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THE IMPACT OF ATMOSPHERE DELAYS IN PROCESSING OF AIRCRAFT'S COORDINATES DETERMINATION

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Abstract

In this article, the study's results of aircraft's coordinates and their accuracy are presented. The airborne test was conducted in military airport in Deblin on 1st of June 2010. The aircraft position was determinate using SPP method in RTKPOST library in RTKLIB software. To calculate the aircraft's coordinates two strategies were used, first include correction of atmosphere delays (I solution) and another without this correction (II solution). Based on these calculations, the average accuracy of aircraft position is less than 5 m for solution I and less than 8 m for solution II, respectively. The mathematical model for recovery of aircraft position; the configuration of parameters in SPP method for solution; the standard deviation values of X, Y and Z coordinates; the values of RMS-3D parameter are presented in the article. In this article, the impact of ionosphere and troposphere delay in processing of recovery of aircraft position is presented. The aircraft's coordinates were obtained using SPP (Single Point Positioning) method for two solutions, e.g. including atmosphere corrections (I solution) and excluding (II solution). The article is divided into 5 sections: introduction, mathematical model for recovery of aircraft position, research experiment, results and discussion, conclusions.

Keywords: *GPS, SPP method, accuracy, standard deviation, atmosphere delays*

1. Introduction

The atmosphere delays in GPS system are divided into ionosphere correction and troposphere correction. The ionosphere delay is a dispersive term and it depends on frequency of GPS signal. The value of ionosphere delay for GPS code observations is always positive and for GPS phase observations is negative, respectively. Moreover, the refraction coefficient of code observations is always more than 1 (e.g. $N_{gr} > 1$), but for phase observations is less than 1 (e.g. $N_{ph} < 1$), respectively [11]. The impact of ionosphere delay for single-frequency receiver is evaluated using Klobuchar model. The ionosphere delay in Klobuchar model is estimated based on 8 coefficients from broadcast navigation message [5]. In case of the dual-frequency receiver, the Geometry-Free linear combination is applied to determinate ionosphere delay [9]. At geomagnetic storm and solar high activity, the value of ionosphere delay can reach up to 100 m. The impact of ionosphere delay is visible especially for value of horizontal coordinates of user's position [2].

The troposphere region is sometimes called the neutral zone of the atmosphere. The refraction coefficient is always more than 1 (e.g. $N_{trop} > 1$) for this zone and sign of value of troposphere, delay is positive. The troposphere delay is a non-dispersive term for GPS observations and it cannot be reduced using any linear combinations [1]. The troposphere correction includes two basic components, e.g. hydrostatic and wet part. The troposphere delay is usually evaluated based on deterministic models (e.g. Hopfield, Saastamoinen, Simple) for single-frequency users. In precise positioning (e.g. Precise Point Positioning method), the component of wet delay can be also estimated using Kalman filter method or least square estimation in sequential processing [7].

In this article, the impact of ionosphere and troposphere delay in processing of recovery of aircraft position is presented. The aircraft's coordinates were obtained using SPP (Single Point Positioning) method for two solutions, e.g. including atmosphere corrections (I solution) and excluding (II solution), respectively. The article is divided into 5 sections: introduction, mathematical model for recovery of aircraft position, research experiment, results and discussion, conclusions.

2. The mathematical model for recovery of aircraft position

The basic mathematical formulation for recovery of aircraft position is based on SPP method, as below [10]:

$$l = d + c \cdot (dtr - dts) + Ion + Trop + Rel + bs + br + M_{L1}, \quad (1)$$

where:

l – the pseudo range value (C/A or P code) at 1st frequency in GPS system,

d – the geometric distance between satellite and receiver, $d = \sqrt{(x - X_{GPS})^2 + (y - Y_{GPS})^2 + (z - Z_{GPS})^2}$,

(x, y, z) – aircraft's coordinates in ECEF frame, $(X_{GPS}, Y_{GPS}, Z_{GPS})$ – GPS satellite coordinates,

c – speed of light,

dtr – receiver clock bias,

dts – satellite clock bias,

Ion – ionosphere delay,

$Trop$ – troposphere delay,

Rel – relativistic effect,

bs – hardware delay for each GPS satellite,

br – hardware delay for receiver,

M_{L1} – multipath effect.

The equation (1) includes ionosphere and troposphere delay as a component of atmosphere correction. The ionosphere delay is evaluated using Klobuchar model, whereas the troposphere delay is calculated based on Saastamoinen model. The other terms from right side of equation (1), such as: satellite clock bias, relativistic effect and hardware delays, are classified to systematic errors in GPS system. The multipath effect is a typical random error and is neglected in SPP method. The number of unknown parameters in equation (1) amounts to 4, e.g. correction to aircraft's coordinates (3 terms) and receiver clock bias (1 term). The equation (1) is solved using least square estimation in adjustment scheme for each measurement epoch. The final coordinates of the aircraft are referenced to the geocentric frame ECEF and standard deviations of coordinates are determined in the same frame. The adjustment scheme is described as below [4]:

$$\begin{cases} \mathbf{A} \cdot \mathbf{dx} - \mathbf{dl} = \mathbf{V}, \\ \mathbf{dx} = (\mathbf{A}^{\mathbf{T}} \cdot \mathbf{P} \cdot \mathbf{A})^{-1} \cdot \mathbf{A}^{\mathbf{T}} \cdot \mathbf{P} \cdot \mathbf{dl}, \\ \mathbf{Cx} = m0^2 \cdot (\mathbf{A}^{\mathbf{T}} \cdot \mathbf{P} \cdot \mathbf{A})^{-1}, \\ mx = \sqrt{\mathbf{Cx}(1.1)}, \\ my = \sqrt{\mathbf{Cx}(2.2)}, \\ mz = \sqrt{\mathbf{Cx}(3.3)}, \end{cases} \quad (2)$$

where:
A – full rank matrix,
dx – vector with unknown parameters, $\mathbf{dx} = [\delta x, \delta y, \delta z, c \cdot dtr]^T$,
dl – misclosure vector,
V – vector of residuals,
P – matrix of weights,
Cx – covariance matrix in ECEF frame,
*m*0 – standard error of unit weight, $m0 = \sqrt{\frac{[\mathbf{P} \cdot \mathbf{V} \cdot \mathbf{V}]}{n-k}}$,
n – number of observations,
k – number of unknown parameters,
mx – standard deviation of X coordinate,
my – standard deviation of Y coordinate,
mz – standard deviation of Z coordinate.

3. The research experiment

The research experiment was conducted using GPS data from Topcon HiperPro receiver from airborne test in Deblin on 1st of June 2010. The Topcon HiperPro receiver was installed in pilot's cabin in Cessna 172 aircraft to collect the raw satellite observations [3]. The satellite observations were saved in RINEX file and time of registration was set up to 1 s. The raw GPS code observations were applied for recovery of aircraft position [8] in RTKPOST library in RTKLIB software. The initial configuration of adjustment processing of GPS code observations in RTKLIB software was presented in Tab. 1 [12]. The numerical computations were executed using least square estimation for SPP method and the cut-off elevations equals to 5°. In Tab 1 the instrumental, geometric and atmosphere, terms are evaluated using data of keplerian orbit parameters from broadcast message in GPS system. The numerical computations of aircraft position were realized for two solutions in RTKLIB software. For first solution, the atmosphere delays (e.g. ionosphere and troposphere delays) were utilized in adjustment processing of GPS code observations. In 2nd solution, the atmosphere corrections are removed from observation equation (1) in SPP method. The results of solutions I and II are presented in section 4 of article.

Tab. 1. The configuration of parameters in SPP method for solution I and II

Parameter	Solution I	Solution II
GNSS system	GPS	GPS
Type of RINEX file	2.11	2.11
Positioning mode	SPP	SPP
Cut-off elevation	5°	5°
Interval of computations	1 s	1 s
Adjustment processing	Applied	Applied
Source of ephemeris	Broadcast	Broadcast
Source of satellite clock	Broadcast	Broadcast
Source of relativistic effect	Broadcast	Broadcast
Model of ionosphere delay	Klobuchar model	Not applied
Model of troposphere delay	Saastamoinen model	Not applied
Hardware delays for satellites	Time Group Delays (TGD) applied	Time Group Delays (TGD) applied
Hardware delay for receiver	Not applied	Not applied
Multipath effect	Not applied	Not applied
Coordinates frame	WGS-84	WGS-84

4. The results and discussion

The accuracy of each coordinate from solution I and II was presented into Fig. 1, 2 and 3. The average accuracy of X coordinates for solution I equals 3.458 m, with range between 2.761 m and 5.749 m. In case of the II solution, the average value of standard deviation of X coordinates amounts to 6.152 m, with range between 4.457 m and 11.452 m. The accuracy of X coordinate was improved by about 43% for the solution I in relation to solution II.

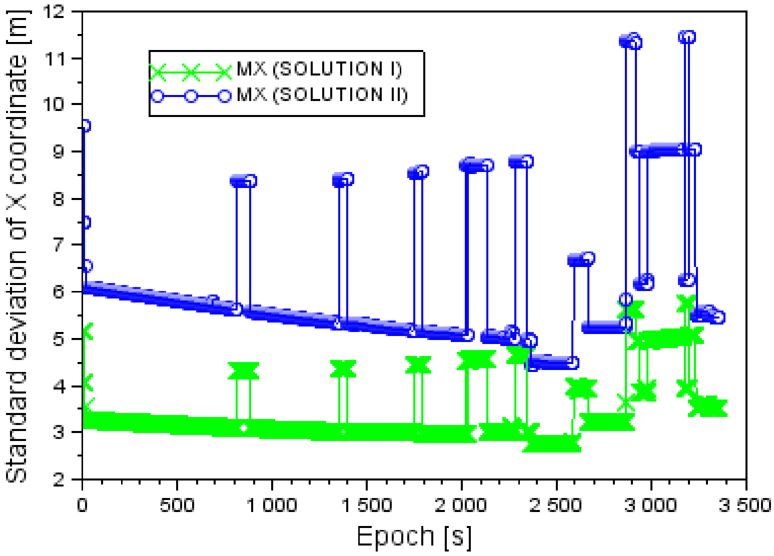

Fig. 1. The standard deviation values of X coordinate

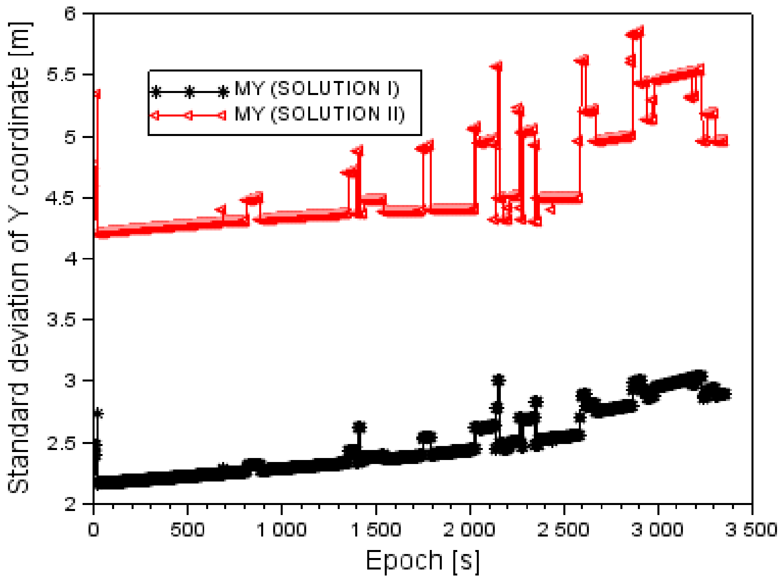

Fig. 2. The standard deviation values of Y coordinate

The Fig. 2 presents results of standard deviation of Y coordinate for each measurement epoch for solution I and II. The typical value of standard deviation of Y coordinate for solution I is about 2.487 m, with magnitude order between 2.166 m and 3.044 m. In case of the solution II, the average accuracy of Y coordinate equals 4.625 m, with range between 4.208 m and 5.860 m. The results of accuracy of Y coordinate are higher for solution I in respect to solution II, similar like for X coordinate. If ionosphere and troposphere delay are applied for solution I, then the accuracy of Y coordinate is improved by about 46% in contrast to solution II.

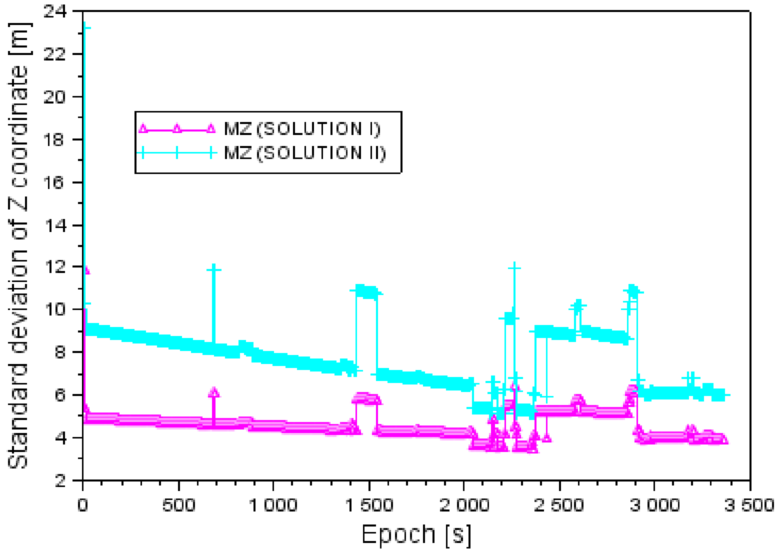

Fig. 3. The standard deviation values of Z coordinate

The Fig. 3 presents results of standard deviation of Z coordinate for each measurement epoch for solution I and II. The average value of component *mz* for solution I is about 4.483 m with range between 3.410 m and 11.809 m. The magnitude order of term *mz* for solution II equals to 5.096 m and 23.237 m, whereas the average value is about 7.725 m. The accuracy of Z coordinate was improved by about 42% for solution I in contrast to solution II.

The Fig. 4 presents the values of RMS-3D parameter based on solution I and II. The RMS-3D term is expressed as follows [6]:

$$RMS - 3D = \sqrt{\Delta X^2 + \Delta Y^2 + \Delta Z^2}\,, \tag{3}$$

where:

$\Delta X = X_{II} - X_I$, the difference between X coordinate for solution I and II,

$\Delta Y = Y_{II} - Y_I$, the difference between Y coordinate for solution I and II,

$\Delta Z = Z_{II} - Z_I$, the difference between Z coordinate for solution I and II.

The average value of RMS-3D parameter equals to 18.089 m, with range between 12.034 m and 29.267 m. The results of RMS-3D have an irregularity characteristic, but the maximum value of RMS-3D term can reach up to about 30 m.

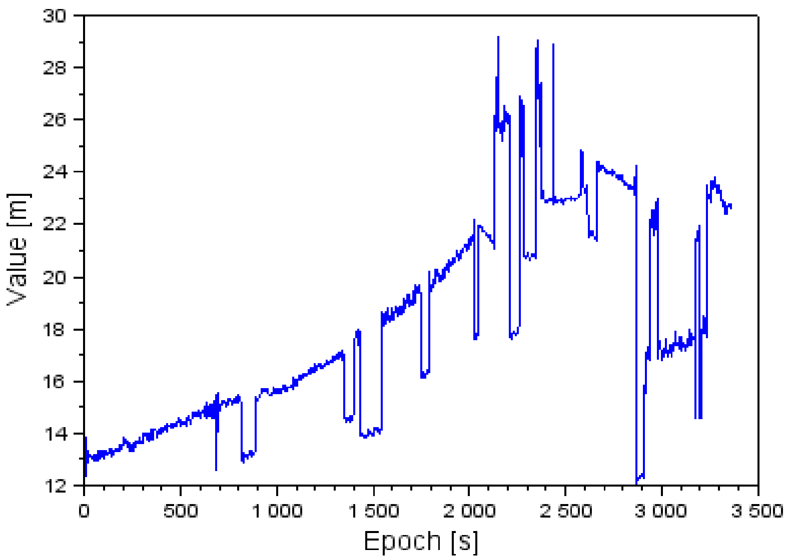

Fig. 4. The values of RMS-3D parameter

5. Conclusions

In this article, the positioning results for GPS system in air navigation were presented. The flight test was conducted in military airport in Deblin on 1st of June 2010. The aircraft's trajectory was recovery using GPS code observations in SPP method in RTKLIB software. The aircraft's coordinates were determined in context of apply the atmosphere corrections (e.g. ionosphere and troposphere delays). For solution I, when the atmosphere terms were applied, the average accuracy of aircraft's coordinates in ECEF frame was less than 5 m. Solution II excluding atmosphere corrections and the average accuracy of aircraft's coordinates was less than 8 m. In this article, the RMS-3D parameter was also calculated based on coordinate's values from solution I and II. The average value of RMS-3D parameter equals to 18.089 m, with range between 12.034 m and 29.267 m.

References

[1] Bessler, W. G., Schulz, C., Lee, T., Jeffries, J. B., Hanson, R. K., *Laser-induced fluorescence detection of nitric oxide in high-pressure flames with A-X (0,1) excitation*, Proceedings of the Western States Section of the Combustion Institute, Spring Meeting, pp. 145-156, Oakland 2001.

[2] Buckmaster, J., Clavin, P., Linan, A., Matalon, M., Peters, N., Sivashinsky, G., Williams, F. A., *Combustion theory and modeling*, Proceedings of the Combustion Institute, Vol. 30, pp. 1-19, Pittsburgh 2005.

[3] Corcione, F. E., et al., *Temporal and spatial evolution of radical species in the experimental and numerical characterization of diesel auto-ignition*, Proceedings of The Fifth International Symposium on Diagnostics and Modeling of Combustion in Internal Combustion Engines (COMODIA 2001), pp. 355-363, Nagoya 2001.

[4] Bosy, J., *Precyzyjne opracowanie satelitarnych obserwacji GPS w lokalnych sieciach położonych w ternach górskich*, Wydawnictwo Akademii Rolniczej we Wrocławiu, Nr 522, str. 68-72, 2005.

[5] Camargo, P. O., Monico, J. F. G., Ferreira, L. D. D., *Application of ionospheric corrections in the equatorial region for L1 GPS users, Earth Planets Space*, Vol. 52, pp. 1083-1089, 2000.

[6] Ćwiklak, J., Ciećko, A., Grzegorzewski, M., Jafernik, H., Oszczak, S., *Monitorowanie ruchu statków powietrznych o pojazdów służb porządku publicznego z wykorzystaniem GNSS – cz. II*, Logistyka, Nr 6, s. 601-610, 2011.

[7] Jafernik, H., Krasuski, K., *Zastosowanie metody PPP do wyznaczenia trajektorii statku powietrznego*, Technika Transportu Szynowego, Nr 12, str. 681-686, 2015.

[8] Kedzierski, M., Wierzbicki D., *Radiometric quality assessment of images acquired by UAV's in various lighting and weather conditions*, Measurement, Vol. 76, pp. 156-169, 2015.

[9] Klobuchar, J. A., *Ionospheric time-delay algorithm for single-frequency GPS users. IEEE Transactions on Aerospace and Electronic Systems*, Vol. AES-23, No. 3, pp. 325-331, 1987.

[10] Krasuski, K., *Utilization GPS/QZSS data for determination of user's position*, Pomiary Automatyka Robotyka, R. 19, Nr 2, str. 71-75, DOI: 10.14313/PAR_216/75, 2015.

[11] Kroszczyński, K., *Mezoskalowe funkcje odwzorowujące opóźnienia troposferycznego sygnałów GNSS*, Redakcja Wydawnictw WAT, ISBN 978-83-62954-99-5, str. 117-139, 2013.

[12] Øvstedal, O., *Absolute positioning with single-frequency GPS receivers*, GPS Solutions, Vol. 5, No. 4, pp. 33-44, 2002.

[13] Sanz Subirana, J., Juan Zornoza, J. M., Hernández-Pajares, M., *GNSS Data Processing, Vol. I: Fundamentals and Algorithms*, Publisher: ESA Communications, ESTEC, Noordwijk, Netherlands, pp. 95-138, 2013.

[14] Schaer, S., *Mapping and predicting the Earth's ionosphere using Global Positioning System*, PhD thesis, Neunundfünfzigster Band, Vol. 59, pp. 50-52, Zürich, Switzerland 1999.

[15] Takasu, T., *RTKLIB ver. 2.4.2 Manual, RTKLIB: An Open Source Program Package for GNSS Positioning*, pp. 129-160. Available at: http://www.rtklib.com/prog/manual_2.4.2.pdf., 2013.