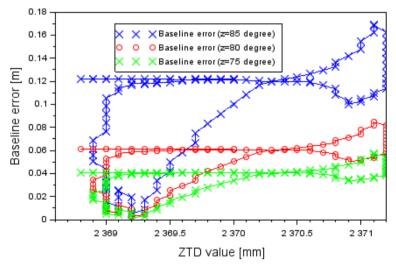


Fig. 6. The baseline error as a function of *ZTD* parameter for vector of VirB reference station-Cessna aircraft [based on Scilab software]

Figure 6 shows the results of determining the baseline measurement error between the reference station VirB and the GNSS on-board receiver. The values of the vector measurement error are presented in the function of the ZTD parameter. It can be concluded that the biggest error measurement of vector $r_{Cessna-VirB}$ arises when the ZTD is equal to 2371.1 mm. Then, for the zenith angle $z = 85^{\circ}$, the parameter dr exceeds 0.169 m. Moreover,

at $z = 80^{\circ}$ the dr is equal to 0.085 m. In addition, at $z = 75^{\circ}$ the vector error dr is equal to 0.057 m. It is worth adding that the average value of the error of vector dr for the zenith angle $z = 85^{\circ}$ equals 0.099 m, and for the angle $z = 80^{\circ}$ it is equal to 0.050 m, whereas for the zenith angle $z = 75^{\circ}$, it is 0.034 m.

Figure 7 shows the results of determining the error measurement of vector $r_{Cessna-VirB}$ in the distance function: reference station – GNSS on-board receiver. The biggest vector error for the baseline $r_{Cessna-VirB}$ is visible when the value $r_{Cessna-VirB}$ exceeds 39.6 km. The reliance of the vector error dr on its length $r_{Cessna-VirB}$ is a linear dependence, as shown in fig. 7. The minimum value of the error of vector dr is visible when the distance $r_{Cessna-VirB}$ is equal to approximately 1.2 km. In fig. 7, it is possible to observe that an increase in the zenith angle for large distances $r_{Cessna-VirB}$ has a direct impact on the results of the parameter dr.

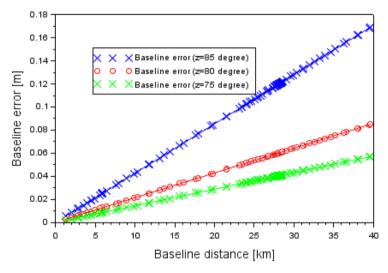


Fig. 7. The baseline error as a distance function for vector of VirB reference station-Cessna aircraft [based on Scilab software]

5. Conclusion

The paper specifies and determines the accuracy of the vector measurement between a reference station and a GNSS on-board receiver after taking into consideration the *ZTD* tropospheric delay factor. The computed error results of vector measurement exert a direct influence on the designation of an aircraft position in the horizontal plane within LNAV navigation. The entire calculations are crucial for the application of the RTK-OTF differential technique [5] within the GBAS augmentation technique in aviation. In case of using the RTK-OTF differential technique for the determination of the accurate aircraft position, the measurement errors of the vector, designated in this work, in accordance with

the propagation of the mean errors of the measurement, affect the estimated aircraft coordinates. Hence, the obtained results of measurement accuracy of the vector between a reference station and a GNSS receiver may be applied when dealing with the concept of designing the GBAS system in Polish aviation, particularly, taking into account that in this manuscript, actual GNSS data, registered by an on-board receiver and individual reference stations, were used. Another important element of the work was to show dependence between designating the vector error and the influence of the *ZTD* tropospheric correction, taking into account the fact that the work is experimental, scientific and may find application in the aerospace industry.

On the basis of the obtained findings, it appears that the highest value of the vector error between the reference station and the GNSS on-board receiver can exceed 0.18 m, for a distance of over 40 km and the *ZTD* value equal to 2428.1 mm. When the length of the vector is greater than 28 km and the *ZTD* is equal to 2436.7 mm, the vector error exceeds 0.12 m. The results of the measurement error of vector are large and must be analysed by means of the RTK-OTF differential technique in the GBAS system.

In the future, the authors plan to conduct further research with regard to the determination of the impact of the *ZTD* tropospheric correction on the designation of an ellipsoidal altitude of an aircraft during an air operation. It should be emphasized that the impact of the *ZTD* tropospheric delay will concern absolute GNSS measurements (e.g. the method of absolute SPP and the PPP measurement technique) in aviation.

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6. References

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