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EXAMINATION OF DIFFERENT MODELS OF TROPOSPHERE DELAYS IN SBAS POSITIONING IN AERIAL NAVIGATION

Summary. This paper presents the results of a study on the use of different tropospheric correction models in SBAS positioning for air navigation. The paper, in particular, determines the influence of the Saastamoinen troposphere and RTCA-MOPS models on the determination of aircraft coordinates and mean coordinate errors in the SBAS positioning method. The study uses real kinematic data from a GPS navigation system recorded by an onboard GNSS satellite receiver as well as SBAS corrections. In the experiment, the authors include SBAS corrections from EGNOS and SDCM augmentation systems. The navigation calculations were performed using RTKLIB v.2.4.3 and Scilab 6.1.1 software. Based on the conducted research, it was found that the difference in aircraft coordinates using different troposphere models can reach up to ±2.14 m. Furthermore, the use of the RTCA-MOPS troposphere model improved the values of mean coordinate errors from 5 to 9% for the GPS+EGNOS solution and from 7 to 12% for the GPS+SDCM solution, respectively. The obtained computational findings confirm the validity of using the RTCA-MOPS troposphere model for SBAS positioning in aerial navigation.

Keywords: troposphere delay, SBAS, aircraft coordinates, mean errors

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1. INTRODUCTION

SBAS satellite positioning plays a key role in air navigation in determining the position of an aircraft. The main purpose of using SBAS in air navigation is to improve the positioning performance of an aircraft. In particular, the improvement of GNSS satellite positioning performance should be understood as a determination of positioning quality parameters in the form of accuracy, continuity, availability and reliability parameters [1]. Of the above four quality parameters for SBAS satellite positioning in air navigation, accuracy and reliability appear to be the most important ones [1]. However, to be able to improve GNSS positioning performance, SBAS corrections must be applied to the Single Point Positioning (SPP) method [2]. Among the SBAS corrections, it is possible to distinguish the following: GNSS satellite position corrections, GNSS satellite clock error corrections, an ionospheric correction and a tropospheric correction [3]. While GNSS satellite position corrections, GNSS satellite clock error corrections and an ionospheric correction are included in the SBAS message, the model of the troposphere has to be calculated empirically [4]. Therefore, a selection of a suitable troposphere model for SBAS positioning is crucial, primarily for determining the ellipsoidal height of an aircraft.

2. SCIENTIFIC KNOWLEDGE ANALYSIS

This second section describes examples of research papers regarding the subject of determining the tropospheric correction in SBAS positioning or the influence of the tropospheric correction in determining the coordinates. Paper [5] shows the significance of a systematic error, that is, the tropospheric correction within the GPS+Galileo, SBAS and GBAS systems. Moreover, publication [6] shows the results of determining the tropospheric correction using the GPT model and the SBAS model. The conducted research proved that the SBAS model is better than the GPT model for the calculation of the tropospheric correction. Also, the paper [7] discusses the impact of using different tropospheric correction models, including the SBAS model, in precise GPS, GLONASS, and GPS+GLONASS positioning for reference station networks. The lowest positioning accuracy was obtained in the GLONASS solution. Publication [8] shows the impact of the tropospheric correction model on the algorithm of determining HPL/VPL integrity parameters in SBAS satellite positioning for aerial navigation. Furthermore, the authors of the publication [9] have developed an algorithm for evaluating the influence of troposphere parameters on SBAS navigation signals using fuzzy functions. The troposphere parameter results obtained were related to the state of the ionosphere to determine the levels of reliability in GPS+SBAS positioning. An interesting study was conducted in [10], in which a new model for determining the tropospheric correction for the SBAS system for the East Asian area was shown. Next, the paper [11] published the results of a study on the application of a tropospheric correction model for the MSAS augmentation system for the area of Japan. Furthermore, the paper [12] shows the application of the tropospheric correction, calculated for the BDSBAS augmentation system, in the PPP measurement technique for single- and dual-frequency observations. A similar study was also conducted in the paper [13], in which different tropospheric correction models were investigated in the PPP measurement technique for a network of reference stations over Asia. Paper [14] presents the impact of different tropospheric correction models in the SPP code method in global, seasonal and geographical terms. A troposphere model dedicated to SBAS systems was also used in the study.

Based on the available data, it appears that:

- the problem of using an appropriate tropospheric correction model for SBAS positioning is relevant [5],
- until now, the problem of determining an appropriate tropospheric correction model has mainly concerned GNSS satellite navigation [6, 7, 12, 13, 14],
- for SBAS positioning, the tropospheric correction model was included in the calculation of the HPL/VPL integrity parameters [8, 9],
- a particular SBAS augmentation system should have an appropriate model and an algorithm for determining the tropospheric correction [10, 11].

As can be observed in the analysis of the current expertise, there is a lack of research work on the actual implementation of the given tropospheric correction algorithm in SBAS positioning for air navigation. In particular, there is no information about the impact of the proposed tropospheric correction model on the determination of aircraft coordinates and their mean errors. Therefore, this paper presents the findings of a study on the application of two tropospheric delay models, that is, the Saastamoinen model [15] and the RTCA-MOPS model [16], in the process of determining the aircraft position. Owing to the developed study results, it is possible to determine which tropospheric delay model is optimal for the SBAS positioning method in air navigation, especially since the research will be conducted for two operationally independent SBAS augmentation systems, that is, EGNOS and SDCM [17]. The flight tests were conducted in north-eastern Poland. The work is universal in nature and may be extended to include other SBAS augmentation systems available in Poland, such as the Indian GAGAN system [17].

3. RESEARCH METHOD

The basic algorithm of the SBAS positioning method in air navigation can be expressed as follows [18, 19]:

$$l = d_{GPS/SBAS} + c \cdot \left(dtr - dts_{GPS/SBAS}\right) + Ion_{SBAS} + Trop_{SBAS} + Re\,l + TGD + MP \quad (1)$$

where:
l- code measurements in the GPS system,
$d_{GPS/SBAS}$- geometric distance satellite-receiver, the long-term and fast SBAS corrections are applied for the designation of the geometric distance satellite-receiver,
$d_{GPS/SBAS} = \sqrt{(X - Xs_{GPS/SBAS})^2 + (Y - Ys_{GPS/SBAS})^2 + (Z - Zs_{GPS/SBAS})^2}$,
(X, Y, Z)- geocentric coordinates of aircraft vehicle;
$Xs_{GPS/SBAS} = Xs_{GPS} + \delta x_{SBAS}$, GPS satellite coordinate along the X-axis,
$Ys_{GPS/SBAS} = Ys_{GPS} + \delta y_{SBAS}$, GPS satellite coordinate along the Y-axis,
$Zs_{GPS/SBAS} = Zs_{GPS} + \delta z_{SBAS}$, GPS satellite coordinate along the Z-axis,
$(Xs_{GPS}, Ys_{GPS}, Zs_{GPS})$- GPS coordinates based on ephemeris data,
$(\delta x_{SBAS}, \delta y_{SBAS}, \delta z_{SBAS})$- the long-term and fast SBAS corrections,
c- speed of light,
dtr- receiver clock bias,

$dts_{GPS/SBAS}$- satellite clock bias, the long-term and fast SBAS corrections are applied for the designation of the satellite clock bias,
$dts_{GPS/SBAS} = dts_{GPS} + \delta dts_{SBAS}$,
dts_{GPS}- satellite clock bias based on ephemeris data,
δdts_{SBAS}- the long-term and fast SBAS corrections,
Ion_{SBAS}- ionosphere correction in the SBAS positioning method,
$Trop_{SBAS}$- troposphere correction in the SBAS positioning method,
$Re\,l$- relativistic effect in the GPS system,
TGD- Timing Group Delay for GPS satellite,
MP- multipath effect in the GPS system.

Based on equation (1), aircraft coordinates are determined from the GPS+SBAS solution using the least squares method. The algorithm of the least squares method is presented below [20]:

$$\begin{cases} Q_X = N^{-1} \cdot L \\ v = A \cdot Q_X - dl \\ m0_{post} = \sqrt{\frac{[v^T pv]}{n-k}} \end{cases} \qquad \begin{cases} C_{Qx} = m0_{post}^2 \cdot N^{-1} \\ m_{Qx} = diag(\sqrt{C_{Qx}}) \end{cases} \tag{2}$$

where:
Q_X - vector of determined parameters,
$N = A^T \cdot p \cdot A$ - matrix of a system of normal equations,
A- matrix of coefficients,
v - correction vector,
p - matrix of weights,
$p = \frac{1}{m0^2 \cdot ml^2}$,
$m0$- a priori average unit error $m0 = 1$,
ml- matrix of pseudo-distance measurement errors,
$ml = \sqrt{(\frac{ml_0}{\sin(El)})^2 + m_{SBAS}^2}$ - average error of pseudo-distance,
ml_0- pseudo-distance standard deviation in the GPS system, $ml_0 = 1\ m$
m_{SBAS} - error of SBAS corrections model,
$L = A^T \cdot p \cdot dl$ – vector of absolute terms,
dl - difference between observations and model parameters,
$m0_{post}$- a posteriori average unit error,
n- number of observations,
k- number of unknown parameters for each measurement epoch,
C_{Qx}- variance-covariance matrix of determined parameters in the XYZ geocentric frame,
m_{Qx}- mean errors of determined parameters, referred to XYZ coordinates,
$m_{Qx} = [mX, mY, mZ]$,
mX- mean errors along the X-axis,
mY- mean errors along the Y-axis,
mZ- mean errors along the Z-axis.

In equation (1), there is a tropospheric delay factor in the form of the parameter $Trop_{SBAS}$, which determines the slant value of the total tropospheric delay for a given GPS satellite in the SBAS positioning model. In the SBAS positioning model, the parameter $Trop_{SBAS}$ is determined based on a given tropospheric delay model. In the analysed example, Saastamoinen and RTCA-MOPS models [4] were used to determine the parameter $Trop_{SBAS}$ in equation (1). Furthermore, equation (1) was implemented for two SBAS augmentation systems, namely EGNOS and SDCM. On this basis, it is possible to determine the position of an aircraft from the GPS+EGNOS and GPS+SDCM solution for a single onboard GNSS receiver. In each solution, the tropospheric correction is used in two ways: first, by using the Saastamoinen model, and second, by using the RTCA-MOPS model.

4. RESEARCH EXPERIMENT

The test experiment was conducted on real GNSS kinematic data recorded by an onboard receiver mounted on a Diamond DA 20-C1 aircraft. The test flight took place during the autumn period of 2020 in north-eastern Poland on the Olsztyn-Suwałki-Olsztyn route. A Septentrio AsterRx2i geodetic receiver was fixed onboard the aircraft [21]. The satellite receiver recorded GNSS observations, including GPS code observations with a time interval of 1 second. In addition, owing to the real-time service: ftp://serenad-public.cnes.fr/SERENAD0 [22], it was possible to collect corrections from EGNOS and SDCM augmentation systems, which were used in the navigation calculations in equation (1). As a first step, navigation calculations for equation (1) were performed in the RTKLIB v.2.4.3 software [23]. In RTKLIB software, the position of the aircraft was determined from the GPS+EGNOS and GPS+SDCM solutions. Two tropospheric delay models were considered in the calculations, that is, the Saastamoinen model and the RTCA-MOPS model. The configuration of the navigation calculation in RTKLIB was set as follows [24]:
- positioning mode: single,
- elevation mask: 5°,
- source of ionosphere delay: SBAS corrections using ionosphere GRID maps,
- source of troposphere delay: Saastamoinen model and RTCA-MOPS model,
- source of satellite coordinates and clocks: broadcast ephemeris and SBAS message,
- GNSS system: GPS+EGNOS and GPS+SDCM,
- source of GPS observations: RINEX format,
- source of EGNOS and SDCM corrections: EMS file,
- reference frame of coordinates: WGS-84 frame,
- interval of computations: 1 s,
- final coordinates: geocentric XYZ coordinates.

Thus, the RTKLIB programme ultimately generated four independent determinations of the aircraft position in the form of:
- GPS+EGNOS solution from the Saastamoinen model for the Septentrio AsterRx2ireceiver (EGNOS-SAAS designation),
- GPS+EGNOS solution from the RTCA-MOPS model for the Septentrio AsterRx2ireceiver (EGNOS-RTCA designation),
- GPS+SDCM solution from the Saastamoinen model for the Septentrio AsterRx2ireceiver (SDCM-SAAS designation),

- GPS+EGNOS solution from the Saastamoinen model for the Septentrio AsterRx2ireceiver (EGNOS-RTCA designation).

The aircraft coordinates were finally expressed in the XYZ geocentric coordinates [20]. The computations findings in graphic, tabular and descriptive forms are presented in Section 5. Scilab v.6.1.1 software [25] was used to present the obtained results.

5. RESULTS AND DISCUSSION

To determine the influence of the proposed tropospheric correction model in the SBAS positioning, the difference of the determined coordinates from the GPS+EGNOS and GPS+SDCM solutions for the Saastamoinen troposphere model and RTCA-MOPS is shown first. For this purpose, the parameters (RX, RY, RZ), were calculated as a difference in the aircraft position coordinates, shown below:

$$\begin{cases} RX = X_{SAAS} - X_{RTCA} \\ RY = Y_{SAAS} - Y_{RTCA} \\ RZ = Z_{SAAS} - Z_{RTCA} \end{cases} \tag{3}$$

where:
$(X_{SAAS}, Y_{SAAS}, Z_{SAAS})$- position of the aircraft from the GPS+SBAS solution using the Saastamoinen model as a tropospheric correction (equation (1)),
$(X_{RTCA}, Y_{RTCA}, Z_{RTCA})$- position of the aircraft from the GPS+SBAS solution using the RTCA-MOPS model as a tropospheric correction (equation (1)).

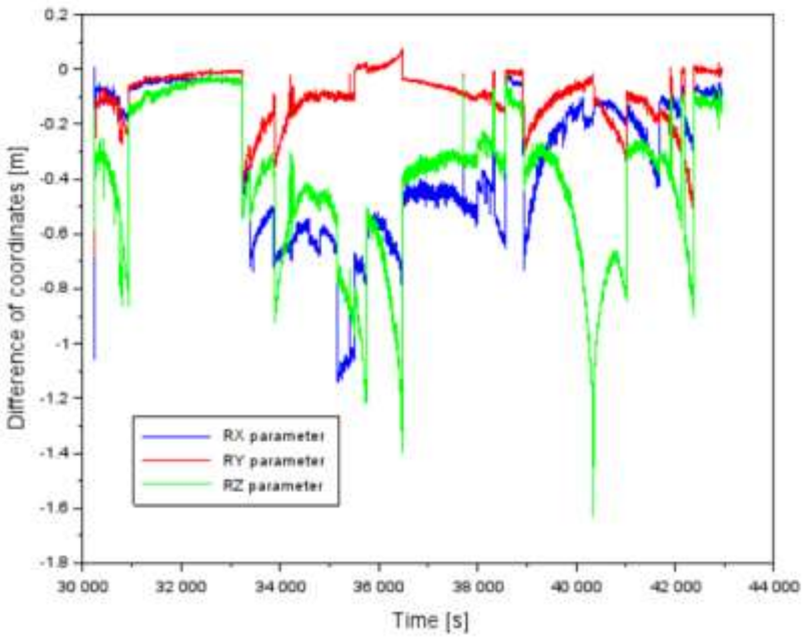

Fig. 1. Difference of aircraft coordinates based on the GPS+EGNOS solution with the applied Saastamoinen and RTCA-MOPS model

Figure 1 shows the results of the (RX, RY, RZ) parameters for the GPS+EGNOS solution. The values of RX coordinate differences range from -1.14 to +0.01 m, with an average value equal to -0.32 m. The RY values of coordinate differences range from -0.68 to +0.08 m, with an average value of -0.10 m. Moreover, the RZ values of the coordinate difference range from -1.62 to -0.02 m, with an average value of -0.40 m.

Figure 2 shows the results of the (RX, RY, RZ) parameters for the GPS+SDCM solution. The values of RX coordinate differences range from -1.19 to +0.01 m, with an average value equal to -0.38 m. The RY values of coordinate differences range from -0.47 to +0.05 m, with an average value of -0.11 m. Furthermore, the RZ values of coordinate difference range from -2.14 to +0.13 m, with an average value of -0.41 m.

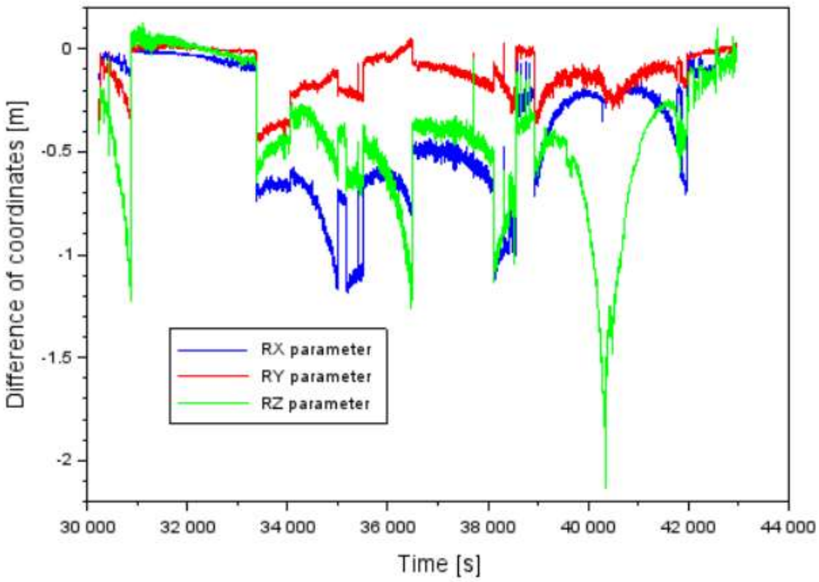

Fig. 2. Difference of aircraft coordinates based on the GPS+SDCM solution with the applied Saastamoinen and RTCA-MOPS model

Next, the average errors of the aircraft coordinates in the form of (mX, mY, mZ) parameters were found for the GPS+EGNOS and GPS+SDCM solutions. The values of the parameters (mX, mY, mZ) were determined using equation (2), including the Saastamoinen model and the RTCA-MOPS model. Figures 3 and 4 show the mean error values along the X-axis from the GPS+EGNOS and GPS+SDCM solutions. Mean error values mX from the GPS+EGNOS solution range from 0.92 to 8.36 m when using the Saastamoinen model for SBAS positioning. In contrast, the mean error values mX from the GPS+EGNOS solution range from 0.84 to 7.97 m when using the RTCA-MOPS model in SBAS positioning. It is worth noting that with the tropospheric correction for the RTCA-MOPS model, the mean errors mX from the GPS+EGNOS solution improved from 5 to 9% compared to the Saastamoinen model in equation (1). For the GPS+SDCM solution using the Saastamoinen model, the mean errors mX ranged from 0.82 to 3.43 m. Furthermore, for the RTCA-MOPS model, the mean errors mX ranged from 0.72 to 3.05 m. In the analysed GPS+SDCM solution, the application of the RTCA-MOPS tropospheric correction model improved the determination of mean errors mX from 9 to 12%.

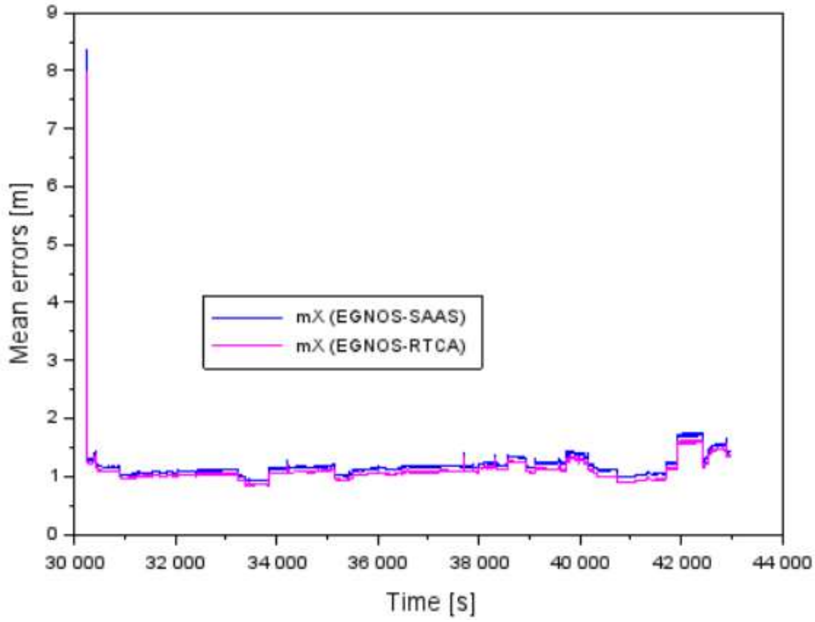

Fig. 3. Mean errors of aircraft position along the X-axis based on the GPS+EGNOS solution with the applied Saastamoinen and RTCA-MOPS model

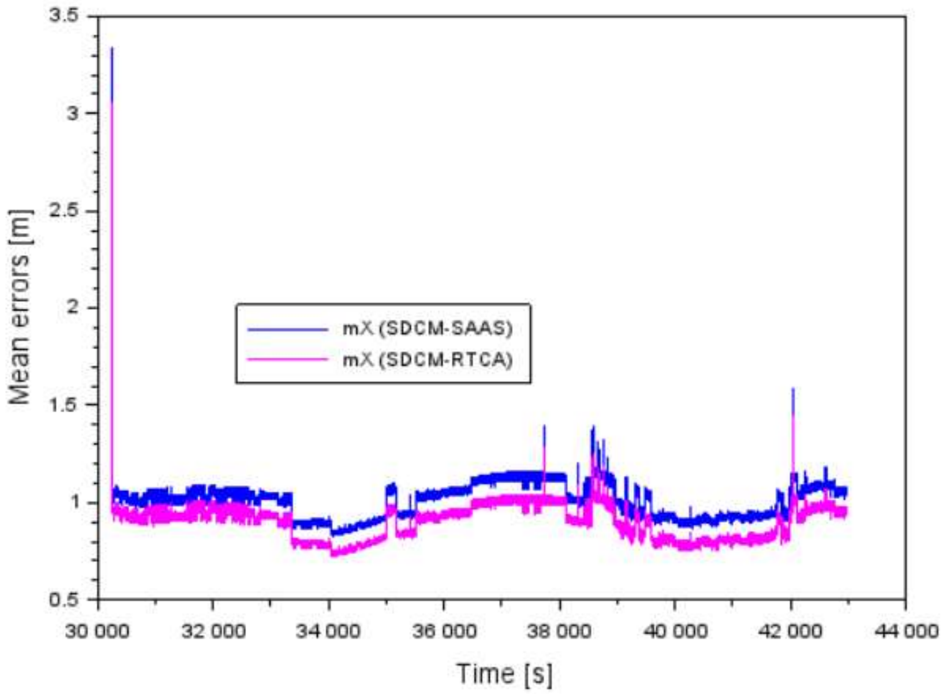

Fig. 4. Mean errors of aircraft position along the X-axis based on the GPS+SDCM solution with the applied Saastamoinen and RTCA-MOPS model.

Figures 5 and 6 show the mean error values along the Y-axis from the GPS+EGNOS and GPS+SDCM solutions. Mean error values mY from the GPS+EGNOS solution range from 0.68 to 2.77 m when using the Saastamoinen model for SBAS positioning. In contrast, the mean error values mY from the GPS+EGNOS solution range from 0.63 to 2.61 m when using the RTCA-MOPS model in SBAS positioning. Remarkably, with the tropospheric correction for the RTCA-MOPS model, the mean errors mY from the GPS+EGNOS solution improved from 5 to 7% compared to the Saastamoinen model in equation (1). For the GPS+SDCM solution using the Saastamoinen model, the mean errors mY ranged from 0.67 to 2.84 m. Furthermore, for the RTCA-MOPS model, the mean errors mY ranged from 0.59 to 2.62 m. In the analysed GPS+SDCM solution, the application of the RTCA-MOPS tropospheric correction model improved the determination of mean errors mY from 7 to 11%.

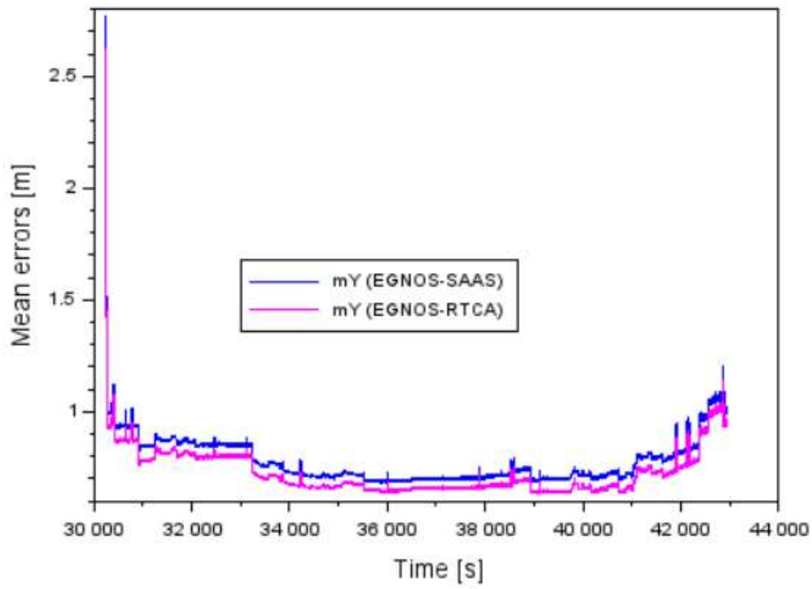

Fig. 5. Mean errors of aircraft position along the Y-axis based on the GPS+EGNOS solution with the applied Saastamoinen and RTCA-MOPS model

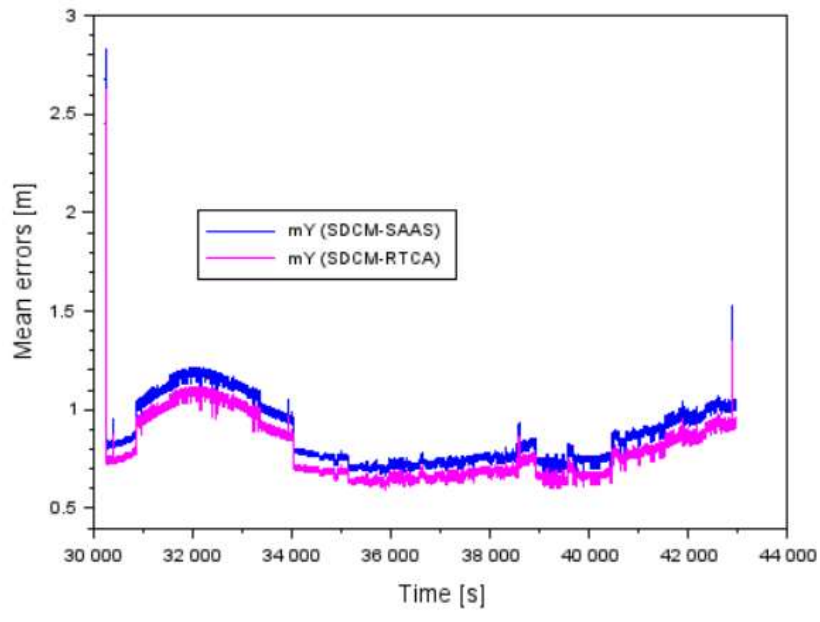

Fig. 6. Mean errors of aircraft position along the Y-axis based on the GPS+SDCM solution with the applied Saastamoinen and RTCA-MOPS model

Figures 7 and 8 show the mean error values along the Z-axis for the GPS+EGNOS and GPS+SDCM solutions. Mean error values mZ from the GPS+EGNOS solution range from 1.20 to 2.36 m when using the Saastamoinen model for SBAS positioning. In contrast, the mean error values mZ from the GPS+EGNOS solution range from 1.10 to 2.21 m when using the RTCA-MOPS model in SBAS positioning. Significantly, with the tropospheric correction for the RTCA-MOPS model, the mean errors mZ from the GPS+EGNOS solution improved from 6 to 8% compared to the Saastamoinen model in equation (1). For the GPS+SDCM solution using the Saastamoinen model, the mean errors mZ ranged from 1.20 to 3.59 m. Additionally, for the RTCA-MOPS model, the mean errors mZ ranged from 1.07 to 3.17 m. In the analysed GPS+SDCM solution, the application of the RTCA-MOPS tropospheric correction model improved the determination of mean errors mZ from 10 to 12%.

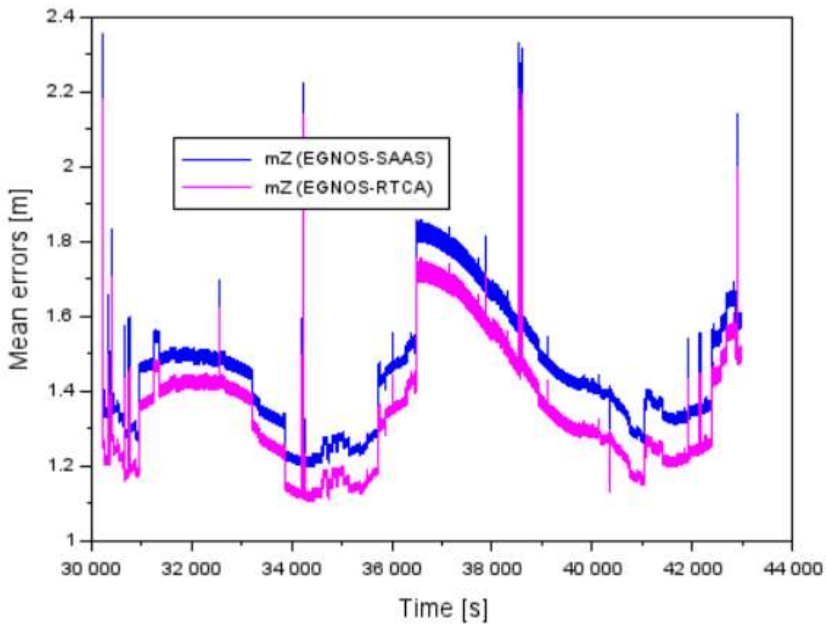

Fig. 7. Mean errors of aircraft position along the Z-axis based on the GPS+EGNOS solution with the applied Saastamoinen and RTCA-MOPS model

When developing the results of the obtained coordinates and their mean errors, the ellipsoid of the point position error is additionally determined [20]. The values of the ellipsoid parameter of the point position error are determined from the relationship [20]:

$$\begin{cases} MP_{SAAS} = \sqrt{mX_{SAAS}^2 + mY_{SAAS}^2 + mZ_{SAAS}^2} \\ MP_{RTCA} = \sqrt{mX_{RTCA}^2 + mY_{RTCA}^2 + mZ_{RTCA}^2} \end{cases} \tag{4}$$

where:
MP_{SAAS}- ellipsoid error of point position, considering the mean errors from the GPS+SBAS solution for the Saastamoinen troposphere model,
MP_{RTCA}- ellipsoid error of point position, considering the mean errors from the GPS+SBAS solution for the RTCA-MOPS troposphere model,

$(mX_{SAAS}, mY_{SAAS}, mZ_{SAAS})$- values of mean errors from the GPS+SBAS solution for the Saastamoinen troposphere model, determined from equation (2); the findings are in Figures 3, 5 and 7.
$(mX_{RTCA}, mY_{RTCA}, mZ_{RTCA})$- values of mean errors from the GPS+SBAS solution for the RTCA-MOPS troposphere model determined from equation (2); the findings are in Figures 4, 6 and 8.

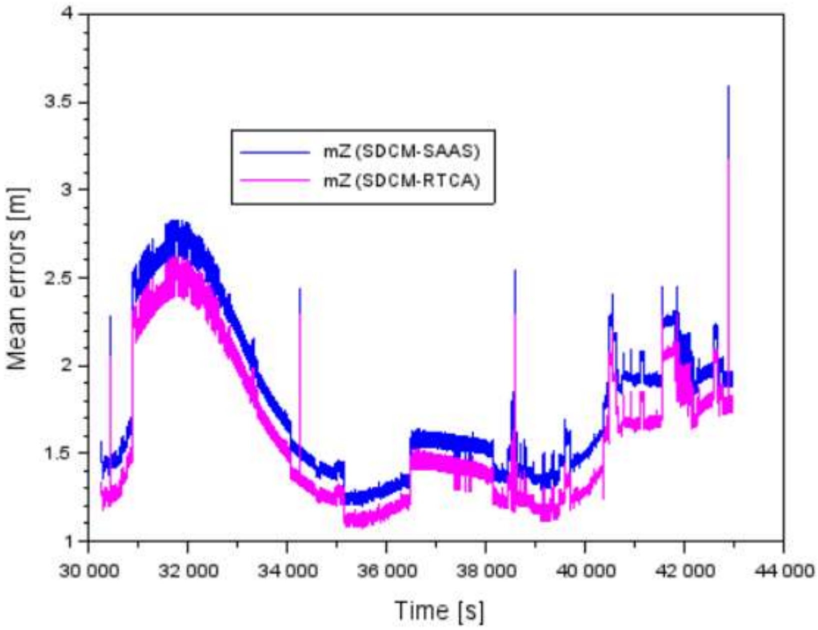

Fig. 8. Mean errors of aircraft position along the Z-axis based on the GPS+SDCM solution with the applied Saastamoinen and RTCA-MOPS model

Figures 9 and 10 show the results of parameters MP_{SAAS} and MP_{RTCA}, calculated from the GPS+EGNOS and GPS+SDCM solutions for different tropospheric delay models. Parameter values MP_{SAAS} from the GPS+EGNOS solution range from 1.74 to 9.12 m when using the Saastamoinen model for the SBAS positioning. In contrast, the mean error values MP_{RTCA} from the GPS+EGNOS solution range from 1.59 to 8.67 m when using the RTCA-MOPS model in the SBAS positioning. The application of the RTCA-MOPS model results in an improvement of the parameter results MP_{RTCA} from 5 to 9% compared to the size results MP_{SAAS}. Parameter values MP_{SAAS} from the GPS+SDCM solution range from 1.66 to 4.65 m when using the Saastamoinen model for the SBAS positioning. In contrast, the mean error values MP_{RTCA} from the GPS+SDCM solution range from 1.48 to 4.23 m when using the RTCA-MOPS model in the SBAS positioning. The application of the RTCA-MOPS model results in an improvement of the parameter results MP_{RTCA} from 9 to 11% compared to the magnitude of results MP_{SAAS}.

The obtained results show the high efficiency of the RTCA-MOPS model over the Saastamoinen model in SBAS positioning for air navigation. Using a selected tropospheric correction model in the positioning method significantly affects the aircraft coordinate findings, as shown in Figures 1 and 2. Most importantly, the RTCA-MOPS troposphere model reduced the values of the mean errors of the determined aircraft coordinates in both the GPS+EGNOS and GPS+SDCM solutions. The repeatability of the test method is true for the two augmentation systems - EGNOS and SDCM. Compared to the state of expertise, similar conclusions were drawn in related works [6, 10, 11, 13], in which the RTCA-MOPS troposphere model in GNSS positioning was also examined. It can, therefore, be stated that the RTCA-MOPS troposphere model is optimal for the SBAS positioning method in air navigation.

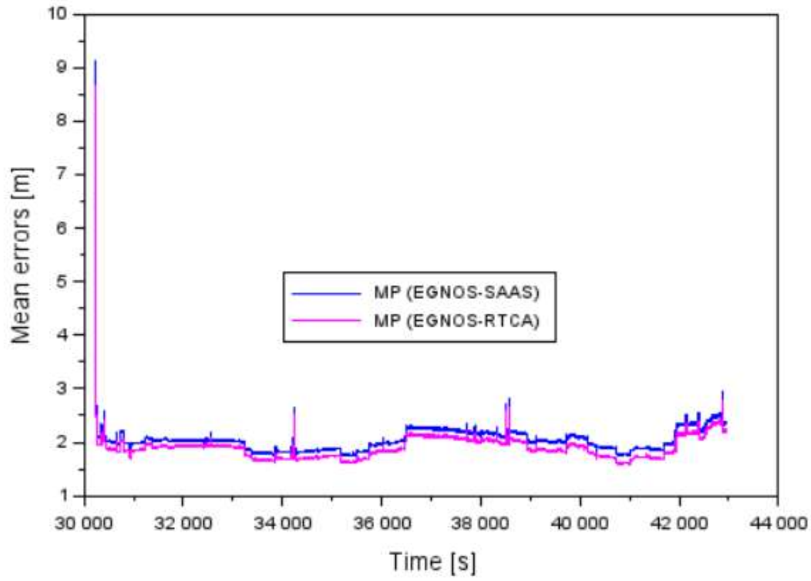

Fig. 9. Ellipsoid error of point position based on the GPS+EGNOS solution with the applied Saastamoinen and RTCA-MOPS model

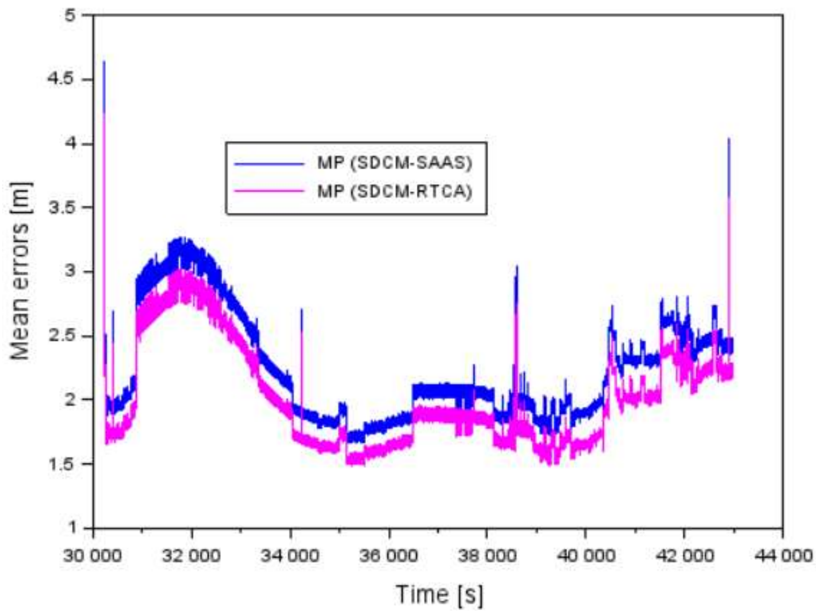

Fig. 10. Ellipsoid error of point position based on the GPS+SDCM solution with the applied Saastamoinen and RTCA-MOPS model

6. CONCLUSIONS

This paper presents the results of a study on the use of different tropospheric correction models in the SBAS precise positioning for aerial navigation. Specifically, this paper determines the influence of the Saastamoinen troposphere and RTCA-MOPS models on the determination of aircraft coordinates and mean coordinate errors in the SBAS positioning method. The flight test was executed in north-eastern Poland in 2020. The test used real kinematic data from a GPS navigation system recorded by an onboard GNSS satellite receiver and SBAS corrections downloaded from a real-time server. In the experiment, the authors included SBAS corrections from EGNOS and SDCM augmentation systems. The navigation calculations were performed using RTKLIB v.2.4.3 and Scilab 6.1.1 software. Based on the conducted research, it was found that the difference in aircraft coordinates using different troposphere models can reach up to ±2.14 m. Furthermore, the use of the RTCA-MOPS troposphere model improved the values of the mean coordinate errors from 5 to 9% for the GPS+EGNOS solution and from 7 to 12% for the GPS+SDCM solution, respectively. Additionally, the ellipsoid values of the point position error were improved from 5 to 9% in the GPS+EGNOS solution and from 9 to 11% in the GPS+SDCM solution, assuming the use of the RTCA-MOPS troposphere model in the SBAS positioning method. The obtained computational findings confirm the validity of using the RTCA-MOPS troposphere model for SBAS positioning in air navigation. The computational strategy presented in this paper is universal and can be extended by its implementation into the GAGAN positioning in air navigation in Poland. The authors intend to conduct further research into the impact of the tropospheric correction in the GNSS positioning for air navigation.

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