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THE IMPACT OF TROPOSPHERE CORRECTION FOR DESIGNATION OF THE ELLIPSOIDAL HEIGHT OF AIRCRAFT AT APPROACH TO LANDING PROCEDURE

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Abstract: The paper reports on research into the effect of the troposphere correction on the accuracy of the vertical component determination of an aircraft's flight as it approaches landing at Deblin Airport. The article presents ellipsoidal height value of the aircraft when the troposphere correction is considered in navigational calculations and when it is not taken into account. Accuracy of the aircraft positioning in the vertical plane using the SPP method is determined. The study shows that application of the troposphere correction in navigational calculations increases the accuracy of the vertical component determination by 25%–32%. The article and the study may serve as a valuable source of information for pilots, flight instructors and aircraft crews during training in operation and implementation of GNSS in aviation.

Key words: GPS, Aircraft, Ellipsoidal Height, Troposphere Correction

1. INTRODUCTION

Studies of the tropospheric state are increasingly used in aviation. Atmospheric weather effect is a dangerous condition during air operations, especially whilst landing. Atmospheric hazards are an unfavourable process during aircraft operation. Study and monitoring of the troposphere seems to be a key technical parameter in modern aviation. Use of GNSS satellite equipment is one of the ways to determine the state of the troposphere during air operations (Krasuski et al., 2017). The parameter of the tropospheric effect is included in the observation equations using both code and carrier phase GNSS measurements (Schaer, 1999). Code measurements on L1 frequency are generally used to determine the position of the aircraft via satellite navigation technology (ICAO, 2006). In this case, the tropospheric effect parameter (troposphere correction) is estimated using deterministic tropospheric models. The Hopfield model, the Saastamoinen model and the Simple model are the most common deterministic tropospheric models.

There is a vast amount of research worldwide aimed to determine the status of the troposphere and how it is applied in aviation, for example:

- determination of the tropospheric status in GBAS aircraft support system (Parameswaran et al., 2008);
- error determination for the troposphere correction in the height function of the aircraft's flight (Kutsenko et al., 2018);
- determination of the tropospheric state using Hopfield and RTCA MOPS models for GPS system (Sultana et al., 2013);
- determination of the tropospheric state using GPS and Galileo satellite navigation systems for air transport (Guilbert, 2016);
- evaluation of the tropospheric effect on the determination of the aircraft's geocentric coordinates (Krasuski et al., 2016);
- evaluation of the tropospheric effect using the MOPS RTCA model within the APV approach procedure in transport aviation (Neri, 2011);
- evaluation of the tropospheric effect on the determination of the aircraft's location (Boon et al., 1997);
- determination of the troposphere correction while in flight (Vyas et al., 2011);
- effect of the troposphere on the determination of the VPL reliability parameter in air transportation (Wang et al., 2017);
- testing of the tropospheric model developed by UNB researchers to determine airplane positioning in air navigation (Collins, 1999).

The paper aims to evaluate the effect of the troposphere on the ellipsoidal height determination of the aircraft's flight. Real navigation data and observations from the onboard GNSS receiver installed on a Cessna 172 aircraft were used in the study. Results of the study directly affect flight safety in the vertical plane VNAV. The developed technique, which studies the effect of the troposphere on the determination of the aircraft's positioning, can be used practically to improve flight safety.

2. THE RESEARCH METHOD

The tropospheric effect on the determination of the aircraft's ellipsoidal height was investigated using the code-based method (SPP) in the GPS navigation system. The basic observation equation using the SPP code positioning method in the GPS system is (Hofmann-Wellenhof et al., 2008):

$$C1 = d + c \cdot (\mathrm{d}tr - dts) + Ion + Trop + TGD + \mathrm{Rel} + Mp \quad (1)$$

where: $C1$ – the code observations at L1 frequency in GPS sys-

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tem (expressed in meters), c – light speed (expressed in m/s), d – geometric distance between satellite and receiver on L1 frequency in GPS system (expressed in meters), $d = \sqrt{(X - X_{sat})^2 + (Y - Y_{sat})^2 + (Z - Z_{sat})^2}$, (X, Y, Z) – XYZ geocentric coordinates of the aircraft, $(X_{sat}, Y_{sat}, Z_{sat})$ – satellite coordinates in GPS system, dtr – receiver clock bias in GPS system (expressed in seconds), dts – satellite clock bias in GPS system (expressed in seconds), Ion – ionosphere delay in GPS system (expressed in meters), $Trop$ – troposphere correction in GPS system (expressed in meters), TGD – Time Group Delay in GPS system (expressed in meters), Rel – relativistic effect in GPS system (expressed in meters), Mp – multipath effect and measurement noise in GPS system (expressed in meters).

In equation (1), the parameter $Trop$ denotes an oblique troposphere correction expressed as dependence (Savchuk et al., 2018):

$$Trop = SHD + SWD = m_H \cdot ZHD + m_W \cdot ZWD \quad (2)$$

where: SHD – slant hydrostatic delay (expressed in meters), SWD – slant wet delay (expressed in meters), ZHD – zenith hydrostatic delay (expressed in meters), ZWD – zenith wet delay (expressed in meters), m_H – mapping function for zenith hydrostatic delay (without a unit), m_W – mapping function for zenith wet delay (without a unit).

Whereas, the ellipsoidal height value is calculated using the recursive process based on the previously determined plane coordinates in the XYZ geocentric system, as shown below (Sanz Subirana et al., 2013):

$$h = \frac{\rho}{\cos B_i} - R \quad (3)$$

where: $\rho = \sqrt{X^2 + Y^2}$ – geocentric distance on the ellipsoid (expressed in meters), R – radius of curvature of the first ellipsoid vertical, $R = \frac{a}{\sqrt{1 - e^2 \cdot \sin^2 B_i}}$ (expressed in meters), a – semi-major axes (expressed in meters), e – eccentricity (without a unit), B – Latitude (expressed in degrees), i – iteration step (without a unit).

3. THE RESEARCH TEST

The effect of the troposphere on the determination of the ellipsoidal height during aircraft's approach to landing was estimated during the research test. The Cessna 172 aircraft made a test flight around the EPDE military airport in Deblin (Ćwiklak et al., 2010). The study focused strictly on the final stage of the flight, namely on the approach to landing and landing itself. Figure 1 shows vertical flight trajectory using the ellipsoidal height values during the approach to landing.

Analysis of the tropospheric effect on the determination of the aircraft's ellipsoidal height was conducted. The analysis intended to detect a change in the ellipsoidal height of the aircraft's flight with troposphere correction and without it. The effect of the troposphere was considered in two deterministic models: the Saastamoinen model and the SBAS model. Consequently, three results were obtained: in the first two results models that took into account tropospheric effect were used, whereas in the third troposphere correction was eliminated and omitted.

The $Trop$ parameter was estimated in Saastamoinen model as below (Abdelfatah et al., 2018):

$$Trop = \frac{1}{\cos z} \cdot (ZHD_{Saas} + ZWD_{Saas}) \quad (4)$$

where:
$ZHD_{Saas} = 0.002277 \cdot \frac{P}{1 - 0.00266 \cdot \cos(2\phi) - 0.00000028 \cdot h}$,
$ZWD_{Saas} = 0.002277 \cdot (\frac{1255}{T} + 0.05) \cdot e$, (P, T, e) – pressure, temperature and water vapor pressure, (ϕ, h) – Latitude and ellipsoidal height paramaters, z – zenith angle.

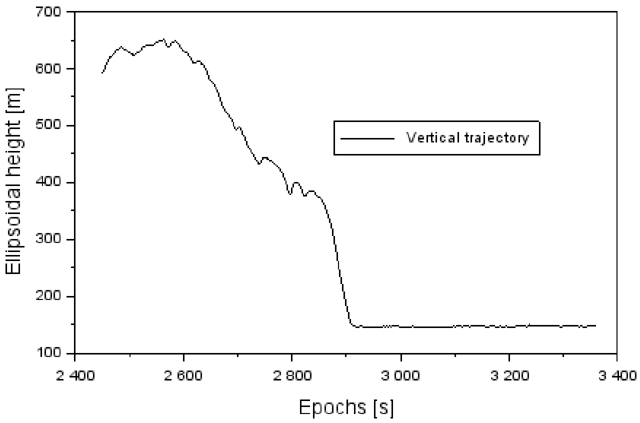

Fig. 1. The vertical trajectory at approach to landing procedure

The $Trop$ parameter was estimated in SBAS model as below (Uemo et al., 2001):

$$Trop = \frac{1.001}{\sqrt{0.002001 + \sin^2 El}} \cdot (ZHD_{SBAS} + ZWD_{SBAS}) \quad (5)$$

where: $ZHD_{SBAS} = ZHD_0 \cdot \left(1 - \frac{\beta \cdot h}{T_K}\right)^{\frac{g}{R_d \cdot \beta}}$, $ZWD_{SBAS} = ZWD_0 \cdot \left(1 - \frac{\beta \cdot h}{T_K}\right)^{\frac{(\lambda+1) \cdot g}{R_d \cdot \beta} - 1}$, (ZHD_0, ZWD_0) – ZHD and ZWD term at sea level, (λ, β) – water vapor lapse rate and temperature lapse rate, (g, R_d) – constant coefficients, h – ellipsoidal height paramaters, T_K – temperature, El – elevation angle.

Calculations of the aircraft's positioning were made in RTKLIB v.2.4.3 software using RTKPOST module. Calculation strategy using the RTKPOST library involved (Takasu, 2013):

- positioning method: SPP;
- elevation angle: 5o, based on ICAO recommendation (ICAO, 2006);
- source of the ionospheric correction: message in the navigation file;
- source of the tropospheric correction: Saastamoinen model for the first result, SBAS for the second result, OFF for the third case;
- source of the ephemeris data and satellite clock corrections: navigation file;
- coordinate system: ellipsoidal BLh;
- a priori average deviation of the pseudorange: $ml = 1m$;
- type of observation: code at L1 frequency;
- weight: in the elevation angle function, $p = \left(\frac{ml}{\sin El}\right)^2$;
- maximum DOP value: 30;

- observation interval: 1 s,
- multipath and measurement noise: applied.

4. THE RESULTS

Ellipsoidal height value with and without troposphere correction was determined during the first stage of the study. Figure 2 shows changes in ellipsoidal height calculated using the SPP code method. Results, where troposphere correction obtained from the Saastamoinen model was used, varied from 143.5 m to 650.6 m. Whereas, ellipsoidal height in the SBAS troposphere model varied from 143.6 m to 651.6 m. Ellipsoidal height value in the third result, where troposphere correction was not considered (OFF), ranged between 152.9 m and 666.6 m.

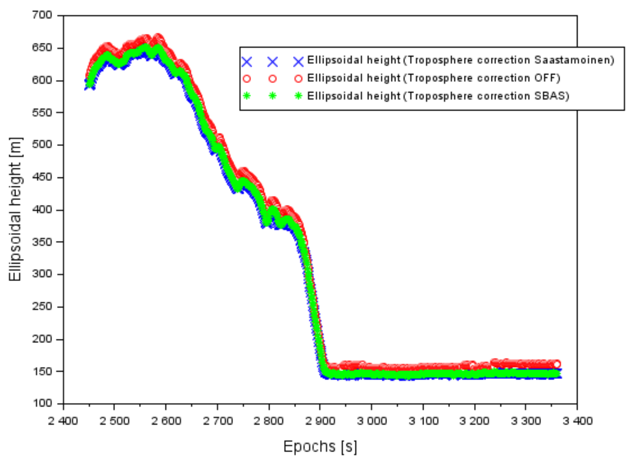

Fig. 2. The results of ellipsoidal height at approach to landing procedure

Values h shown in Figure 2 were compared to analyze the results of the aircraft's ellipsoidal height (h). For this purpose, differences in the aircraft's ellipsoidal height h were determined (Auh et al., 2018):

$$\begin{cases} dh1 = h_{OFF}^{SPP} - h_{Saastamoinen}^{SPP} \\ dh2 = h_{OFF}^{SPP} - h_{SBAS}^{SPP} \\ dh3 = h_{SBAS}^{SPP} - h_{Saastamoinen}^{SPP} \end{cases} \quad (6)$$

where: h_{OFF}^{SPP} – ellipsoidal height of aircraft without troposphere correction, see equation (3) (expressed in meters), $h_{Saastamoinen}^{SPP}$ – ellipsoidal height of aircraft with troposphere correction of Saastamoinen model, see equation (3) (expressed in meters), h_{SBAS}^{SPP} – ellipsoidal height of aircraft with troposphere correction of SBAS model, see equation (3) (expressed in meters).

Value of the aircraft's ellipsoidal height difference is defined as a function of time (Figure 3). The corresponding differences of the ellipsoidal height dh1 are in the range of 6.7 m and 17.3 m, the average ellipsoidal height difference is 13.1 m and its RMS error equals 13.4 m. Meanwhile, aircraft's ellipsoidal height difference dh2 ranges from 6.8 m to 16.0 m, the average height difference equals 12.6 m, and the RMS error is 12.7 m. Whereas, aircraft's ellipsoidal height difference dh3 varies from -0.1 m to 1.3 m, the average ellipsoidal height difference equals 0.5 m, and the RMS error is 0.7 m. This, therefore, shows that troposphere correction effect is essential to determining the ellipsoidal height of the aircraft during landing approach. Ignoring the tropospheric effect on the positioning of the aircraft causes significant errors in determination of its height.

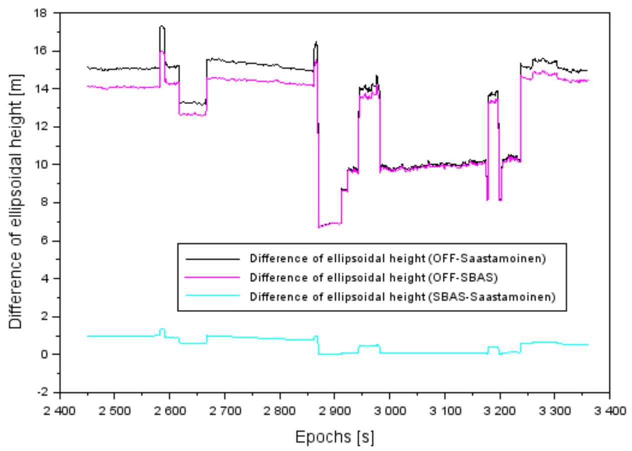

Fig. 3. The difference of ellipsoidal height at approach to landing procedure

The obtained results of the height differences (dh1, dh2, dh3) were also presented in a function of the ellipsoidal height change during the Cessna 172 aircraft's flight (see Fig. 4). Figure 4 shows that (dh1, dh2) parameters have the highest value in the range of 350 and 700 m. Moreover, significant differences in the (dh1, dh2) parameters occur directly during landing at Deblin Airport. In air navigation, information about the significant tropospheric effect on the determination of the aircraft's ellipsoidal height during its approach to landing is negative for the safety of the flight. Thus, studying the tropospheric effect on the determination of the aircraft's ellipsoidal height in this flight stage is of a grave importance in aviation. The change in the ellipsoidal height of the aircraft is not that significant for dh3 parameter – the difference of ellipsoidal height is relatively small, less than 1.3 m. Therefore, the use of the troposphere model in equation (1) is important for the SPP code method in air navigation.

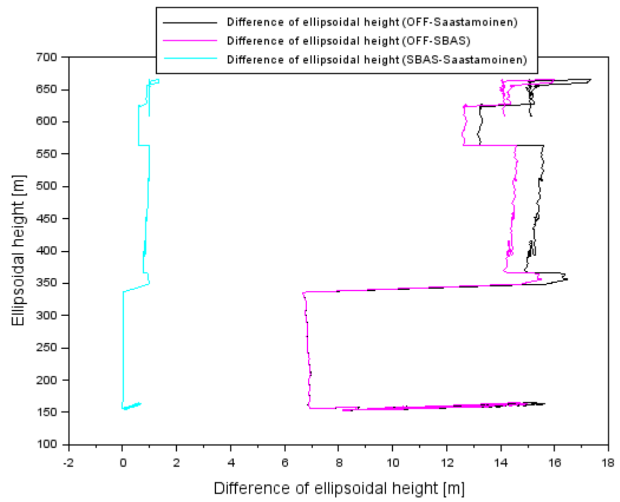

Fig. 4. The difference of ellipsoidal height at approach to landing procedure

The next stage of the study focused on determining the accuracy of the vertical component h in aircraft positioning using the

SPP code method. Therefore, ellipsoidal height determined using the SPP method was compared with its more accurate value obtained using the dual-frequency L1/L2 PPP method. Using this method, the h-component of an aircraft can be determined with an average error of about 0.1 m. Thus, PPP technology is also used in air navigation to recreate the exact flight trajectory of an aircraft. Accuracy of the vertical component h in aircraft positioning is determined below using the SPP code method (Uemo et al., 2001):

$$\begin{cases} rh1 = h_{OFF}^{SPP} - h_{PPP} \\ rh2 = h_{Saastamoinen}^{SPP} - h_{PPP} \\ rh3 = h_{SBAS}^{SPP} - h_{PPP} \end{cases} \quad (7)$$

where: h_{PPP} – ellipsoidal height of aircraft based on PPP solution (expressed in meters).

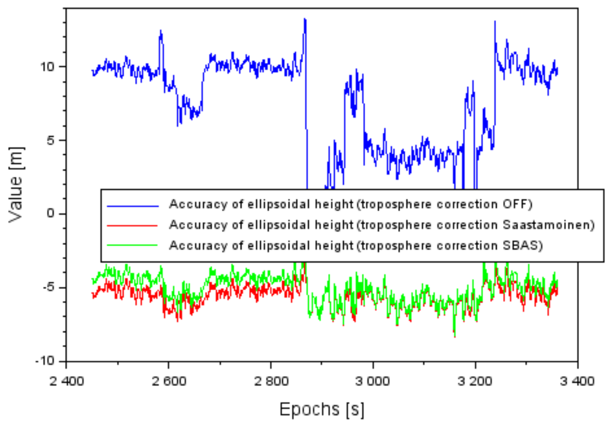

Fig. 5. The accuracy of ellipsoidal height at approach to landing procedure

Figure 5 shows the accuracy of the aircraft's h component obtained after using the SPP code method. When the troposphere correction is not applied (OFF), the accuracy of the h component varies from -0.3 m to +13.4 m with an average accuracy value of 7.5 m and RMS error being 8.1 m. When troposphere correction is determined using the Saastamoinen model with SPP method, the accuracy of the ellipsoidal height of the aircraft ranges from -8.4 m to -2.9 m, while an average accuracy equals 5.6 m and RMS error is 5.6 m. When the SBAS model is used, the accuracy of the aircraft's ellipsoidal height varies from -8.3 m to -1.6 m, the average accuracy is -5.1 m and the RMS error is 5.2 m.

The results of the study show that the use of the SBAS model increases the accuracy of the h-component positioning by 32% compared to when troposphere correction is not taken into account (OFF) in the positioning of the aircraft. Furthermore, the use of the tropospheric SBAS model increases the accuracy of the h positioning component by approximately 10% in comparison to Saastamoinen model. However, the use of the Saastamoinen model increases the accuracy of the h positioning component by approximately 25% when troposphere correction is not considered in the navigational calculations (OFF).

5. CONCLUSIONS

The paper presents the results of the navigational calculations measuring the tropospheric effect on the determination of the ellipsoidal height of an aircraft as it approaches landing. The accuracy of the aircraft's navigational positioning with and without troposphere correction was analysed. Navigational calculations for the SPP code method were done in RTKLIB v.2.4.3 software. Calculations were based on real GPS navigation data and observations from an onboard GNSS receiver installed on a Cessna 172 aircraft. As part of the study, the position of the aircraft was determined using three methods: 1) the Saastamoinen troposphere model, 2) the SBAS troposphere model, 3) without troposphere correction (OFF). Values of the aircraft's ellipsoidal height obtained using the SPP code method were compared with more accurate data obtained using the PPP measurement technique. The study shows that:

- Omission of the troposphere correction in the navigational calculations causes low accuracy (over 13 m) in determination of the vertical component h.
- Consideration of the troposphere correction in navigational calculations increases the accuracy of the vertical component h determination by 25%–32%.
- Troposphere correction effect plays a crucial role in determining the ellipsoidal height accuracy of the aircraft's flight in navigation calculations.

In the future, the authors will estimated the troposphere delay, especially Zenith Troposphere Delay (ZTD) in kinematic test in aviation. In addition, the ZTD will be calculated using the PPP method for dual-frequency onboard GNSS receiver. This solution will be tested in absolute and differential GNSS positioning in aviation.

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