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ACCURACY ANALYSIS OF UAV COORDINATES USING EGNOS AND SDCM AUGMENTATION SYSTEMS

Summary. SBAS systems are applied in precise positioning of UAV. The paper presents the results of studies on the improvement of UAV positioning with the use of the EGNOS+SDCM solutions. In particular, the article focuses on the application of the model of totaling the SBAS positioning accuracy to improve the accuracy of determining the coordinates of UAVs during the realisation of a test flight. The developed algorithm takes into account the position errors determined from the EGNOS and SDCM solutions. as well as the linear coefficients that are used in the linear combination model. The research was based on data from GPS observations and SBAS corrections from the AsteRx-m2 UAS receiver installed on a Tailsitter platform. The tests were conducted in September 2020 in northern Poland. The application of the proposed algorithm that sums up the positioning

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accuracy of EGNOS and SDCM allowed for the improvement of the accuracy of determining the position of the UAV by 82-87% in comparison to the application of either only EGNOS or SDCM. Apart from that, another important result of the application of the proposed algorithm was the reduction of outlier positioning errors that reduced the accuracy of the positioning of UAV when a single SBAS solution (EGNOS or SDCM) was used. The study also presents the effectiveness of the proposed algorithm in terms of calculating the accuracy of EGNOS+SDCM positioning for the weighted average model. The developed algorithm may be used in research conducted on other SBAS supporting systems.

Keywords: SBAS, EGNOS, SDCM, accuracy, position errors, UAV

1. INTRODUCTION

The preparation and development of the project, the construction as well as the final validation and certification of the UAV (Unmanned Aerial Vehicle) for performing flights also involves the necessity to implement mathematical algorithms to improve the UAV coordinates in real time and to carry out the necessary navigation analyses in post-processing mode [1]. In consequence, this requires an appropriate selection of sensors and equipment to localise the platform and the correct configuration of input data and mathematical models to describe the equation of the position of UAV movement [2]. In the 21st century, the navigational position of the UAV was estimated using GNSS (Global Navigation Satellite System) data [3, 4]. Other, optional navigation functions of the flight include the estimation of the acceleration and the angles of UAV orientation in the aerial space [5]. The knowing of the position of the UAV is essential from the point of view of navigation [6], as well as of the dynamics and kinematics of the flight [7] and, finally, of the safety process of the flight itself [8]. All the more reasons for the issues of improving the positioning to be continuously developed as part of the UAV technology. This is obviously a result of the development of the GNSS systems and precise positioning methods in aerial navigation [9]. Moreover, the UAV-related topics are being increasingly used in photogrammetric, remote sensing and geoinformation applications [5, 10, 11, 12, 13]. As a standard, the low-cost on-board GNSS receivers usually employ the SPP (Single Point Positioning) method [14] to designation the coordinates of the UAV in near-real time. However, one of the problems of this method in aviation applications in UAVs is its low positioning accuracy, which may reach even up to 10 m [15, 16, 17]. This method is used by single-frequency receivers installed on the UAV platform [18]. This led to various attempts to develop mathematical algorithms that would improve the positioning of UAVs in the SPP method [19]. One of the GNSS satellite positioning methods that allows for the improvement of code positioning results is the SBAS (Satellite Based Augmentation System) method [20]. Although it still uses the algorithm of the code-based SPP method, its calculations are based on the corrections from the given SBAS support system [21]. However, the SBAS method significantly increases the accuracy of UAV positioning, to the level of 1÷3 m [22], which, in turn, influences the value of the determined coordinates of the UAV and, obviously, the linear elements of external orientation

2. RELATED WORKS

The literature on the subject of this study provides numerous references to the application of SBAS support systems in the navigation solution of UAV positioning. For example, publication [23] presents a concept of the application of the SBAS system for the territory of South Korea for the purposes of the UAV technology. In particular, various aspects of using UAV as part of the KASS (Korea Augmentation Satellite System) support system are discussed. Study [24] presents a possibility to employ the SBAS support system for the purposes of determining the position of UAV during a performed photogrammetric flight. The authors also compare the SBAS positioning method with the DGPS (Differential GPS) differential technique. The authors of [25] present the possibilities to employ UAV for mapping the passability of roads. In another publication [26], the WAAS support system was used in the process of the determination of the coordinates of the centres of the projection with use of aerial data obtained from the UAV. Moreover, the authors of [27] presented the possibility to employ the WAAS support system in the UAV technology in agriculture, for the purposes of drainage of agricultural areas. The authors compared the terrain mapping results obtained from the SBAS/WAAS systems and the RTK (Real Time Kinematic) solution. Publication [28] analyses the results of the EGNOS and Galileo (European Navigation Satellite System) positioning for the purposes of improving the flight safety of UAV. The study presents various scenarios of configuration of Galileo+EGNOS positioning for the UAV technology. The authors of [29] proposed a plan of developing new onboard avionics for UAV, based on the SBAS and GBAS (Ground Based Augmentation System) systems and other radio navigation systems for the unmanned platform. The works [30, 31] present a concept of the application of the Australian GATBP (Geoscience Australia Test Bed Project) support system to be used in UAV applications for agricultural and forestry purposes. The authors of [32] proposed a concept of using UAV in industrial and business applications. To this end, the SBAS system was used to improve the accuracy and integrity of UAV positioning in terms of the altitude of flight of the platform. Publication [33] shows the results of UAV positioning accuracy for the navigation solution from the GPS (Global Positioning System) system and also GPS+EGNOS. Furthermore, the authors of [34] described the results of research on the implementation of the PBN (Performance Based Navigation) concept for UAV navigation based on the SBAS solution. Other publications [35, 36] present the application of UAV for flight inspection, taking into consideration the environmental factors and financial costs. Those publications also propose a SBAS positioning model that is based on the correction data from the SBAS system. The authors of [37] presented the results of the research on the management of UAV air traffic and the navigation of UAV based on the BDSBAS (BeiDou SBAS) system for the territory of China. The research work [38] is an elaboration of publication [37]. The authors of [38] presented a model of operation, the configuration, architecture, and specific elements of the BDSBAS support system, taking into account aviation applications, including for the UAV technology. Publication [39] presented numerous applications of the SBAS-Africa support system, including aviation applications, also for the UAV technology. The authors of [40] presented the possibility of integrating inertial data from the INS (Inertial Navigation System) with the corrections from the MSAS (Multi-functional Satellite Augmentation System) system for the purposes of UAV positioning during flight. Apart from that, the authors also used the DGPS navigation data. Another publication [41] presented the accuracy and integrity parameters of UAV positioning based on MSAS solution. Article [42] presented the results of the application of the GNSS system in the digital aerotriangulation process for the determination of the Digital Terrain Model with use of aerial photos obtained from the UAV.

However, the conducted research revealed that it was impossible to use the SBAS solution during the test flight. Finally, only the RTK and PPK (Post-Processing Kinematic) solutions could be implemented. Paper [43] described various scenarios of application and challenges faced by SBAS support systems in the urban, highly developed environment. The authors discussed various aspects of the application of SBAS systems in the UAV technology for urban areas. Moreover, the publication [44] provided a direct reference to the application of UAV in transport, logistics, and industry, considering the SBAS support systems. Very interesting research results were presented in article [45], namely the percentage of application of SBAS support systems in the UAV area was described. It revealed that many users for not use the SBAS support systems in the UAV technology. The authors of [46] developed a new algorithm to designation the planes of the UAV based on the GNSS/SBAS or ILS (Instrument Landing System) systems, but additionally with the use of a visual camera during the landing process of the UAV. The computational algorithm takes into account the solution of the position of the UAV for Kalman filtration. Finally, the authors of [47, 48] presented a possibility to apply the EGNOS support system to improve the flight safety of the UAV in various aviation operations. The basic conclusions from literature review focus on:

- the positioning of UAV based on SBAS system is important in navigation but also for the safety of flight [28, 47, 48];
- SBAS support systems were also applied in the UAV technology for the purposes of photogrammetric studies [24-27, 42];
- various support systems, e.g. EGNOS [28], WAAS [25], BDSBAS [38], MSAS [41], etc. were used in research;
- the utilization of SBAS systems for UAV allows optimising the financial costs, has a lower negative influence on the natural environment [35, 36], and may enhance the development of the industry in urban and highly urbanised areas [43, 44];
- the SBAS positioning method is better than the code-based SPP method [22, 33].

The analysis of the state of knowledge on the topic in question revealed that the accurate positioning of UAV based on SBAS augmentation system is an important issue in aviation. Moreover, it has a direct influence on the navigation aspect of determining the coordinates of the UAV position, and, in photogrammetric terms, on the determination of the linear elements of external orientation. It should be noted, as subject literature reveals, that so far, only one SBAS support system has been used for the precise positioning of UAV. However, this may change if data from two or more SBAS support systems are elaborated. This is an important research issue in the search for new solutions and algorithms that would improve the accuracy of UAV positioning and thus the position of the unmanned platform. The application of SBAS systems is crucial for satellite positioning that employs single-frequency GNSS receivers installed on the UAV platform. Moreover, such a solution might contribute to the improvement of the determination of linear elements of external orientation, whose approximate values are required at the initial stages of the digital aerotriangulation process [3, 5].

For that reason, the authors of the present paper have carried out an analysis of the accuracy of UAV positioning based on EGNOS+SDCM solutions in UAV applications. To this end, the variant of integration of EGNOS and SDCM data in the navigation process of solution of the position of the UAV was developed and presented here. Namely, the following were applied in the model summating the parameters of UAV positioning accuracy. The developed algorithm involves the use of linear coefficients, which, in this case, will be determined as the reverse of the UAV flight velocity from the EGNOS solution and, respectively, SDCM solution. The value of the linear coefficient was selected in such a way that it refers both to the navigation aspect and to the flight dynamics of the UAV. The developed computational strategy was tested on actual GNSS kinematic data recorded by a single-frequency receiver installed on a UAV platform. The variant of analysing the accuracy of SBAS positioning described here allows the user to select the optimum model of the navigation solution of UAV positioning. It should be mentioned that the developed algorithm may also consider other linear coefficients that are adjusted to the needs of a specific user.

In conclusion, the main research achievements of the study refer to: developing an algorithm to integrate the EGNOS and SDCM navigation data in the process of determining the coordinates of the UAV; determining the linear coefficients as a function of the flight speed of the UAV for the proposed mathematical algorithm; testing the correctness of the functioning of the proposed mathematical algorithm on GNSS kinematic data that were recorded by an on-board GNSS satellite receiver installed on a UAV platform; demonstrating the appropriateness of the mathematical algorithm for the integration of the EGNOS+SDCM data in reference to only EGNOS and also SDCM solutions; demonstrating the appropriateness of the mathematical algorithm regarding the weighted average model for calculating the accuracy of EGNOS+SDCM positioning.

The paper is divided into 7 sections and a list of all bibliographic references is provided at the end of the paper.

3. RESEARCH METHOD

For the purposes of the analysis of the accuracy of EGNOS+SDCM positioning for UAV, a variant of the mathematical algorithm was presented in form of the model summating the accuracy parameters in the geodetic coordinates BLh (B is Latitude, L is Longitude, h is ellipsoidal height), as presented below:

$$\begin{cases} dB = \sum_1^n \alpha_{SBASi} \cdot dB_{SBASi} \\ dL = \sum_1^n \alpha_{SBASi} \cdot dL_{SBASi} \\ dh = \sum_1^n \alpha_{SBASi} \cdot dh_{SBASi} \end{cases} \tag{1}$$

where:
(dB, dL, dh) – final accuracy of EGNOS+SDCM positioning,
n – number of SBAS augmentation systems; in this case $n = 2$,
$SBAS_i$ – individual SBAS augmentation systems, i.e. EGNOS and SDCM,
$(dB_{SBASi}, dL_{SBASi}, dh_{SBASi})$ – single positioning accuracy from the SBAS solution [49], i.e. EGNOS or SDCM.

If a EGNOS and SDCM solution is included in equation (1), the final result will be a mathematical expression in the model of the sum of products of the accuracy parameter, as presented below:

$$\begin{cases} dB = \alpha_{EGNOS} \cdot dB_{EGNOS} + \alpha_{SDCM} \cdot dB_{SDCM} \\ dL = \alpha_{EGNOS} \cdot dL_{EGNOS} + \alpha_{SDCM} \cdot dL_{SDCM} \\ dh = \alpha_{EGNOS} \cdot dh_{EGNOS} + \alpha_{SDCM} \cdot dh_{SDCM} \end{cases} \tag{2}$$

The consecutive position errors $(dB_{EGNOS}, dL_{EGNOS}, dh_{EGNOS})$ from the EGNOS solution and, respectively, the position errors $(dB_{SDCM}, dL_{SDCM}, dh_{SDCM})$ from the SDCM solution may be expressed in form of the coordinates of the position of the UAV, to obtain:

$$\begin{cases} dB = \alpha_{EGNOS} \cdot (B_{EGNOS} - B_{RTK-OTF}) + \alpha_{SDCM} \cdot (B_{SDCM} - B_{RTK-OTF}) \\ dL = \alpha_{EGNOS} \cdot (L_{EGNOS} - L_{RTK-OTF}) + \alpha_{SDCM} \cdot (L_{SDCM} - L_{RTK-OTF}) \\ dh = \alpha_{EGNOS} \cdot (h_{EGNOS} - h_{RTK-OTF}) + \alpha_{SDCM} \cdot (h_{SDCM} - h_{RTK-OTF}) \end{cases} \quad (3)$$

where:
$(B_{EGNOS}, L_{EGNOS}, h_{EGNOS})$ – geodetic position of the UAV position from the EGNOS solution,
$(B_{SDCM}, L_{SDCM}, h_{SDCM})$ – geodetic position of the UAV position from the SDCM solution,
$(B_{RTK-OTF}, L_{RTK-OTF}, h_{RTK-OTF})$ – geodetic position of the UAV position from the RTK-OTF (Real Time Kinematic – On The Fly) solution, flight reference position [50].

Further transformation of equation (3) results in:

$$\begin{cases} dB = \alpha_{EGNOS} \cdot B_{EGNOS} - \alpha_{EGNOS} \cdot B_{RTK-OTF} + \alpha_{SDCM} \cdot B_{SDCM} - \alpha_{SDCM} \cdot B_{RTK-OTF} \\ dL = \alpha_{EGNOS} \cdot L_{EGNOS} - \alpha_{EGNOS} \cdot L_{RTK-OTF} + \alpha_{SDCM} \cdot L_{SDCM} - \alpha_{SDCM} \cdot L_{RTK-OTF} \\ dh = \alpha_{EGNOS} \cdot h_{EGNOS} - \alpha_{EGNOS} \cdot h_{RTK-OTF} + \alpha_{SDCM} \cdot h_{SDCM} - \alpha_{SDCM} \cdot h_{RTK-OTF} \end{cases} \quad (4)$$

Then, individual parameters may be grouped and the equation may be written in the form:

$$\begin{cases} dB = \alpha_{EGNOS} \cdot B_{EGNOS} + \alpha_{SDCM} \cdot B_{SDCM} - (\alpha_{EGNOS} + \alpha_{SDCM}) \cdot B_{RTK-OTF} \\ dL = \alpha_{EGNOS} \cdot L_{EGNOS} + \alpha_{SDCM} \cdot L_{SDCM} - (\alpha_{EGNOS} + \alpha_{SDCM}) \cdot L_{RTK-OTF} \\ dh = \alpha_{EGNOS} \cdot h_{EGNOS} + \alpha_{SDCM} \cdot h_{SDCM} - (\alpha_{EGNOS} + \alpha_{SDCM}) \cdot h_{RTK-OTF} \end{cases} \quad (5)$$

Equation (5) describes the algorithm to determine the EGNOS+SDCM positioning for UAV, but it also presents the integration of the EGNOS+SDCM navigation solution for the UAV. Thus, equation (5) is the basic equation for analysing the EGNOS+SDCM positioning accuracy for the UAV in the model summating the accuracy parameters.

The key parameters for the presented equations (1-5) are the linear coefficients denoted by the symbols: $(\alpha_{EGNOS}, \alpha_{SDCM})$. The values of these linear coefficients were determined as a function of the reverse velocity of flight of the UAV [51], as presented below:

$$\begin{cases} \alpha_{EGNOS} = \frac{1}{V_{EGNOS}} = \frac{1}{\sqrt{V_{EGNOS,B}^2 + V_{EGNOS,L}^2 + V_{EGNOS,h}^2}} \\ \alpha_{SDCM} = \frac{1}{V_{SDCM}} = \frac{1}{\sqrt{V_{SDCM,B}^2 + V_{SDCM,L}^2 + V_{SDCM,h}^2}} \end{cases} \quad (6)$$

where:
V_{EGNOS}- resultant flight velocity of the UAV based on EGNOS solution,
$V_{EGNOS,B}$- flight velocity of the UAV based on EGNOS result for the B axis,
$V_{EGNOS,L}$- flight velocity of the UAV based on EGNOS result for the L axis,
$V_{EGNOS,h}$- flight velocity of the UAV based on EGNOS result for the h axis,
V_{SDCM}- resultant flight velocity of the UAV based on SDCM solution,
$V_{SDCM,B}$- flight velocity of the UAV based on SDCM result for the B axis,

$V_{SDCM,L}$- flight velocity of the UAV based on SDCM result for the L axis,
$V_{SDCM,h}$- flight velocity of the UAV based on SDCM result for the h axis.

The proposed algorithm (1-6) will be tested on actual kinematic GNSS data that were recorded by a single-frequency satellite receiver installed on the UAV platform. The test results are discussed in Section 5.

4. RESEARCH EXPERIMENT

Section 4 contains a presentation and detailed description of the course of the research test. The research process was divided into three stages as follows: a) Stage 1 consisted in the realisation of the test flight of the UAV with the aim of collecting GNSS navigation data by the AsteRx-m2 UAS receiver installed on the Tailsitter platform; b) Stage 2 involved the calculation of the position of the UAV with the use of the code-based SPP method and the corrections from EGNOS and SDCM; c) Finally, stage 3 consisted in the implementation and realisation of the proposed mathematical algorithm (1-6).

During stage 1, a test flight was performed with the use of a Tailsitter platform equipped with a single-frequency AsteRx-m2 UAS receiver. The test flight took place in September 2020 in northern Poland, before noon. The Figure 1 presents the horizontal trajectory of the flight. The dispersion in the geodesic coordinate B was from 54.351375^{o} to 54.359209^{o}. Furthermore, the dispersion in the geodesic coordinate L ranged from 19.661528^{o} to 19.676888^{o}.

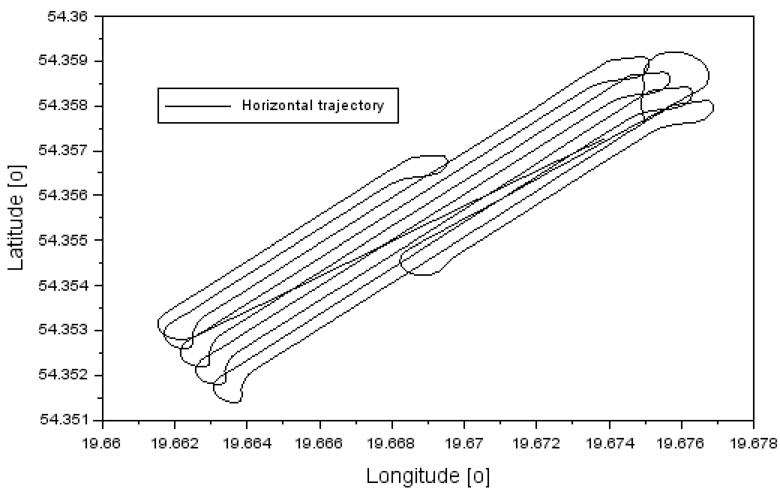

Fig. 1. The horizontal trajectory of the UAV

Figure 2 presents the vertical trajectory of the flight in relation to the time. The change in the flight altitude of the UAV was from 100.777 m to 131.723 m. The lowest ellipsoidal altitude of flight was obviously noted during take-off of the UAV platform.

During the flight, the AsteRx-m2 UAS receiver recorded, respectively, from 4 to 9 GPS satellites, for which SDCM corrections were calculated. Apart from that, the AsteRx-m2 UAS receiver recorded, respectively, from 5 to 10 GPS satellites, for which EGNOS corrections were calculated. The number of GPS satellites with SDCM and EGNOS corrections is presented in Figure 3. As one may notice, the lowest number of tracked GPS satellites with SDCM and EGNOS corrections was visible in the initial phase of flight, during take-off. With time, the number of follow satellites with SDCM and EGNOS corrections continued to increase.

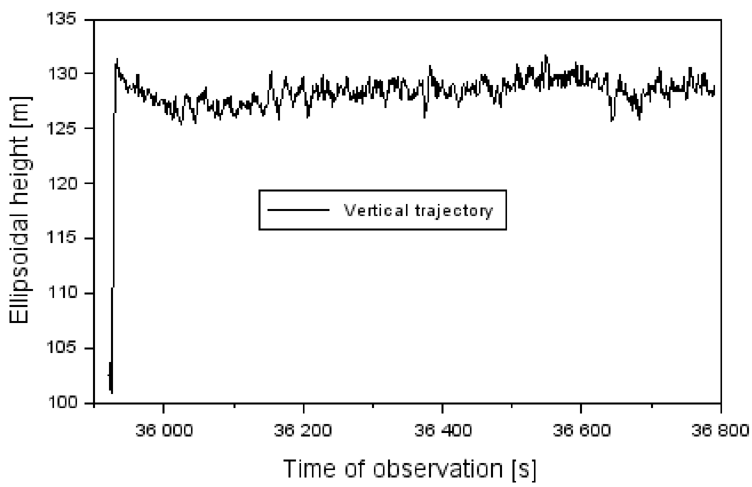

Fig. 2. The vertical flight of the UAV

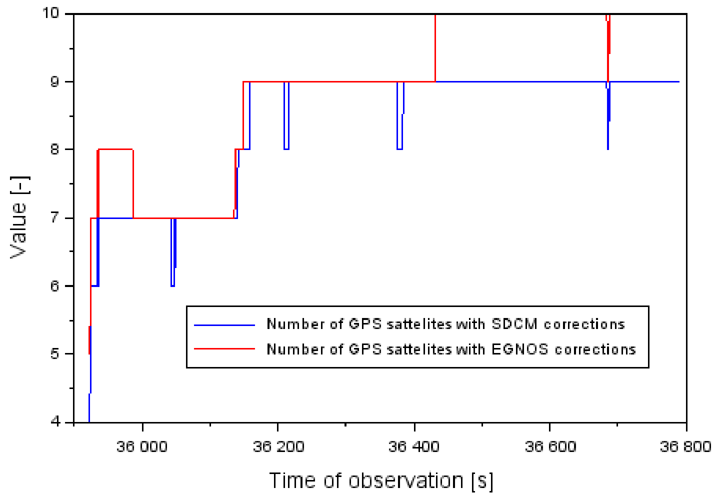

Fig. 3. Number of GPS satellites with SDCM and EGNOS corrections

Stage 2 of the research consisted in calculating the coordinates of the UAV based on GPS code observations and EGNOS and SDCM corrections. The calculations were performed with the use of the code SPP positioning method in the RTKPOST module of the RTKLIB v.2.4.3 software [52]. For each SDCM and EGNOS solution, the coordinates of the UAV were determined at a time interval of 1 s. Additionally, the reference trajectory of the UAV flight was defined with the use of the RTK-OTF positioning technique [53]. The positioning accuracy of SDCM and EGNOS was determined based on equation (3). Moreover, the usability of the GPS constellation for the navigation solution of the position of the UAV was also determined, in form of the PDOP (Position DOP) geometric coefficient [54]. As a result, Figure 4 presents the results of PDOP for the SDCM and EGNOS solutions. The values of the PDOP coefficient based on SDCM solution ranged from 1.8 to 3.9, while the values based on EGNOS solution ranged from 2.0 to 4.2. One may notice that the worst values of the PDOP coefficient were noted in the initial phase of flight, when the AsteRx-m2 UAS receiver recorded the fewest GPS observations with SDCM and EGNOS corrections. With time, the values of the PDOP coefficient decreased below 2.5, which means, in practice, that the conditions for conducting GNSS measurements were very good.

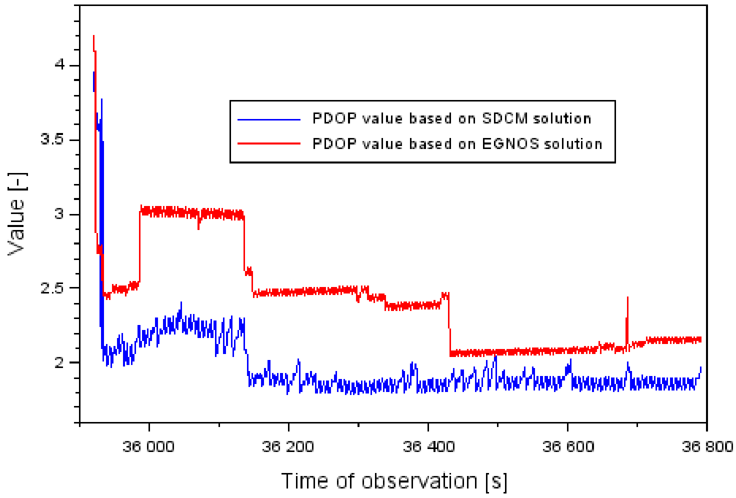

Fig. 4. The PDOP values based on SDCM and EGNOS solutions

Stage 3 of the research involved the final implementation and performing the proposed mathematical algorithm (1-6) in the Scilab v.6.0.0 language environment [55]. The whole source code in which the mathematical algorithm (1-6) was written with the commands that are necessary to perform the graphic analysis of the obtained research results was developed in a numerical script in the Scilab environment.

5. RESULTS

Chapter 5 presents the obtained research results, starting from the flight velocity (V_{SDCM}, V_{EGNOS}) from the SDCM and EGNOS solutions to the values of the linear coefficients (α_{SDCM}, α_{EGNOS}) from the SDCM and EGNOS solutions, and finally, the positioning accuracy (dB, dL, dh) from the EGNOS+SDCM solution. Figure 5 shows the values of the flight velocity parameters (V_{SDCM}, V_{EGNOS}) based on the SDCM and EGNOS solutions. The flight speed of the UAV based on the SDCM solution ranged from 9.2 m/s to 27.6 m/s, while the velocity based on the EGNOS solution ranged from 9.3 m/s to 23.3 m/s. The highest values of the movement speed of the UAV were noted in the initial phase of flight.

Figure 6 presents the values of the linear coefficients (α_{SDCM}, α_{EGNOS}) based on the SDCM and EGNOS solutions, calculated from equation (6). The values of the linear coefficients α_{SDCM} based on the SDCM solution ranged from 0.036 to 0.109, whereas the values of the linear coefficients α_{EGNOS} based on the EGNOS solution ranged from 0.043 to 0.108. The lowest values of the coefficients (α_{SDCM}, α_{EGNOS}) were noted in the initial phase of flight, which obviously results from the values of the velocity of the UAV.

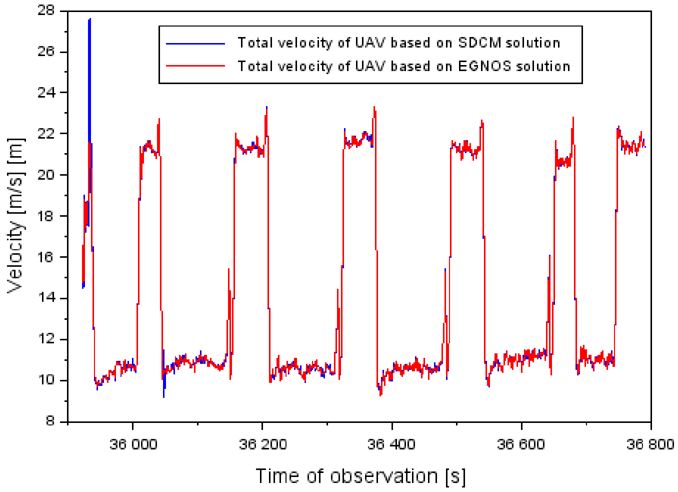

Fig. 5. The total velocity of UAV based on SDCM and EGNOS solutions

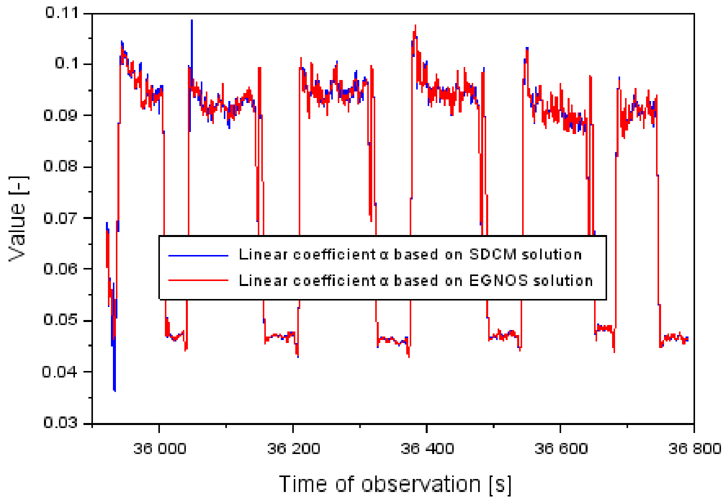

Fig. 6. The values of linear coefficients(α_{SDCM}, α_{EGNOS})

Figures 7, 8, and 9 show the position errors of EGNOS+SDCM solution in reference to the positioning accuracy from the EGNOS system and the SDCM system. According to the mathematical equations (1-6), the positioning accuracy is presented in form of position error parameters for the ellipsoidal coordinates BLh of the position of the UAV. Figure 7 presents the results of position errors for the B component. These position errors for the B component based on the SDCM solution ranged from -1.9 m to +5.7 m. Analogically, the position errors based on the EGNOS solution ranged from -1.2 m to +1.4 m. As a result of the application of the proposed mathematical algorithm (1-6), the positioning errors took the values from -0.3 m to +0.2 m. As far as the accuracy of the B coordinate is concerned, one may conclude that the proposed mathematical algorithm (1-6) for the EGNOS+SDCM solution increased the accuracy by 83% in comparison to the SDCM solution and by 86% in comparison to the EGNOS solution. Figure 8 presents the values of position errors for the L component. These position errors for the L component based on the SDCM solution ranged from -2.6 m to +1.6 m. Analogically, the position errors based on the EGNOS solution ranged from -1.3 m to +1.2 m. When the EGNOS+SDCM solution was applied, the position errors took the values ranging from -0.2 m to +0.2 m. As far as the accuracy of the L coordinate is concerned, one may conclude that the proposed mathematical algorithm (1-6) for the EGNOS+SDCM solution increased the accuracy by 84% in comparison to the SDCM solution and by 87% in comparison to the EGNOS solution. Figure 9 shows the values of position errors for the h coordinate. These position errors for the h component based on the SDCM solution ranged from -3.5 m to +14.3 m. Analogically, the position errors based on the EGNOS solution ranged from -2.4 m to +5.5 m. When the EGNOS+SDCM solution was applied, the position errors took the values ranging from -0.5 m to +0.9 m. As far as the accuracy of the h coordinate is concerned, one may conclude that the proposed mathematical algorithm (1-6) for the EGNOS+SDCM solution increased the accuracy by 82% in comparison to the SDCM solution and by 86% in comparison to the EGNOS solution. The analysis of specific position errors along the BLh axes reveals that the application of the proposed mathematical algorithm (1-6) brought a quite significant reduction of the position errors. This is rather vital when low positioning accuracy results are obtained from the EGNOS or SDCM solutions, which is noticeable in the initial phase of flight of the Tailsitter platform. This makes the development of algorithms that would improve the accuracy of determining the horizontal components, but especially the vertical component h even more important for the safety of performing aviation operations with the use of UAV. The proposed EGNOS+SDCM solution summating the positioning accuracy may prove to be a very interesting algorithm in the process of developing SBAS data for the UAV technology.

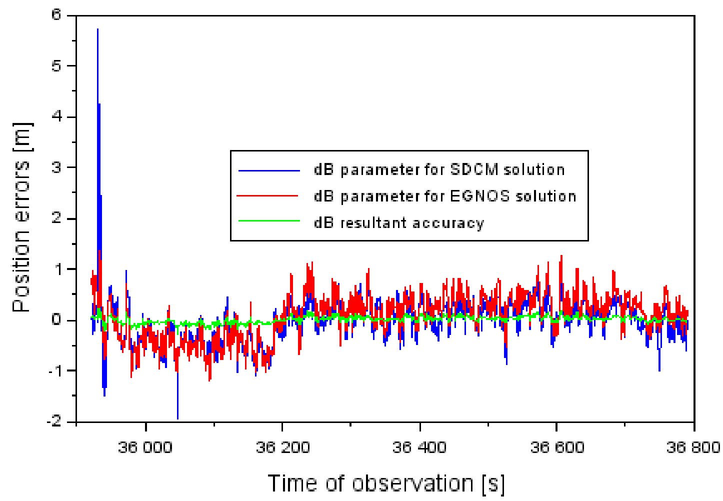

Fig. 7. The position errors along B axis

6. DISCUSSION

The Discussion Section of this paper has been divided into three parts. The first part refers to the comparison of the obtained results of the EGNOS+SDCM positioning accuracy based on the proposed algorithm (1-6) with the EGNOS+SDCM positioning accuracy calculated from the weighted average model. The second part contains a presentation of the results of EGNOS+SDCM positioning accuracy in the context of the repeatability of the calculation process. Finally, the third stage of the discussion provides a comparison of the obtained research results in the light of the analysis of the state of knowledge concerning the analysed research problems.

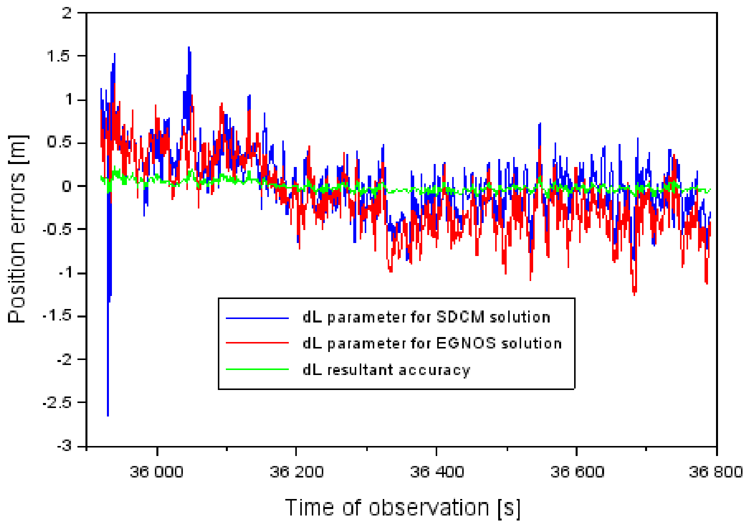

Fig. 8. The position errors along L axis

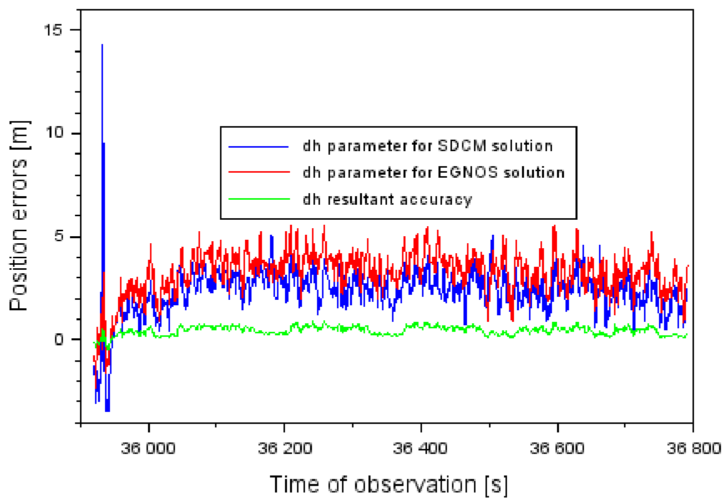

Fig. 9. The position errors along h axis

6.1. Comparison of the obtained results with the weighted average model of positioning accuracy

The weighted average model for the determination of the accuracy parameter in the EGNOS+SDCM solution may be presented in the following form:

$$\begin{cases} dB = \sum_1^n \frac{\alpha_{SBASi} \cdot dB_{SBASi}}{\alpha_{SBASi}} \\ dL = \sum_1^n \frac{\alpha_{SBASi} \cdot dL_{SBASi}}{\alpha_{SBASi}} \\ dh = \sum_1^n \frac{\alpha_{SBASi} \cdot dh_{SBASi}}{\alpha_{SBASi}} \end{cases} \tag{7}$$

Using a single SBAS solution (EGNOS or SDCM) in equation (7), the final result will be a mathematical expression in the weighted average model of the accuracy parameter, as presented below:

$$\begin{cases} dB = \frac{\alpha_{EGNOS} \cdot dB_{EGNOS} + \alpha_{SDCM} \cdot dB_{SDCM}}{\alpha_{EGNOS} + \alpha_{SDCM}} \\ dL = \frac{\alpha_{EGNOS} \cdot dL_{EGNOS} + \alpha_{SDCM} \cdot dL_{SDCM}}{\alpha_{EGNOS} + \alpha_{SDCM}} \\ dh = \frac{\alpha_{EGNOS} \cdot dh_{EGNOS} + \alpha_{SDCM} \cdot dh_{SDCM}}{\alpha_{EGNOS} + \alpha_{SDCM}} \end{cases} \tag{8}$$

Just like in equation (3), the position errors may be written with the help of the UAV coordinates, which is shown below:

$$\begin{cases} dB = \frac{\alpha_{EGNOS} \cdot (B_{EGNOS} - B_{RTK-OTF}) + \alpha_{SDCM} \cdot (B_{SDCM} - B_{RTK-OTF})}{\alpha_{EGNOS} + \alpha_{SDCM}} \\ dL = \frac{\alpha_{EGNOS} \cdot (L_{EGNOS} - L_{RTK-OTF}) + \alpha_{SDCM} \cdot (L_{SDCM} - L_{RTK-OTF})}{\alpha_{EGNOS} + \alpha_{SDCM}} \\ dh = \frac{\alpha_{EGNOS} \cdot (h_{EGNOS} - h_{RTK-OTF}) + \alpha_{SDCM} \cdot (h_{SDCM} - h_{RTK-OTF})}{\alpha_{EGNOS} + \alpha_{SDCM}} \end{cases} \tag{9}$$

Further transformation of equation (9) and grouping individual parameters results in:

$$\begin{cases} dB = \frac{\alpha_{EGNOS} \cdot B_{EGNOS} + \alpha_{SDCM} \cdot B_{SDCM} - (\alpha_{EGNOS} + \alpha_{SDCM}) \cdot B_{RTK-OTF}}{\alpha_{EGNOS} + \alpha_{SDCM}} \\ dL = \frac{\alpha_{EGNOS} \cdot L_{EGNOS} + \alpha_{SDCM} \cdot L_{SDCM} - (\alpha_{EGNOS} + \alpha_{SDCM}) \cdot L_{RTK-OTF}}{\alpha_{EGNOS} + \alpha_{SDCM}} \\ dh = \frac{\alpha_{EGNOS} \cdot h_{EGNOS} + \alpha_{SDCM} \cdot h_{SDCM} - (\alpha_{EGNOS} + \alpha_{SDCM}) \cdot h_{RTK-OTF}}{\alpha_{EGNOS} + \alpha_{SDCM}} \end{cases} \tag{10}$$

Equation (10) describes the final form of the weighted average model for the accuracy parameter of the coordinates of the UAV position based on the EGNOS+SDCM solution. Figures 10, 11, and 12 show the results of comparison of the positioning accuracy based on the EGNOS+SDCM solution for the model summating the accuracy (equations (1-6)) and the weighted average model (equations (7-10)). The values of positioning accuracy based on the EGNOS+SDCM solution for the summating model are presented in Figures 7, 8, and 9, and they have already been discussed in detail. On the other hand, the values of position errors for the BLh components of the position of the UAV in the weighted average model are, respectively: from -1.5 m to +2.5 m for the B coordinate, from -1.1 m to +1.4 m for the L coordinate, and from -2.7 m to +5.9 m for the h coordinate. As far as the determination of the accuracy of the B coordinate is concerned, one may conclude that the proposed algorithm summating the positioning accuracy for the EGNOS+SDCM solution resulted in a reduction of position errors by 84% in comparison to the EGNOS+SDCM solution for the weighted average model. Moreover, for the determination of the accuracy of the L coordinate, it was noted that the proposed algorithm summating the positioning accuracy for the EGNOS+SDCM solution resulted in a reduction of position errors by 85% in comparison to the EGNOS+SDCM solution for the weighted average model. Finally, for the determination of the accuracy of the h coordinate, one may conclude that the proposed algorithm summating the positioning accuracy for the EGNOS+SDCM solution resulted in a reduction of position errors by 84% in comparison to the EGNOS+SDCM solution for the weighted average model. The comparison of the obtained results of position errors for the mathematical equations (1-6) and (7-10) reveals a noticeable high effectiveness of the proposed model summating the positioning accuracy. In reference to the weighted average model, the proposed model for the EGNOS+SDCM solution can rightfully be used in navigational calculations.

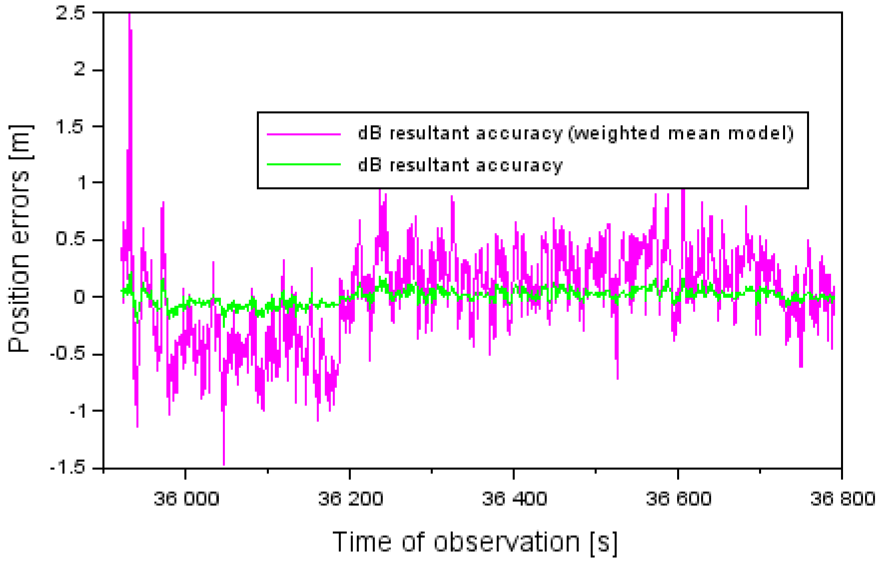

Fig. 10**.** The position errors along B axis from summation model of accuracy and the weighted average model

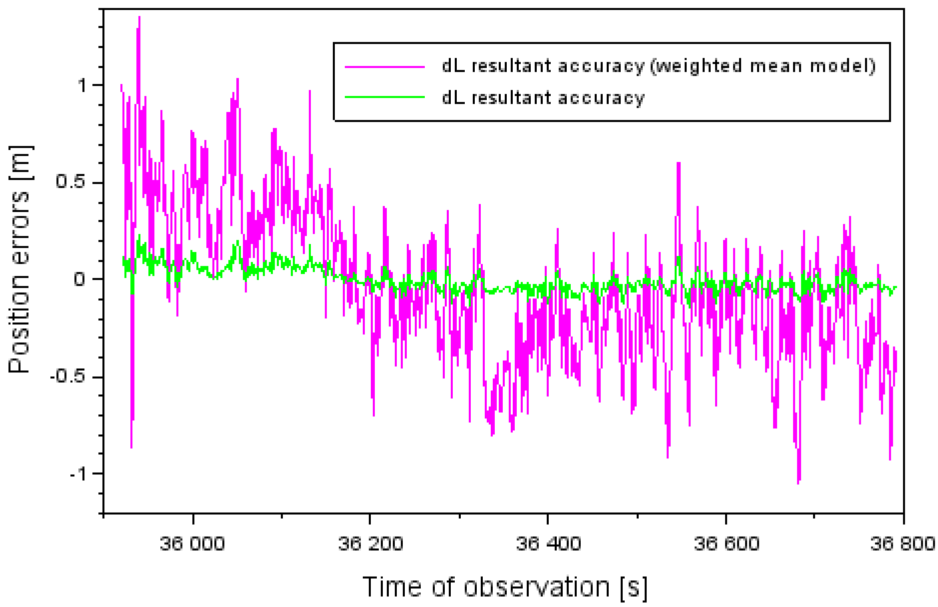

Fig. 11. The position errors along L axis from summation model of accuracy and the weighted average model

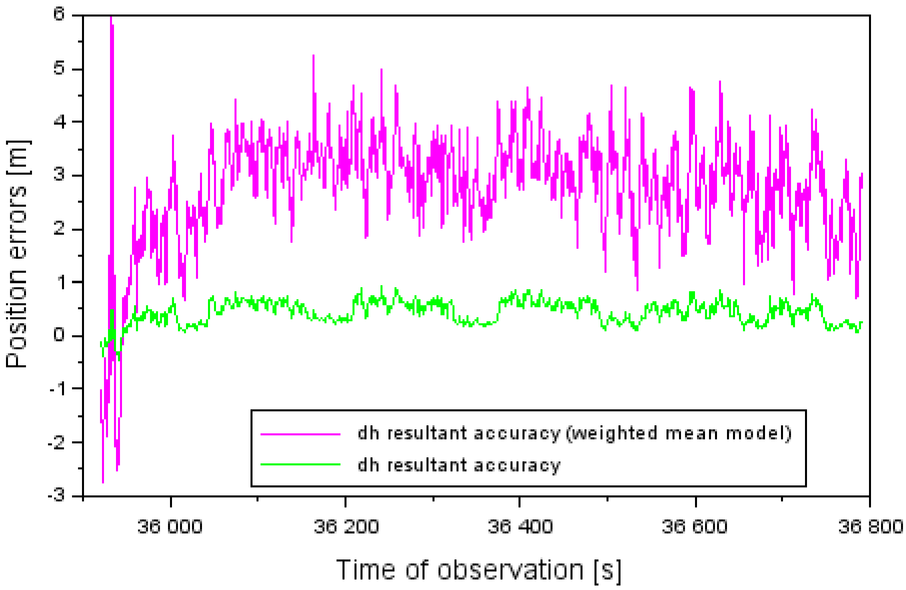

Fig. 12. The position errors along h axis from summation model of accuracy and the weighted average model

6.2. Repeatability of computational processing of the summation model of accuracy

The second part of the discussion describes the repeatability of the computational process for the application of the proposed mathematical algorithm (1-6) but based on another sample of GPS and SBAS data (EGNOS and SDCM). Namely, the calculations were performed on GPS satellite data and EGNOS and SDCM corrections from a test flight that took place on the same day, but in the afternoon. The test flight took place in the village of Nowy Świat, which is in northern Poland. It should be noted that the test flight was performed by a Tailsitter platform with an installed AsteRx-m2 UAS receiver. Figures 13 and 14 present, respectively, the horizontal and vertical trajectory of the flight of the UAV. The changes in the geodesic latitude coordinate B ranged from 54.348965^{o} to 54.356494^{o}, while the changes in the geodesic longitude coordinate L ranged from 19.311990^{o} to 19.331175^{o}.

The change in the flight altitude of the UAV was from 105.552 m to 227.487 m. Similarly to the first test flight, the lowest ellipsoidal altitude of flight was obviously noted during take-off of the UAV platform.

Furthermore, Figure 15 shows the number of tracked GPS satellites with EGNOS and SDCM corrections, while Figure 16 presents the values of the PDOP coefficients separately for the EGNOS and SDCM solutions. During the second flight, the number of tracked GPS satellites with SDCM corrections ranged from 4 to 8. At the same time, AsteRx-m2 UAS tracked from 7 to 12 GPS satellites, for which EGNOS corrections were calculated. Similarly, as during the first flight that, during flight 2 the lowest number of tracked GPS satellites with SDCM and EGNOS corrections was also noticed in the initial phase of the experiment. As the test progressed, the number of tracked GPS satellites with SDCM and EGNOS corrections increased.

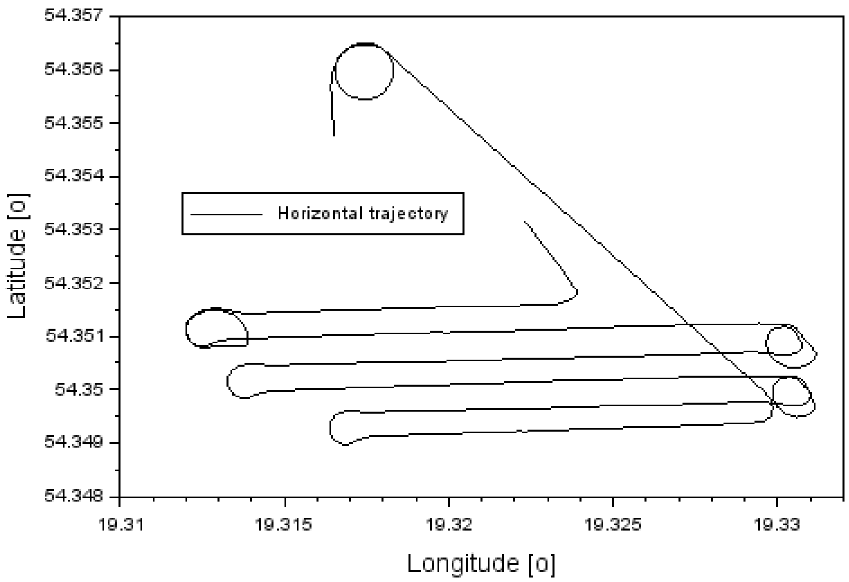

Fig. 13. The horizontal trajectory of the UAV in the 2nd test flight

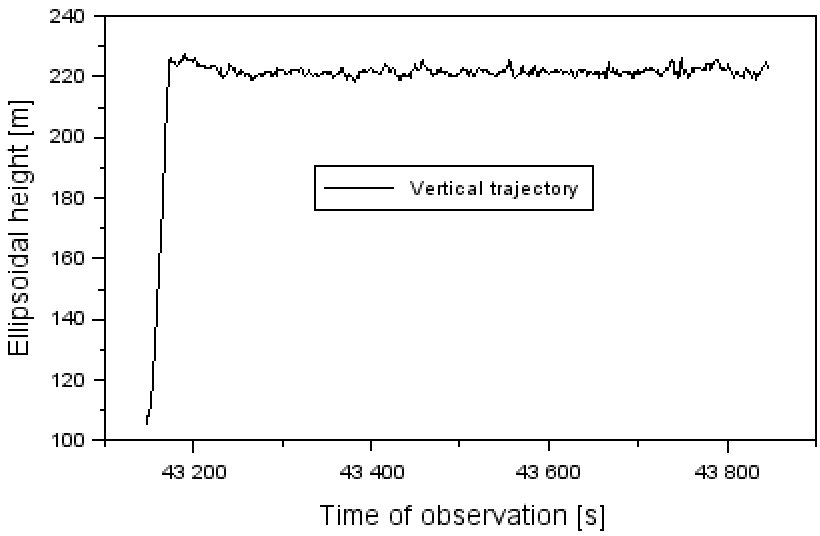

Fig. 14. The vertical trajectory of the UAV in the 2nd test flight

The values of the geometric coefficient PDOP ranged from 1.7 to 2.7 for the SDCM solution and, respectively, from 1.6 to 2.8 for the EGNOS solution. Similarly, as in test flight 1, the worst results of the PDOP coefficient were noted in the initial phase of flight, when the AsteRx-m2 UAS receiver recorded the fewest GPS observations with SDCM and EGNOS corrections. As the recording time elapsed, the PDOP coefficients became lower than 2.2.

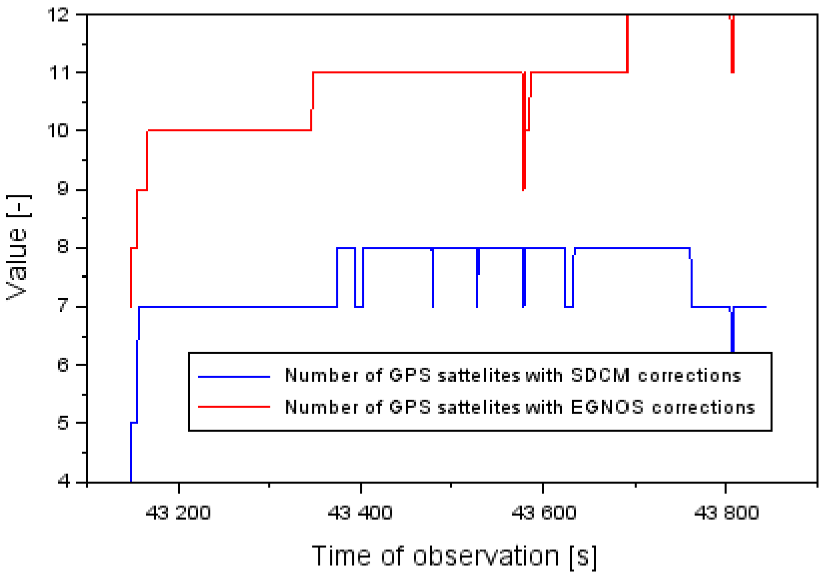

Fig. 15. Number of GPS satellites with SDCM and EGNOS corrections in the 2nd test flight

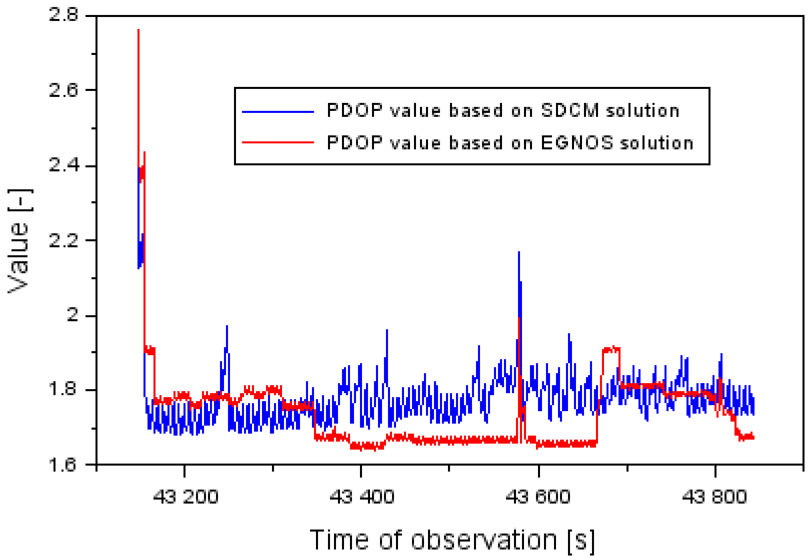

Fig. 16. The PDOP values based on SDCM and EGNOS solutions in the 2nd test flight

Figure 17 shows the parameters of flight of the UAV separately for the EGNOS and SDCM solutions. Further, Figure 18 presents the values of the linear coefficients calculated from equation (6). The flight velocity of the UAV based on the SDCM solution ranged from 3.9 m/s to 28.6 m/s. At the same time, the flight velocity based on the EGNOS solution also ranged from 3.9 m/s to 28.6 m/s. The highest velocity values were noted in the final phase of flight.

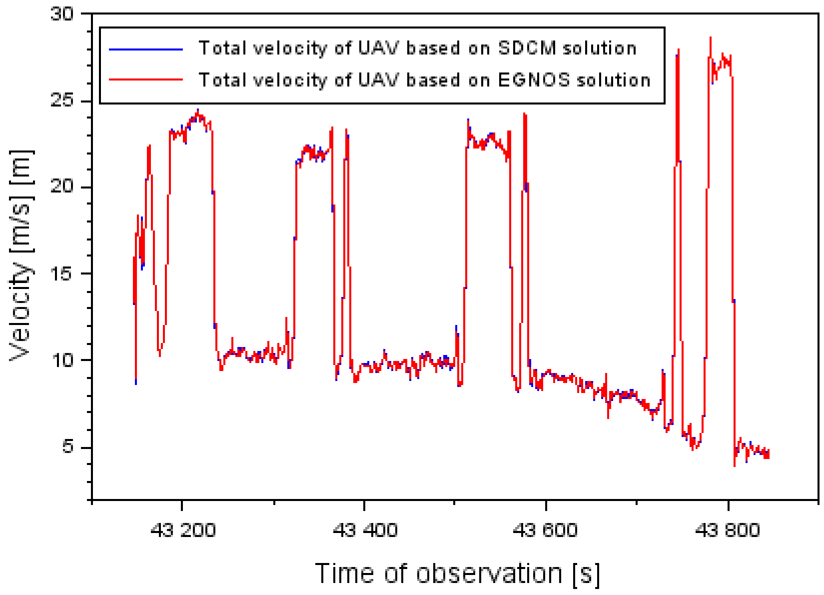

Fig. 17. The total velocity of UAV based on SDCM and EGNOS solutions in the 2nd test flight

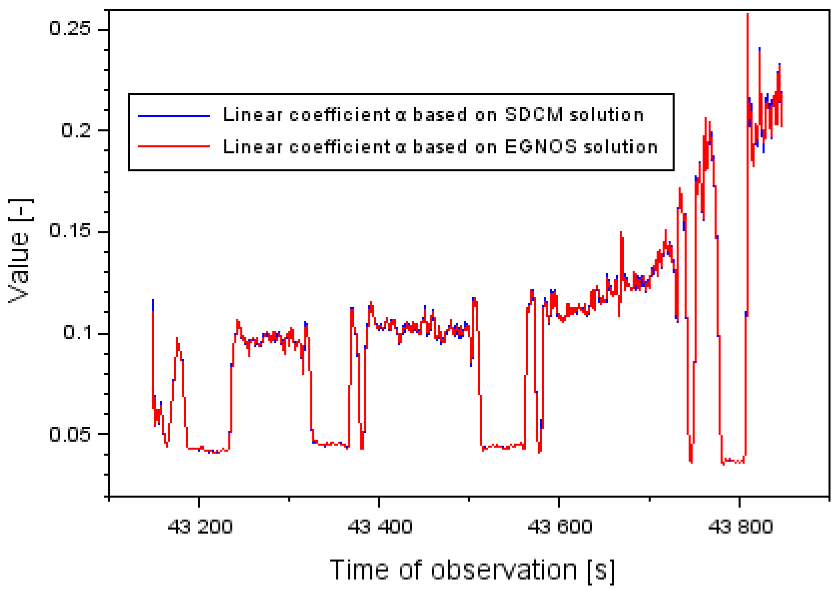

Fig. 18. The values of linear coefficients (α_{SDCM}, α_{EGNOS}) in the 2nd test flight

The values of the α_{SDCM} linear coefficients based on the SDCM solution ranged from 0.035 to 0.257, while the values of the α_{EGNOS} linear coefficients based on the EGNOS solution were similar and ranged from 0.035 to 0.257. The highest values of the linear coefficients (α_{SDCM}, α_{EGNOS}) were noted in the final phase of flight, which, obviously, results from the velocity of the UAV shown in Figure 17.

Figures 19, 20, and 21 present the values of EGNOS+SDCM positioning accuracy based on algorithm (1-6) in reference to the positioning accuracy values determined separately for the EGNOS and SDCM systems. The position errors for the B component based on the SDCM solution ranged from -2.1 m to +7.7 m. Analogically, the position errors based on the EGNOS solution ranged from -1.9 m to +6.9 m. After the application of the proposed mathematical algorithm (1-6) that sums positioning accuracy, the position errors take the values from -0.3 m to +1.4 m. As far as the accuracy of the B coordinate is concerned, one may conclude that the proposed mathematical algorithm (1-6) for the EGNOS+SDCM solution increased the accuracy by 87% in comparison to the SDCM solution and by 77% in comparison to the EGNOS solution. The position errors for the L component based on the SDCM solution ranged from -15.8 m to +1.5 m. Analogically, the position errors based on the EGNOS solution ranged from -15.4 m to +1.1 m. When the EGNOS+SDCM solution was applied, the position errors took the values ranging from -3.3 m to +0.5 m. As far as the accuracy of the h coordinate is concerned, one may conclude that the proposed mathematical algorithm (1-6) for the EGNOS+SDCM solution increased the accuracy by 86% in comparison to the SDCM solution and by 84% in comparison to the EGNOS solution. The position errors for the h component based on the SDCM solution ranged from -15.4 m to +5.1 m, while the position errors based on the EGNOS solution ranged from -14.4 m to +6.6 m. When the EGNOS+SDCM solution was applied, the position errors took the values ranging from -3.0 m to +1.8 m. As far as the accuracy of the h coordinate is concerned, one may conclude that the proposed mathematical algorithm (1-6) for the EGNOS+SDCM solution increased the accuracy by 78% in comparison to the SDCM solution and by 82% in comparison to the EGNOS solution. Similarly, as for flight 1, the application of the proposed algorithm (1-6) enabled to reduce the values of position errors in flight 2 as well, and thus to improve the EGNOS+SDCM positioning accuracy. This is important, as the mathematical algorithm (1-6) allows for the reduction of outliers for position errors, which is visible in Figures 19, 20, and 21 in the initial phase of flight, when the positioning accuracy of EGNOS and SDCM is low. Thus, it may be concluded that the repeatability of the computational process was verified in test flight 2. The level of the obtained results of the reduction of position errors are similar as in the test flight performed. This means that the verification of the mathematical algorithm (1-6) proved to be effective in UAV positioning for the EGNOS+SDCM solution.

6.3. Comparison between the proposed research method and the analysis of scientific knowledge

The last part of the discussion contains a comparison of the applied research method in reference to the state of knowledge. The comparison of the accuracy results of EGNOS+SDCM positioning with the analysis of the state of knowledge allows us to draw the following conclusions:

- the accuracy of UAV positioning based on EGNOS+SDCM positioning described here is higher than the accuracy results described in papers [20, 21, 28, 33, 51],
- the EGNOS and SDCM support systems were used in precise positioning of aerial vehicles in aviation navigation, which was described in studies [51],
- the mathematical algorithm presented here may be used in photogrammetric applications in the digital aerotriangulation process [5, 10-13, 17].

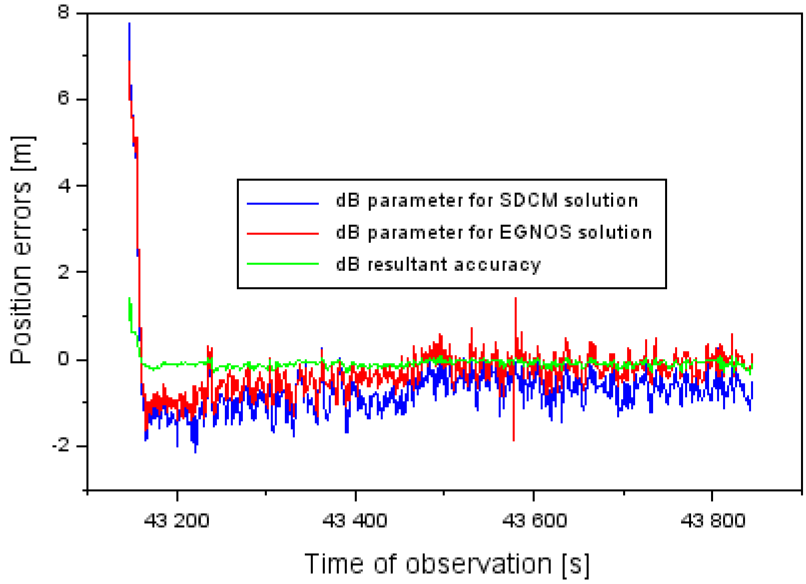

Fig. 19. The position errors along B axis in the 2nd test flight

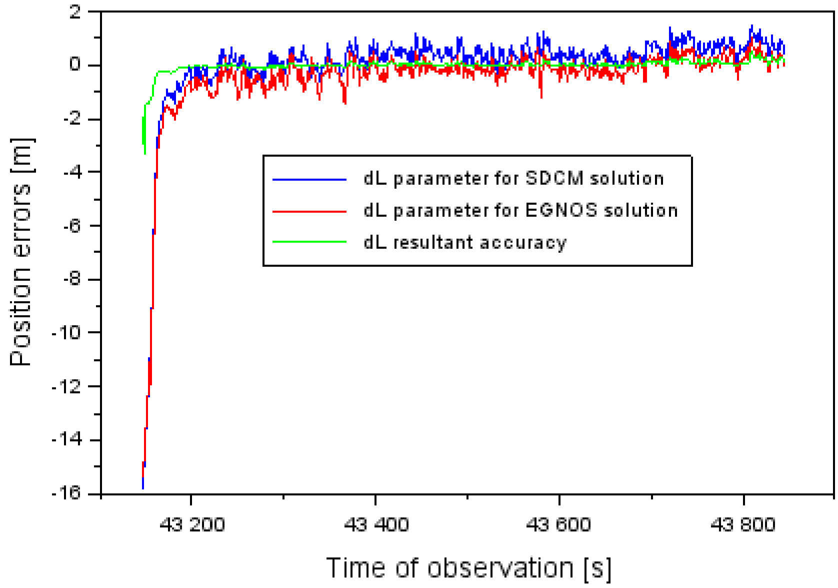

Fig. 20. The position errors along L axis in the 2nd test flight

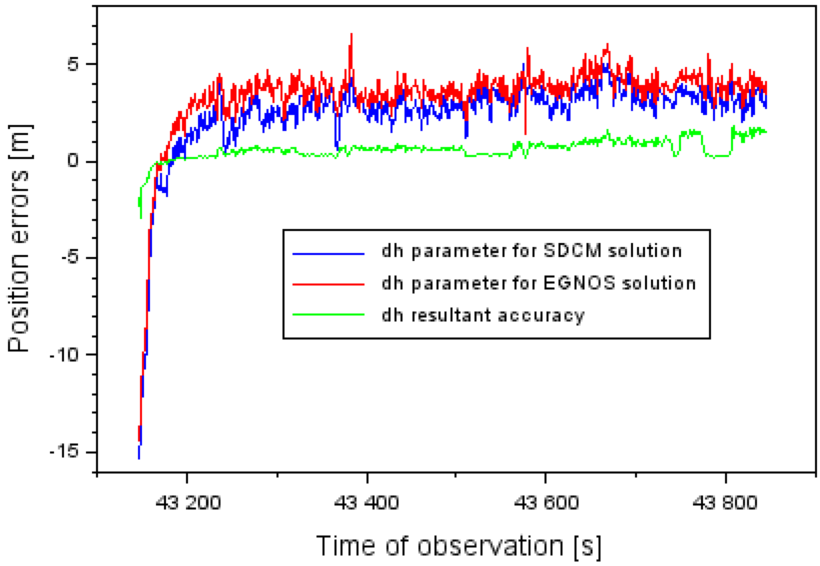

Fig. 21. The position errors along h axis in the 2nd test flight

7. CONCLUSIONS

The article presents the results of research on the improvement of EGNOS+SDCM positioning accuracy for the UAV technology. To this end, the mathematical algorithm in the form of the summation model of SBAS positioning accuracy was applied. The proposed algorithm is based on the position errors determined with a single SBAS solution and the values of linear coefficients used in the model. In the example analysed in this study, SBAS data from the EGNOS and SDCM support systems were used, and the linear coefficients were calculated as a function of the reverse velocity of movement of the UAV. The research was based on GPS observation data and SBAS corrections registered by the AsteRx-m2 UAS receiver installed on an unmanned platform. The necessary calculations were conducted first in the RTKLIB software, and then a proprietary numerical script was applied in the Scilab language environment. The application of the proposed algorithm allowed us to improve the position accuracy of the UAV by 82-87% in comparison to the application of either only EGNOS or SDCM. Apart from that, another important result of the application of the proposed algorithm was the reduction of outlier positioning errors that reduced the accuracy of the positioning of UAV when a EGNOS or SDCM was used. The authors also tested the proposed algorithm in the second test flight that was performed in the town of Nowy Świat, which is located in northern Poland. As far as this flight is concerned, the EGNOS+SDCM positioning accuracy was improved by 77% to 87% in comparison to the results of single EGNOS or SDCM solutions. The study also presents the effectiveness of the proposed algorithm in relation to the weighted average model. Future studies will be expanded by applying the correction data from the GAGAN augmentation system in the accurate positioning of UAV.

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