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Accuracy Examination of the SDCM Augmentation System in Aerial Navigation

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Abstract: The paper presents a modified algorithm for determining the accuracy parameter of the system for differential corrections and monitoring (SDCM) navigation solution in air navigation. For this purpose, a solution to determine the resultant accuracy parameter was proposed by using two on-board global navigation satellite system (GNSS) receivers. The mathematical algorithm takes into account the calculation of a single point positioning accuracy for a given GNSS receiver and a weighting factor combining the position error values. The weighting factor was determined as a function of the number of tracked GNSS satellites used in the SDCM single point positioning solution. The resultant accuracy parameter was expressed in ellipsoidal coordinates BLh (B—latitude, L—longitude, h—ellipsoidal height). The study used GNSS kinematic data recorded by two on-board receivers: Trimble Alloy and Septentrio AsterRx2i, located in a Diamond DA 20-C1 aircraft. The test flight was performed near the city of Olsztyn in north-eastern Poland. Calculations and analyses were performed using RTKLIB software and the Scilab environment. On the basis of the performed tests, it was found that the proposed algorithm for SDCM system allows for improvement in the determination of the resultant accuracy value by 56–80% in relation to the results of position errors from a single GNSS receiver. Additionally, the proposed algorithm was tested for the European Geostationary Navigation Overlay Service (EGNOS) system, and in this case, the improvement in the accuracy parameter was even better and was in the range of 69–89%. The resulting SDCM and EGNOS positioning accuracy met the International Civil Aviation Organization (ICAO) certification requirements for SBAS systems in air navigation. The mathematical algorithm developed in this work was tested positively and can be implemented within the SBAS augmentation system in air navigation.

Keywords: SDCM; accuracy; SBAS; EGNOS; position errors

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1. Introduction

Satellite-based augmentation system (SBAS) positioning plays a huge role in air navigation [1]. This is mainly because SBAS augmentation systems are designed to improve positioning performance, i.e., accuracy, continuity, availability and integrity [2]. While global navigation satellite systema (GNSS) enable the accuracy, availability and continuity to be measured, the integrity of GNSS positioning in aviation cannot be determined [3]. This makes SBAS navigation solutions even more of a future for the aviation industry and air transport [4]. As of today, we have eight operational SBAS augmentation systems, according to the current recommendation of the International GNSS Service (IGS) [5]. Among them, we can list the following SBAS augmentation systems:

– BeiDou SBAS (BDSBAS)—a Chinese SBAS positioning system [6],
– European Geostationary Navigation Overlay Service (EGNOS)—the European SBAS positioning system [7],
– GPS Aided Geo Augmented Navigation (GAGAN)—an Indian SBAS positioning system [8],

- Geoscience Australia (SBAS) Test-Bed Project (GATBP)—an Australian SBAS positioning system [9],
- Multi-functional Satellite Augmentation System (MSAS)—a Japanese SBAS positioning system [10],
- Nigerian Satellite Augmentation System (NSAS)—the Nigerian SBAS positioning system [11],
- System for Differential Corrections and Monitoring (SDCM)—Russian SBAS positioning system [12],
- Wide Area Augmentation System (WAAS)—an American SBAS positioning system [13].

Among the above-mentioned SBAS systems, the EGNOS augmentation system was and still is used in Poland for air navigation purposes. Research experiments on the EGNOS system in Poland were mainly focused on the following research areas:

- testing the accuracy of EGNOS positioning with respect to the precise solution of the aircraft position based on the real-time kinematic—on the fly (RTK-OTF) differential technique [14–17],
- determining the requirements and performance of EGNOS positioning within the SBAS approach with vertical guidance (APV) landing procedure [18–20],
- determining the integrity of EGNOS positioning in aviation by means of determining the horizontal protection level (HPL) and vertical protection level (VPL) integrity levels [21–24],
- determining the accuracy and precision of the navigation solution using EGNOS corrections [25–28].

The scope of research conducted in Poland was relatively very broad as far as the EGNOS system in aviation was concerned. Furthermore, the research was focused on the use of particular methods or measurement techniques in air navigation in Poland. The conducted research only emphasized the great advantage of introducing and implementing the EGNOS system in Poland. The EGNOS system is, therefore, an important element in the development of GNSS satellite navigation in Poland.

However, it turns out that in Poland, in addition to the EGNOS augmentation system, the SDCM augmentation system can be fully used to conduct air navigation [29–32]. This is important because then the SDCM system enables the navigation position to be determined independently of the EGNOS system. Work on the construction of the SDCM augmentation system started simultaneously with the modernization of the Globalnaja Navigatsionnaya Sputnikovaya Sistema (GLONASS) navigation system. It should be noted that the nature of the SDCM system is intended to be the same as the WAAS or EGNOS systems. In addition, the SDCM system's main purpose is to transmit corrections for global positioning system (GPS) and GLONASS positioning and to improve positioning performance, i.e., accuracy, continuity, availability and integrity, especially since SDCM can be used in civil aviation, as recommended by the International Civil Aviation Organization (ICAO). The SDCM system currently provides coverage with differential corrections over Asia and the eastern part of Europe. More information on the development strategy, modernization, the whole plan of building the SDCM augmentation system can be found in the works [33–39].

As the state-of-the-art analysis shows, the SDCM system is supposed to be fully operational in aviation, including in Europe. So far, this SBAS function in Europe is performed by EGNOS. However, in order for SDCM to meet ICAO certification requirements, ICAO technical standards for SBAS positioning quality must be defined, specified and flight-tested. Therefore, the aim of this work is to develop and determine optimal technical standards for the implementation of SDCM in air navigation, in accordance with ICAO requirements. In particular, the work will show and present algorithms for improving the determination of the SDCM positioning accuracy parameter in aviation. For the purposes of the research carried out in this paper, a very interesting mathematical solution was applied, in which a weighting factor was used as a function of the number of tracked satellites. This solution allows for quite a significant reduction in position errors from the SDCM solution, thus, improving the positioning accuracy. This is important because the optimal selection of the measurement weight is crucial, first, for determining the positioning accuracy of SDCM in aviation, and additionally, of course, to create recommendations and technical standards for performing flight operations with the use of the SDCM system. Furthermore, this navigation solution, supported by numerical analyses and test results, should take into account the aircraft position accuracy results from at least two on-board GNSS receivers. Such a navigation solution has its advantages because we then have control of position accuracy readings from a single SDCM solution from a single GNSS receiver. Additionally, we obtain the resultant position accuracy solution for a number of degrees of freedom equal to 1 [40]. Furthermore, the use of a weighting model to determine the resultant position accuracy from two independent SDCM solutions is much more efficient and enables the reduction of gross errors from a single SDCM solution. This paper proposes such a navigation solution, precisely based on aircraft position readings from two independent GNSS receivers during flight. This will obviously allow us, with the appropriate choice of the optimal configuration of measurement weights, to determine the resultant values of the SDCM positioning accuracy parameter in air navigation. Therefore, this will provide an important navigation solution for the certification requirements of the SDCM system in air navigation.

The most significant contributions of the authors in the article are:

- development of an algorithm to integrate SDCM positioning accuracy from two independent SDCM solutions,
- development of an algorithm to reduce position errors and, thus, improve positioning accuracy with respect to a single SDCM solution,
- conducting navigational analyses to confirm the validity of the research methodology developed,
- carrying out navigational studies and analyses for the EGNOS system,
- comparison of accuracy results against ICAO recommendations.

2. Research Method

2.1. Performance of SDCM Accuracy Positioning for Single Receiver—Basic Solution

For SDCM positioning based on a single GNSS receiver, the mathematical equations for determining the positioning quality parameters can be written as shown below:

- for the accuracy parameter [41]:

$$\begin{cases} dB_{Rx1} = B_{Rx1} - B_{RTK} \\ dL_{Rx1} = L_{Rx1} - L_{RTK} \\ dh_{Rx1} = h_{Rx1} - h_{RTK} \end{cases} \quad (1)$$

where:

- $(dB_{Rx1}, dL_{Rx1}, dh_{Rx1})$—position errors for ellipsoidal coordinates BLh (B—latitude, L—longitude, h—ellipsoidal height) of the aircraft, calculated as the difference between the SDCM navigation solution from a single GNSS receiver and the flight reference position from the RTK-OTF solution [42],
- $(B_{Rx1}, L_{Rx1}, h_{Rx1})$—SDCM position navigation solution for a single GNSS receiver,
- $(B_{RTK}, L_{RTK}, h_{RTK})$—flight reference position from the RTK-OTF solution,
- $Rx1$—GNSS receiver identification number 1.

Equation (1) concerns the determination of the SDCM positioning accuracy parameter for only one GNSS receiver. In the case of Equation (1), the accuracy is calculated by comparing the aircraft BLh ellipsoidal coordinates between the SDCM navigation solution and the flight reference position calculated for the RTK-OTF technique. It should be noted that the phrase SDCM navigation solution means the single point positioning (SPP) code positioning method with SDCM corrections [43]. In the case of SDCM corrections, it is possible to speak of long-term corrections, i.e., correction of the satellite position and correction of the satellite clock error, and furthermore, correction of the ionosphere model and correction of the troposphere model, and possibly, fast SDCM corrections [44]. It should be added that the accuracy from Formula (1) is calculated separately for the 3 BLh components and, of course, with a specific time interval, usually every 1 s of flight.

2.2. Performance of SDCM Accuracy Positioning for Dual Receivers—Modified Solution

The mathematical Equation (1) is valid, but only for one on-board GNSS receiver. As written in the introduction to the paper, for the certification of a given SBAS in aviation, at least two on-board GNSS receivers with SBAS positioning function, in this case SDCM, should be used in flight. This is needed due to the control of navigation calculations and on-board instrument readings. Moreover, it is important because then we can talk about the determination of the resultant values of the SDCM positioning accuracy parameter in aviation. The resultant values can be determined with the use of weighting coefficients, due to which we will obtain an increase in positioning accuracy in comparison with the solution from a single GNSS receiver. The following calculation scheme was proposed for the model under analysis:

$$dX_i = a \cdot dX_{Rx1} + b \cdot dX_{Rx2} \tag{2}$$

where:

- dX_i—resultant accuracy value for a given coordinate component BLh,
- i—denotes a given component of B or L or h,
- a—linear coefficient of the measurement weight for the receiver $Rx1$,
- b—linear coefficient of the measurement weight for the receiver $Rx2$,
- $Rx2$—GNSS receiver identification number 2.
- dX_{Rx1}—the determined accuracy value for the receiver $Rx1$ from the SDCM navigation solution,
- dX_{Rx2}—the determined accuracy value for the receiver $Rx2$ from the SDCM navigation solution.

In Equation (3), coefficients with the following value were proposed:

$$a = \frac{1}{ns_{Rx1}}; b = \frac{1}{ns_{Rx2}} \tag{3}$$

where:

- ns_{Rx1}—number of tracked GNSS satellites for the receiver $Rx1$ from the SDCM navigation solution,
- ns_{Rx2}—number of tracked GNSS satellites for the receiver $Rx2$ from the SDCM navigation solution.

Expressing Equation (2) through the mathematical Equation (3), we obtain:

$$dX_i = \frac{1}{ns_{Rx1}} \cdot dX_{Rx1} + \frac{1}{ns_{Rx2}} \cdot dX_{Rx2} \tag{4}$$

Finally, Equation (2) can be presented in the form:

$$dX_i = \frac{dX_{Rx1}}{ns_{Rx1}} + \frac{dX_{Rx2}}{ns_{Rx2}} = \frac{ns_{Rx2} \cdot dX_{Rx1} + ns_{Rx1} \cdot dX_{Rx2}}{ns_{Rx1} \cdot ns_{Rx2}} \tag{5}$$

Furthermore, in a general mathematical scheme, the expression (5) can be written in the form:

$$dX_i = \frac{b \cdot dX_{Rx1} + a \cdot dX_{Rx2}}{a \cdot b} \tag{6}$$

Expressing Equation (6) with specific accuracy parameters for the BLh components, we obtain:

- algorithm for resultant accuracy along the B axis:

$$dB = \frac{ns_{Rx2} \cdot dB_{Rx1} + ns_{Rx1} \cdot dB_{Rx2}}{ns_{Rx1} \cdot ns_{Rx2}} \tag{7}$$

– algorithm for resultant accuracy along the L axis:

$$dL = \frac{ns_{Rx2} \cdot dL_{Rx1} + ns_{Rx1} \cdot dL_{Rx2}}{ns_{Rx1} \cdot ns_{Rx2}} \tag{8}$$

– algorithm for resultant accuracy along the h-axis:

$$dh = \frac{ns_{Rx2} \cdot dh_{Rx1} + ns_{Rx1} \cdot dh_{Rx2}}{ns_{Rx1} \cdot ns_{Rx2}} \tag{9}$$

where:

– $(dB_{Rx2}, dL_{Rx2}, dh_{Rx2})$—position errors for ellipsoidal coordinates BLh (B—latitude, L—longitude, h—ellipsoidal height) of the aircraft for the receiver $Rx2$,
– (dB, dL, dh)—resultant values of position errors for the BLh components.

Equations (7)–(9) is the final mathematical solution to improve the positioning accuracy of SDCM for two GNSS receivers. The effectiveness of Equations (7)–(9) was tested, and the results will be shown in Chapters 3 and 4. A summary of the presented mathematical algorithm is shown in the form of a block diagram in Figure 1. The block diagram in Figure 1 includes the equation computation process for the mathematical Equations (2)–(9).

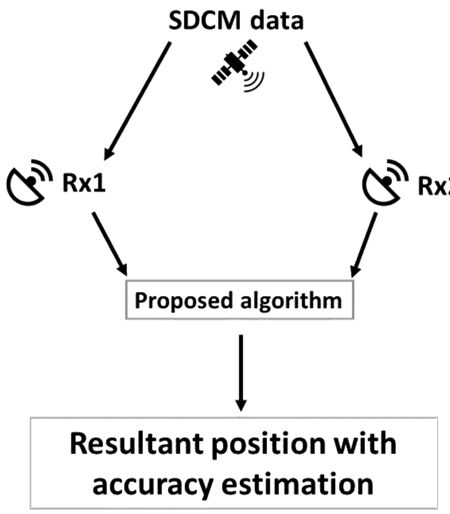

Figure 1. The flowchart of presented mathematical algorithm.

3. Research Test

The proposed mathematical algorithm was checked and tested on GNSS kinematic data. For this purpose, GNSS kinematic data recorded by two independently operating Trimble Alloy and Septentrio AsterRx2i satellite receivers placed onboard of a Diamond DA 20-C1 aircraft were used. Figure 2 shows a photo of a Diamond DA 20-C1 aircraft belonging to the Aeroclub of Warmia and Mazury in Olsztyn.

The GNSS antennas were placed in the cockpit so that they were next to each other. For the Septentrio receiver, a satellite antenna type AT1675-29S PolaNt_GG was installed, while for the Trimble receiver, a satellite antenna type GA830 was used, respectively. The GNSS kinematic data recording time was set to 1 s. The test time was from 08:23:56 (30,236 s) to 11:55:59 (42,959 s) according to GPS time (GPST). The flight was performed on a route in north-eastern Poland with the start and end point at the airport at the Warmia and Mazury Aero Club in Olsztyn. The flight was performed by a pilot in accordance with the visual flight rules (VFR) procedure. An overview sketch of the flight route of the Diamond DA 20-C1 aircraft is shown in Figure 3. In addition, Figure 4 shows the horizontal flight trajectory on a Google Earth terrain map. During the entire flight, the range of the geodetic latitude coordinate B was from 53.458116° to 54.097632°, while the span of the geodetic longitude coordinate L was contained between 20.363367° and 22.982003°. The flight speed along all BLh components was up to 100 m/s.

Figure 2. The Diamond DA 20-C1 aircraft taking part in the experiment and location of the GNSS antennas [45].

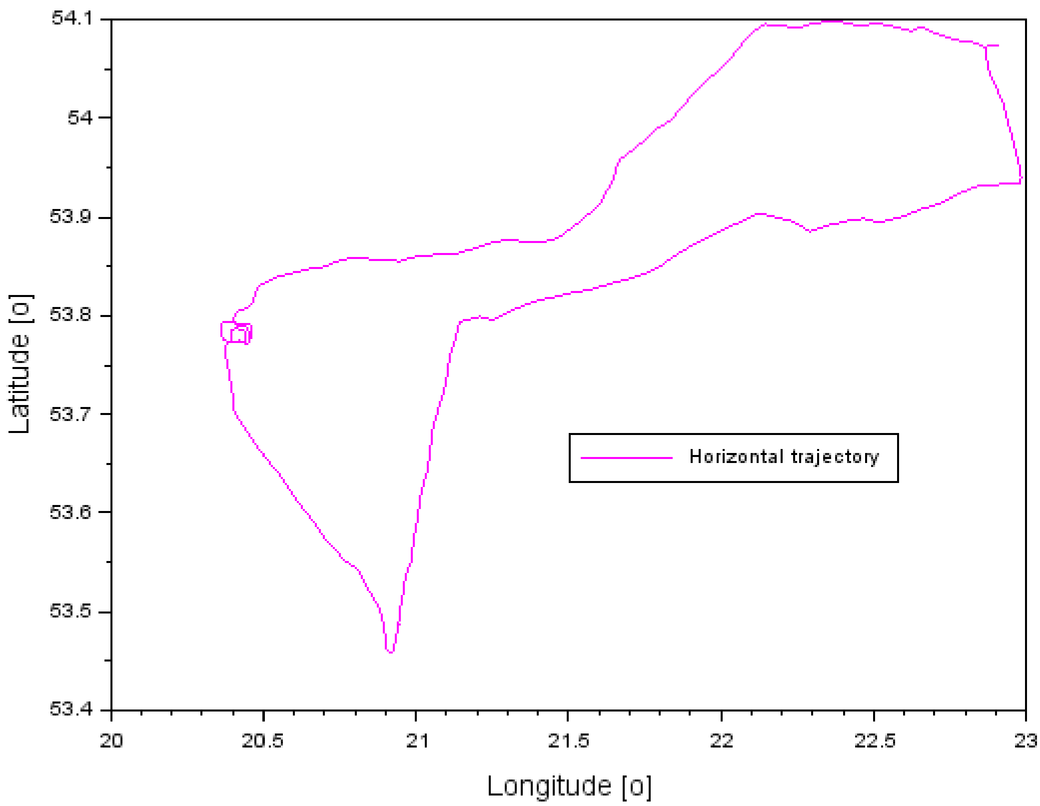

Figure 3. The horizontal trajectory of Diamond DA 20-C1 aircraft.

Figure 5 shows the vertical trajectory of the Diamond DA 20-C1 aircraft flight. The flight altitude varied from 161 m to 604 m. During the flight, the pilot changed altitude several times, as shown in Figure 5. The landing approach commenced at 11:38:31 UTC (41,911 s). At this time, the pilot made three landing approach attempts. During the flight test, the Diamond aircraft performed the landing approach in accordance with the procedure for the Europe Poland Olsztyn Dajtki (EPOD) airport from the NOVEMBER navigation point from an altitude of 500 m. The process of one landing approach lasted approximately 5 min. The landing to EPOD airport was made for runway 27 L.

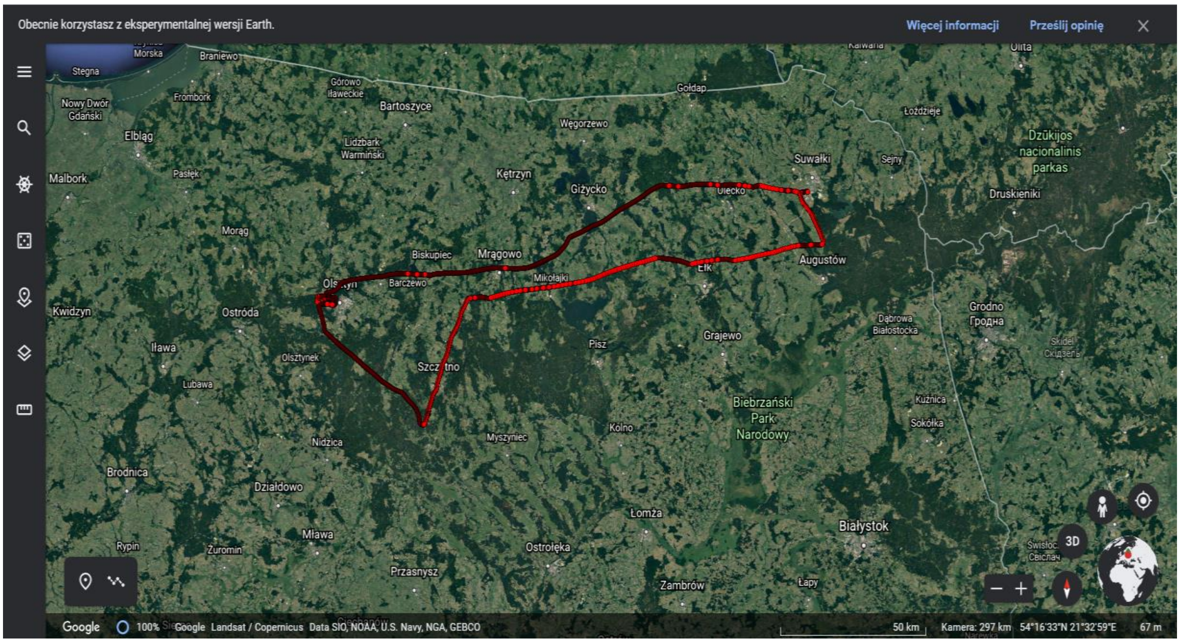

Figure 4. The horizontal trajectory of Diamond DA 20-C1 aircraft in the Google Earth platform [46].

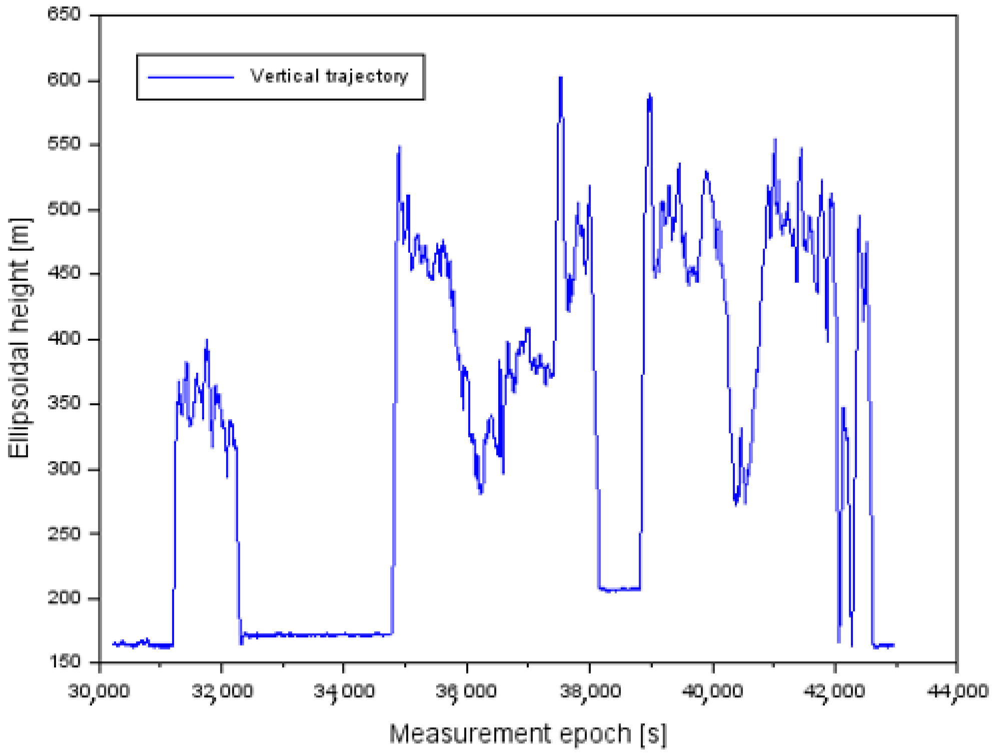

Figure 5. The vertical trajectory of Diamond DA 20-C1 aircraft.

Figure 6 shows the results of the observation conditions during the flight. The values of position dilution of precision (PDOP) parameters [47] for the SDCM solution for both Trimble Alloy and Septentrio AsterRx2i receivers are presented. For the Trimble Alloy receiver, the PDOP values range from 1.48 to 3.94, while for the Septentrio AsterRx2i receiver, the PDOP values take the results from 1.48 to 4.23. It can be said that during the flight, the PDOP results were good or very good in terms of observation conditions. Moreover, the best PDOP values were noticeable in the middle phase of the flight. On the other hand, the worst PDOP results were noticeable in the initial phase of the flight.

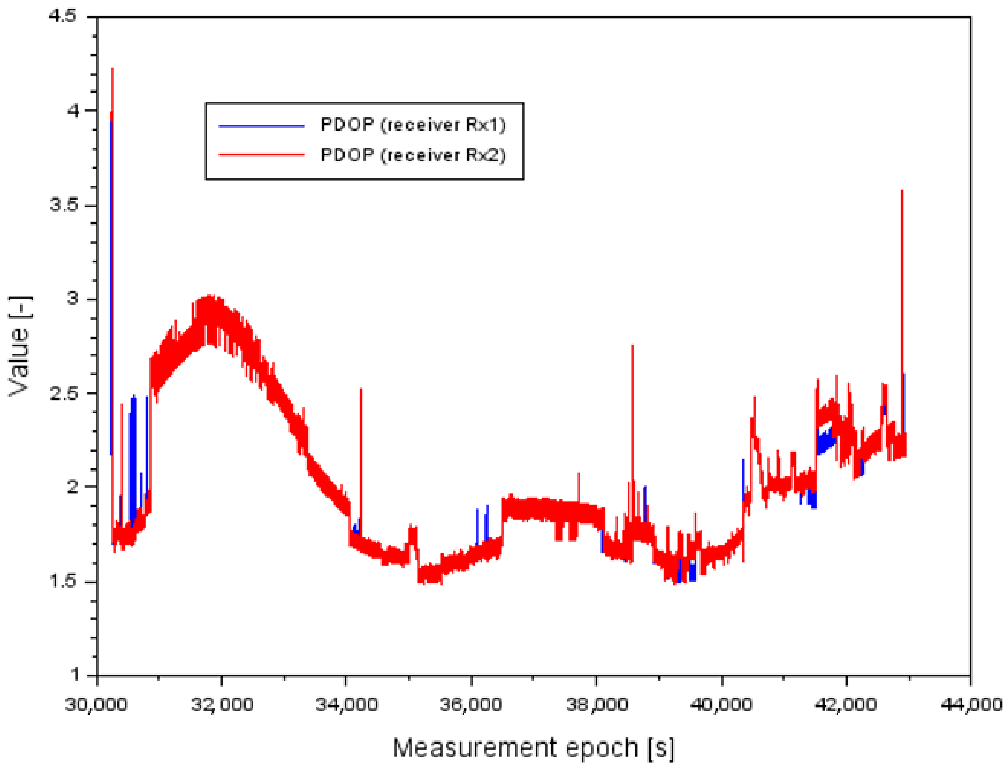

Figure 6. The PDOP values for SDCM solution for each receivers during the flight test.

In Figure 7, the number of GPS satellites tracked by the Trimble Alloy and Septentrio AsterRx2i receivers during the flight is shown. It should be noted that the number of tracked GPS satellites represents the GPS satellites for which SDCM corrections were used in calculation within the SPP positioning method. For both the Trimble Alloy receiver and the Septentrio AsterRx2i receiver, the number of tracked GPS satellites ranged from 4 to 9 during the flight. With reference to the results in Figure 6, it should be noted that the PDOP decreases when the number of tracked GPS satellites increases.

The recorded GNSS kinematic data were used to determine the position of the aircraft for the SDCM navigation solution. For this purpose, the SPP code method [43] was used to determine the coordinates of the aircraft based on GNSS satellite data from two onboard satellite receivers. Aircraft position calculations for the SPP method were performed in the RTKLIB program [48]. The calculations used SDCM correction data downloaded from: ftp://serenad-public.cnes.fr/SERENAD0 (accessed on 30 August 2021) [49]. This made it possible to determine the flight coordinates of the aircraft for two independent GNSS receivers. The obtained positions from the SDCM solution for two GNSS receivers were compared with the reference flight trajectory calculated from the RTK solution [42] in the RTKLIB program. On this basis, the positioning accuracy, defined according to Equation (1), was obtained. The positioning accuracy of the SDCM was determined separately for the receiver $Rx1$ and $Rx2$. In the study analyzed, the Trimble Alloy receiver was designated as $Rx1$, and the Septentrio AsterRx2i receiver was designated as $Rx2$. Subsequently, it was possible to implement the mathematical Equations (2)–(9), due to which the resultant positioning accuracy of the SDCM was determined. The proposed scheme of the Equations (2)–(9) was written from scratch as a script and implemented in the Scilab v.6.0.0 environment [50].

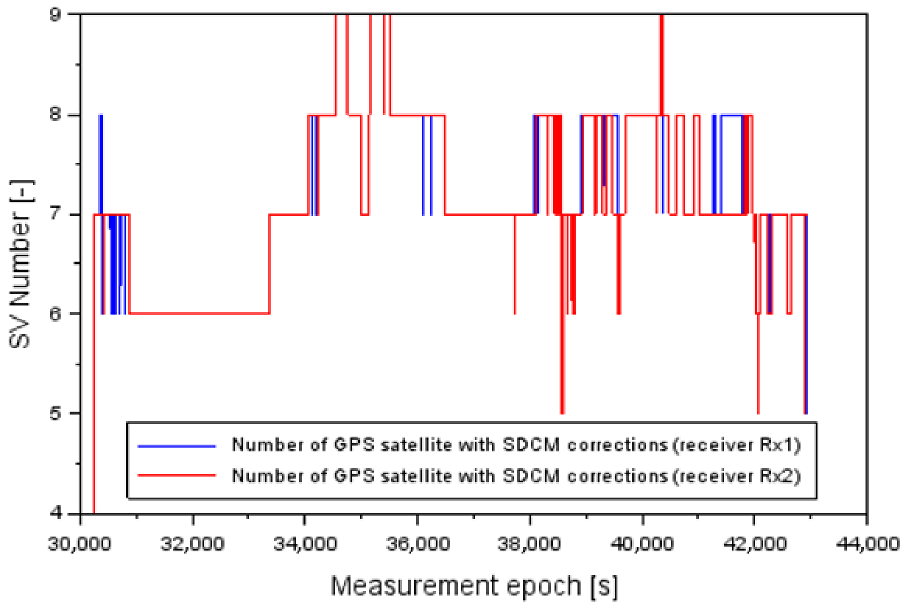

Figure 7. The number of GPS satellites with SDCM corrections for each receiver at flight test.

4. Results

The presentation of the test results began with the determination of the measurement weights (a, b). The values of the weight coefficients (a, b) are shown in Figure 8. The study shows that the values of the weighting coefficients (a, b) range from 0.111 to 0.250. This implies explicitly that the number of tracked GNSS satellites taken for the SDCM solution range from 4 to 9. A low number of tracked GNSS satellites causes the measurement weights to increase, and this relationship obviously occurs in reverse. It can be seen from Figure 8 that the lowest number of tracked GNSS satellites is in the initial phase of the flight. In contrast, the highest number of tracked GNSS satellites is seen in the middle phase of the flight. One can additionally notice a certain regularity with respect to the results in Figure 6. The smaller the PDOP, the smaller the measurement weight value. On the other hand, when PDOP increases, the measurement weight also increases and the number of tracked GNSS satellites decreases.

Figures 9–11 show the positioning accuracy results for the SDCM solution separately for the receivers $Rx1$ and $Rx2$. The position error values were calculated according to Equation (1). Figure 9 shows the position error results for the B component. Position error values dB for the receiver $Rx1$ range from −2.73 m to +1.82 m with an average accuracy value of −0.58 m. In turn, the position error results dB for the receiver $Rx2$ are between −2.80 m and +3.62 m with an average accuracy of −0.41 m. Figure 10 presents the position error results for the L component. The scatter of accuracy results for the receiver $Rx1$ is between −2.55 m and +1.45 m with an average value of −0.37 m. On the other hand, for the receiver $Rx2$, the accuracy ranges from −2.70 m to +8.27 m with an average value of −0.20 m. Figure 11 shows the position errors dh for the receiver $Rx1$ and $Rx2$. For the receiver $Rx1$, the accuracy along the h axis is from −5.74 m to +5.10 m with an average value of +0.39 m. Furthermore, for the receiver $Rx2$, accuracy along the h-axis is from −5.43 m to +10.83 m with an average value of +0.77 m. From the accuracy results shown along the BLh axis, it can be concluded that the highest observable accuracy is achieved for the L component and the lowest for the h component.

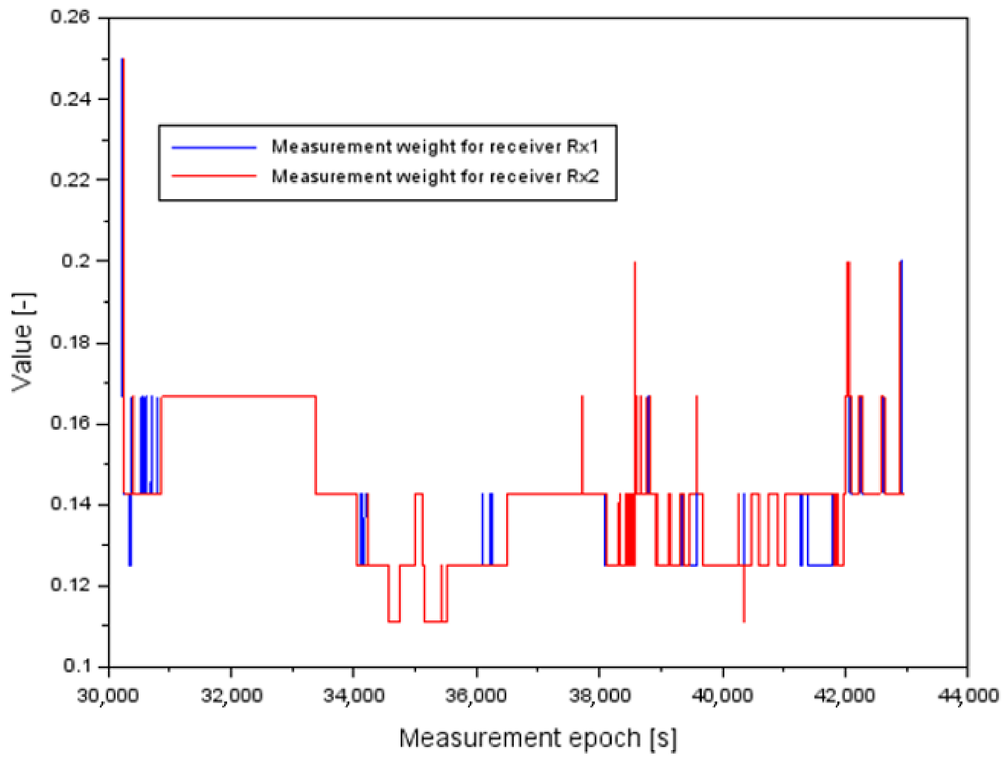

Figure 8. The results of measurement weights.

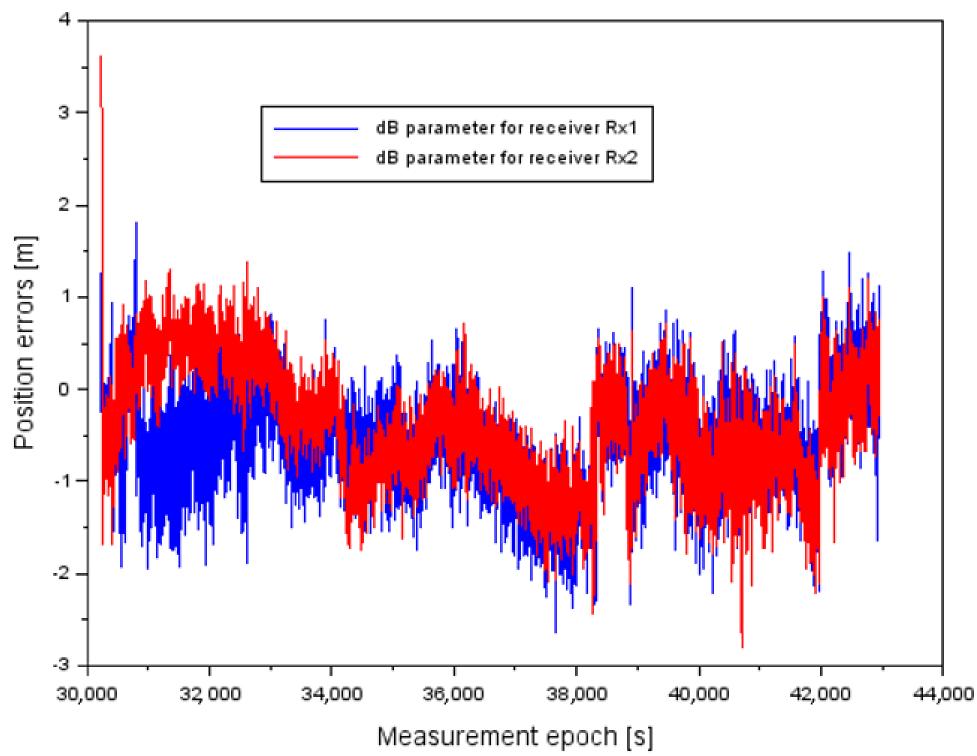

Figure 9. The results of dB position errors for $Rx1$ and $Rx2$ receivers.

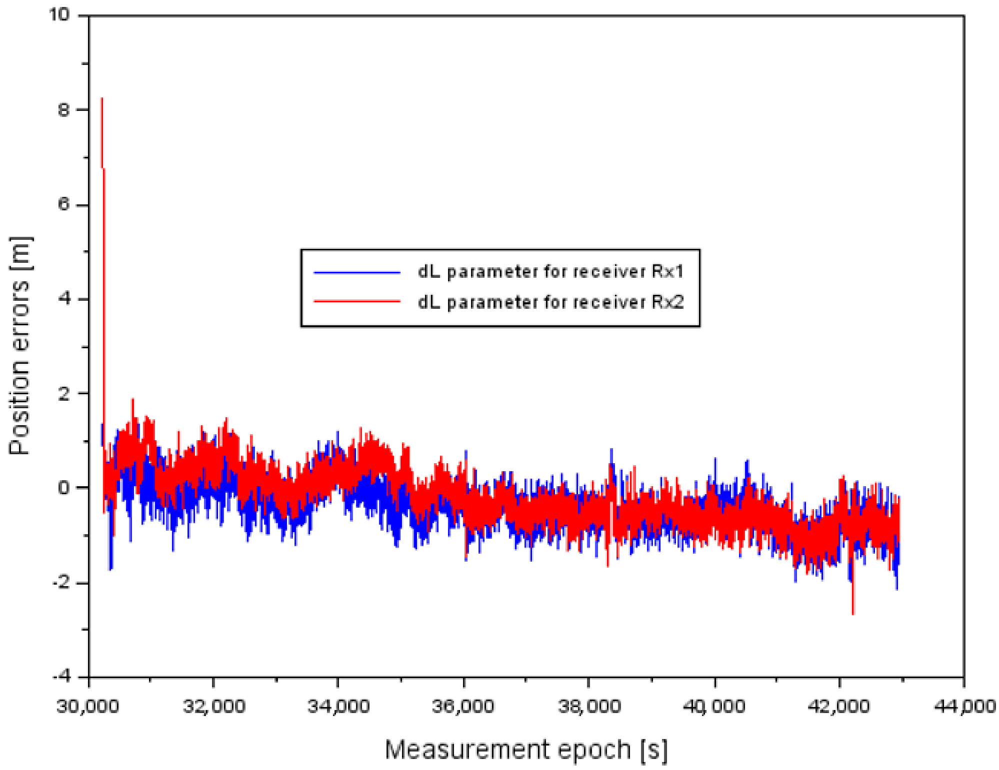

Figure 10. The results of dL position errors for $Rx1$ and $Rx2$ receivers.

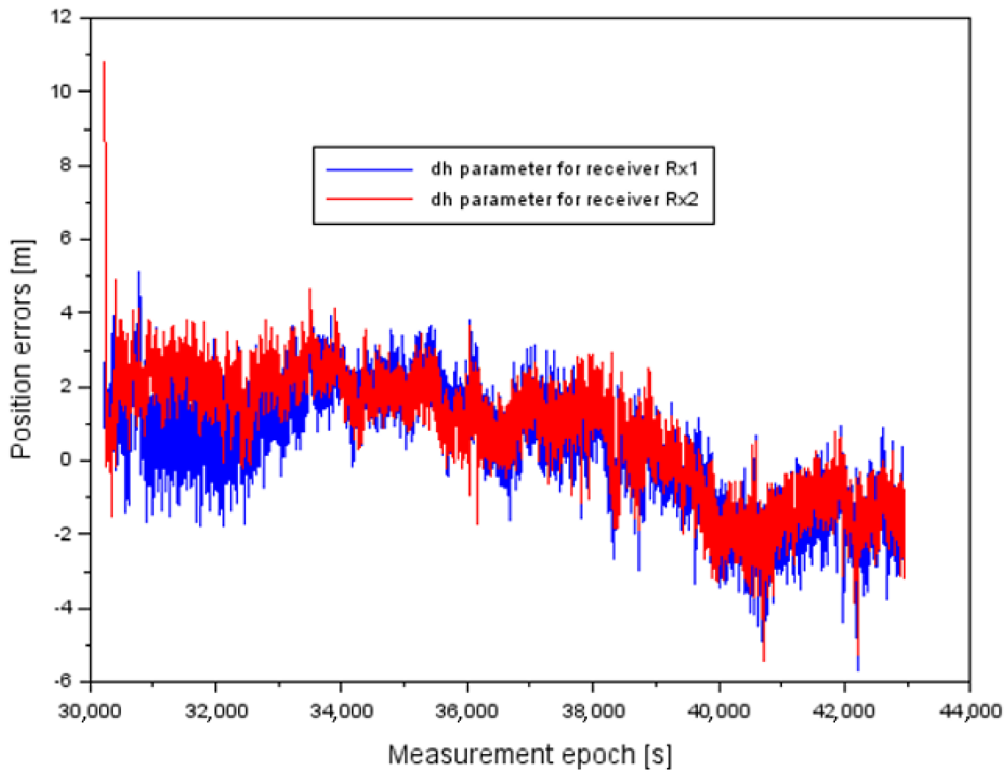

Figure 11. The results of dh position errors for $Rx1$ and $Rx2$ receivers.

Figure 12 shows the results of the resultant positioning accuracy values from the SDCM solution according to Equations (7)–(9). The results of the resultant values of the dB parameter range from −0.69 m to +1.22 m with an average accuracy value of −0.13 m. On the other hand, the resultant values of the dL parameter range from −0.81 m to +2.29 m with an average value of −0.07 m. In addition, the resultant values of the *dh* parameter are between −1.70 m and +2.92 m, and the mean value of the accuracy along the h-axis is equal to +0.17 m. The highest resultant accuracy is observed for the L component, while the lowest for the h component.

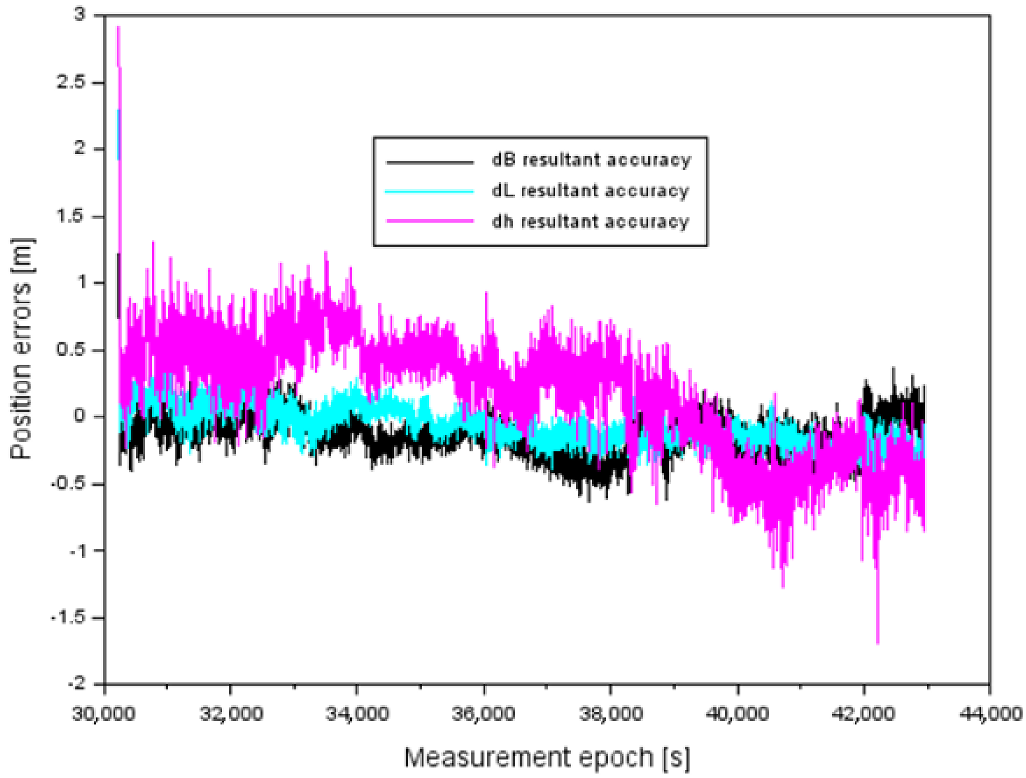

Figure 12. The resultant accuracy of (*dB*, *dL*, *dh*) parameters.

The results of the resultant accuracy values (*dB*, *dL*, *dh*) should be additionally referred to the position errors for a given receiver to show how the proposed algorithm improves the positioning accuracy for the SDCM system. For this purpose, the percentage change in positioning accuracy improvement is estimated as follows:

– for the *B* component:

$$pdB[\%] = \begin{cases} \frac{\overline{dB} - \overline{dB_{Rx1}}}{\overline{dB_{Rx1}}} \cdot 100\% \\ \frac{\overline{dB} - \overline{dB_{Rx2}}}{\overline{dB_{Rx2}}} \cdot 100\% \end{cases} \quad (10)$$

– for the *L* component:

$$pdL[\%] = \begin{cases} \frac{\overline{dL} - \overline{dL_{Rx1}}}{\overline{dL_{Rx1}}} \cdot 100\% \\ \frac{\overline{dL} - \overline{dL_{Rx2}}}{\overline{dL_{Rx2}}} \cdot 100\% \end{cases} \quad (11)$$

– for the *h* component:

$$pdh[\%] = \begin{cases} \frac{\overline{dh} - \overline{dh_{Rx1}}}{\overline{dh_{Rx1}}} \cdot 100\% \\ \frac{\overline{dh} - \overline{dh_{Rx2}}}{\overline{dh_{Rx2}}} \cdot 100\% \end{cases} \quad (12)$$

where:

– *pdB*—percentage improvement in SDCM positioning accuracy for the *B* component,
– *pdL*—percentage improvement in SDCM positioning accuracy for the *L* component,
– *pdh*—percentage improvement in SDCM positioning accuracy for component *h*,

- $\left(\overline{dB},\ \overline{dL},\ \overline{dh}\right)$—mean values of the resultant accuracy $(dB,\ dL,\ dh)$,
- $\left(\overline{dB_{Rx1}},\ \overline{dL_{Rx1}},\ \overline{dh_{Rx1}}\right)$—average positioning accuracy values calculated for the receiver $Rx1$,
- $\left(\overline{dB_{Rx2}},\ \overline{dL_{Rx2}},\ \overline{dh_{Rx2}}\right)$—average positioning accuracy values calculated for the receiver $Rx2$.

Table 1 shows the results of how Equations (2)–(9) improves the SDCM positioning accuracy for a single receiver. For the horizontal components B and L, it can be seen that the best percentage improvement is relative to the receiver $Rx1$ results and equals 77–80%. On the other hand, with respect to the results of $Rx2$ receiver, improvement in accuracy for B and L components is in the range of 63–67%. The situation is rather different for the vertical component h, where the best improvement in accuracy is seen in relation to the results from the $Rx2$ receiver and amounts to 77%. However, with respect to the results from the $Rx1$ receiver, this improvement in accuracy is slightly lower and amounts to 56%.

Table 1. Percentage change in resultant positioning accuracies relative to a single SDCM position error solution.

Coordinate	Relation	Improvement [%]
B	$\frac{\overline{dB}-\overline{dB_{Rx1}}}{\overline{dB_{Rx1}}}\cdot 100\%$	77
B	$\frac{\overline{dB}-\overline{dB_{Rx2}}}{\overline{dB_{Rx2}}}\cdot 100$	67
L	$\frac{\overline{dL}-\overline{dL_{Rx1}}}{\overline{dL_{Rx1}}}\cdot 100\%$	80
L	$\frac{\overline{dL}-\overline{dL_{Rx2}}}{\overline{dL_{Rx2}}}\cdot 100$	63
H	$\frac{\overline{dh}-\overline{dh_{Rx1}}}{\overline{dh_{Rx1}}}\cdot 100\%$	56
H	$\frac{\overline{dh}-\overline{dh_{Rx2}}}{\overline{dh_{Rx2}}}\cdot 100\%$	77

5. Discussion

The discussion for the presented research methodology is divided into three parts. In the first part the results of tests after the implementation of the proposed Equations (2)–(9) for the EGNOS system are shown. The second part of the discussion compares the obtained results of the resultant accuracy values in relation to ICAO technical standards. In the last part of the discussion, the contribution of the presented paper in relation to the analysis of the state of the art is addressed.

5.1. Implementation of the Research Method for EGNOS System

For the analyzed GNSS data, calculations were also performed for EGNOS [43]. For this purpose, Equations (2)–(9) was implemented under the EGNOS solution. The results are shown in Figures 13–16, respectively. Figure 13 shows the results of the measurement weights (a, b) for the EGNOS solution. The measurement weight a takes values from 0.077 to 0.166. In turn, the measurement weight b results are between 0.077 and 0.200. It can be concluded that the number of tracked GNSS satellites for the EGNOS solution for the receiver $Rx1$ receiver ranges from 6 to 13 and, respectively, for the receiver $Rx2$, from 5 to 13. Compared to the SDCM solution, more GNSS satellites are used in the EGNOS solution. The smallest measurement weights are found in the middle phase of the flight, while the largest weights in terms of value are seen in the initial phase of flight.

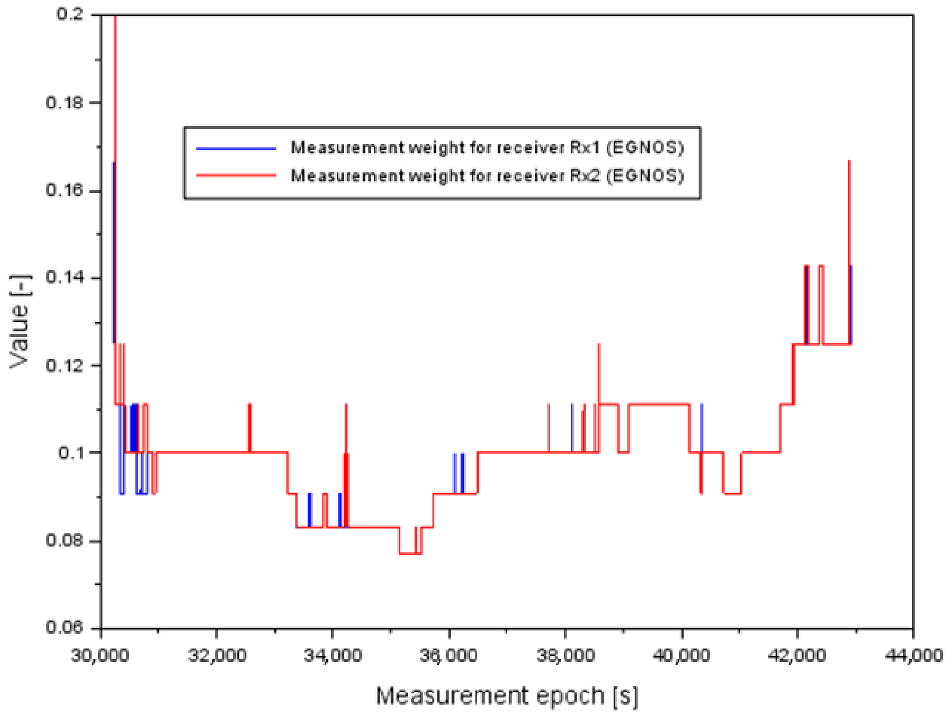

Figure 13. The results of measurement weights for EGNOS solution.

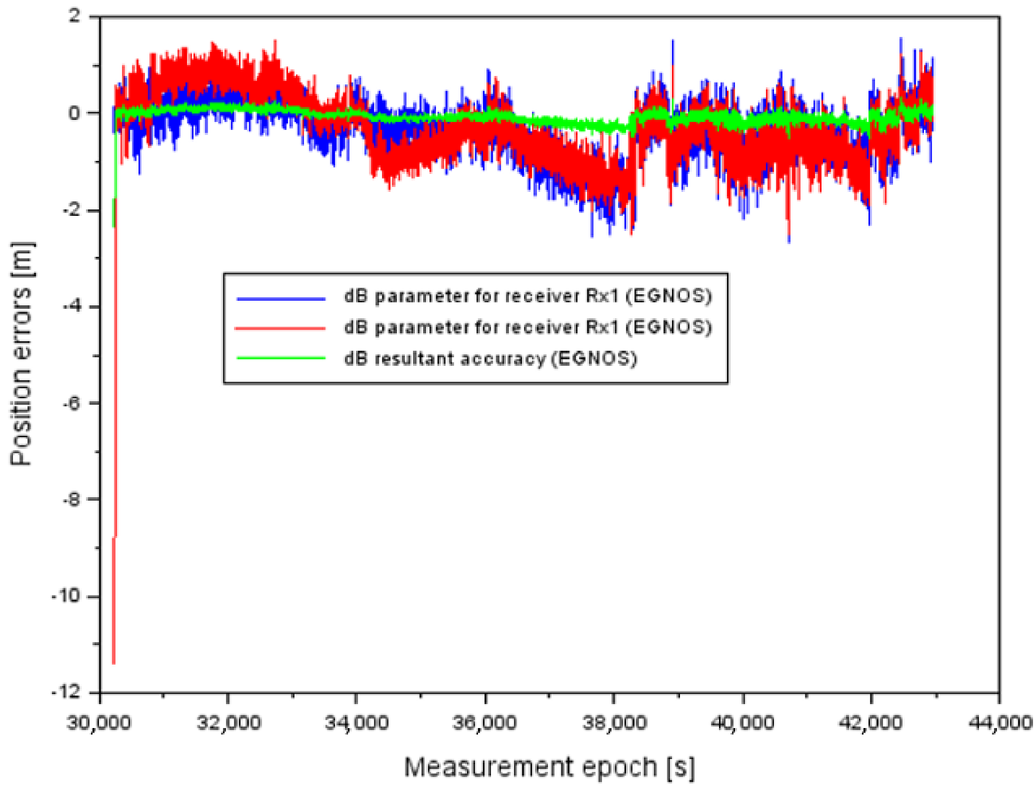

Figure 14. The results of *dB* position errors for EGNOS solution.

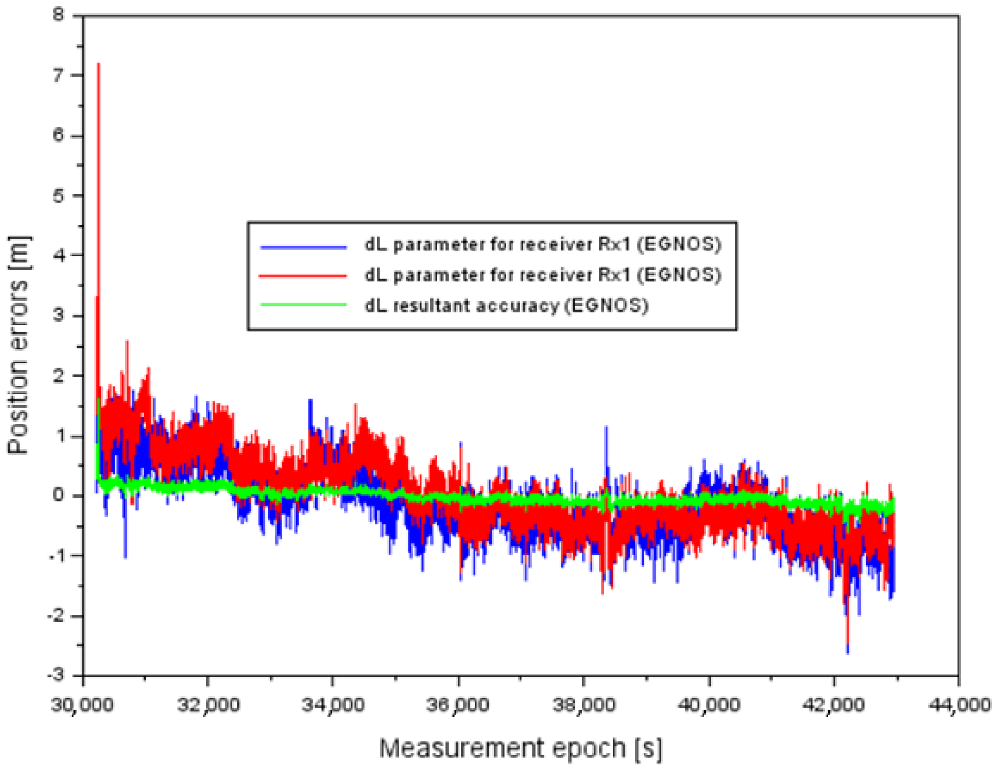

Figure 15. The results of *dL* position errors for EGNOS solution.

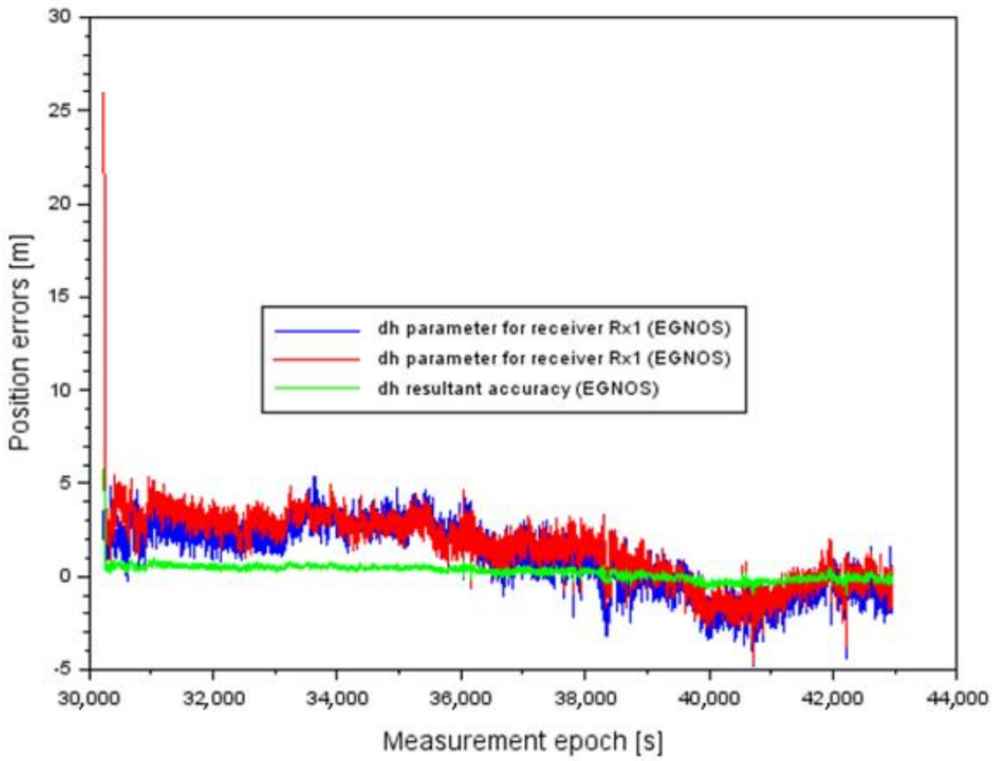

Figure 16. The results of *dh* position errors for EGNOS solution.

Figures 14–16 show the position error results for the receiver $Rx1$, $Rx2$ and the resultant EGNOS positioning accuracy values. Figure 14 shows the accuracy results of the EGNOS solution for the B component. The accuracy of the EGNOS solution for the receiver $Rx1$ is between −2.68 m and +1.55 m with an average value of −0.35 m. The accuracy of the

EGNOS solution for the receiver $Rx2$ is between −11.41 m and +1.52 m with an average value of −0.29 m. In turn, the resultant parameter scores dB are between −2.35 m and +0.35 m with an average accuracy of −0.06 m. The resultant value of the parameter dB has improved by 82% relative to the receiver $Rx1$ accuracy results and 78% relative to the receiver $Rx2$ accuracy results. Figure 15 presents the EGNOS positioning accuracy results along the L axis. The position errors for the receiver $Rx1$ range from −2.62 m to +1.88 m with an average accuracy value of −0.11 m. Position errors for the receiver $Rx2$ are between −2.47 m and +7.22 m with an average accuracy of −0.039 m. The resultant accuracy for dL parameter have values between −0.64 m and +1.64 m, with an average of −0.012 m. The resultant value of the parameter dL has improved by 89% relative to the receiver $Rx1$ accuracy results and, respectively, 69% relative to the receiver $Rx2$ accuracy results. Figure 16 shows the EGNOS positioning accuracy results along the h-axis. The position accuracy for the receiver $Rx1$ is between −4.81 m and +5.43 m, with an average value of +1.09 m, respectively. The positioning accuracy for the h-component for the receiver $Rx2$ is between −4.73 m and +25.96 m with an average of +1.51 m. In turn, the resultant value of the parameter dh results in a range of −1.03 m to +5.79 m with an average accuracy of +0.24 m. The resultant value of the parameter dh has improved by 78% relative to the receiver $Rx1$ accuracy results and, respectively, 84% compared to the accuracy results for the receiver $Rx2$. As can be seen for the horizontal components B and L, the best improvement in positioning accuracy is seen relative to the receiver $Rx1$ results. On the other hand, for the h component, the resultant accuracy results have improved best relative to the position error values of the receiver $Rx2$. Now comparing the results of the improvement in the resultant positioning accuracy of SDCM and EGNOS it can be seen that for EGNOS, these results are better and higher in percentage. In general, for the B and L components in the SDCM solution, the improvement in accuracy is 63–80%, and for the EGNOS system 69–89%, respectively. On the other hand, for the h component, SDCM improves the resultant accuracy by 56–77%, while EGNOS improves it by 78–84%, respectively. This is mainly influenced by the individual position error results for a given receiver for the navigation solution with a given SBAS system, which, in turn, depends on the geometry of satellites, i.e., PDOP coefficient and the number of tracked GNSS satellites by a given receiver. Nevertheless, the results of the improvement in the resultant accuracy values $(dB,\ dL,\ dh)$ are quite significant for both SBAS systems.

5.2. Comparison of the Resultant Accuracy of BLh Aircraft Coordinates with Reference to ICAO Recommendations for SBAS System

In the second stage of the discussion, the problem in the obtained results of the resultant accuracy of SDCM and EGNOS positioning in relation to ICAO recommendations for SBAS in air navigation was addressed. The performance of SBAS positioning accuracy under SBAS APV-I and SBAS APV-II approach procedure was used for comparison. For the SBAS APV-I and SBAS APV-II approach certification requirements, the horizontal positioning accuracy of the aircraft should not be less than ±16 m. In turn, in the vertical plane, the positioning accuracy in the SBAS APV-I procedure cannot be worse than ±20 m, while in the SBAS APV-II procedure, respectively, worse than ±8 m [51]. Out of the results obtained for the presented test method (Equations (2)–(9)), the resultant positioning accuracy is much higher than the ICAO technical standards, as shown in Table 2. As can be seen from Table 2, the worst SDCM positioning accuracy for horizontal coordinates is 2.29 m and is much better than the ICAO minimum recommendations for SBAS APV-I and SBAS APV-II flight operations. The results for EGNOS are similar, where the worst accuracy is 2.35 m in the horizontal plane. For ellipsoidal altitude, the worst SDCM positioning accuracy is 2.92 m, while EGNOS is 5.79 m, respectively, and both are within the accuracy limit of the SBAS APV-I and SBAS APV-II procedure. Therefore, it can be concluded that the proposed accuracy improvement algorithm (Equations (2)–(9)) meets the ICAO certification requirements for both SDCM and EGNOS in air navigation.

Table 2. Comparison of resultant accuracy results from SDCM and EGNOS solutions with reference to ICAO technical standards [51].

SDCM Solution	ICAO Recommendations	Conclusion
Resultant accuracy of Latitude is between −0.69 m and +1.22 m. Resultant accuracy of Longitude is between −0.81 m and +2.29 m.	Horizontal accuracy of aircraft equals to ±16 m in SBAS APV-I and SBAS APV-II.	The obtained accuracy for horizontal coordinates did not exceed the ICAO standard.
Resultant accuracy of ellipsoidal height is between −1.70 m and +2.92 m.	Vertical accuracy of aircraft equals to ±20 m in SBAS APV-I and ±8 m in SBAS APV-II.	The obtained accuracy for vertical coordinate did not exceed the ICAO standard.
EGNOS solution	**ICAO recommendations**	**Conclusion**
Resultant accuracy of Latitude is between −2.35 m and +0.35 m. Resultant accuracy of Longitude is between −0.64 m and +1.64 m.	Horizontal accuracy of aircraft equals to ±16 m in SBAS APV-I and SBAS APV-II.	The obtained accuracy for horizontal coordinates did not exceed the ICAO standard.
Resultant accuracy of ellipsoidal height is between −1.03 m and +5.79 m.	Vertical accuracy of aircraft equals to ±20 m in SBAS APV-I and ±8 m in SBAS APV-II.	The obtained accuracy for vertical coordinate did not exceed the ICAO standard.

5.3. Comparison between Research Method and Analysis of Scientific Knowledge

In the third part of the chapter, the discussion touches upon the contribution of the presented research method in relation to the current state-of-the-art technology. The problem of SBAS positioning accuracy in air navigation in Poland was addressed in papers [14–17,21]. The work [14] showed some of the first solutions of EGNOS operation in Poland. Accordingly, the accuracy of EGNOS positioning was not the highest and was up to ±12 m for BLh components. However, the accuracy results were considered only for a single GNSS receiver. On the other hand, the paper [15] showed the results of EGNOS positioning for two test flights, which allowed us to determine the repeatability of the accuracy parameter. The worst EGNOS positioning accuracy of up to ±20 m for BLh components for a single GNSS receiver was obtained from these tests. Publication [16] describes the results of accuracy tests for EGNOS in eastern Poland. The study used two receivers, operating independently with SBAS/EGNOS positioning function. The worst accuracy of EGNOS positioning was up to ±22 m for BLh components. EGNOS tracking interruptions were observed in the study, which undoubtedly negatively affected the obtained SBAS positioning accuracy results. The paper [17] shows the results of the position errors of the EGNOS solution considering the positioning mode, the location of the flight test and the influence of the ionosphere on the positioning accuracy. The study determined that better accuracy results were obtained in post-processing mode than in real time. In addition, there were problems with access to the SBAS solution in eastern Poland due to the lack of continuity of EGNOS corrections. Moreover, it was emphasized that the influence of the ionosphere is significant in determining the accuracy of SBAS positioning and this parameter should be monitored permanently also for airborne applications. The paper [21] presents the results of EGNOS positioning accuracy under enroute navigation and the precision approach (PA) procedure. The research test was carried out near the city of Olsztyn in north-eastern Poland. The obtained SBAS/EGNOS positioning accuracy results were better than 5.3 m in the horizontal plane and 2.9 m in height for enroute navigation. On the other hand, for the PA procedure, SBAS/EGNOS positioning accuracies were better than 3.2 m in the horizontal plane and 1.8 m in height.

In the scientific research conducted in the world, the problem of accuracy in SBAS positioning was addressed in papers [52–57], among others. In the work [52], the problem of determining the accuracy with GPS and GPS+GAGAN solution was shown. The application of the GAGAN system resulted in an increase in positioning accuracy to the level of 2.7–3.3 m. Paper [53] presents the results of GPS and GPS+EGNOS positioning accuracy in an airborne experiment carried out in Slovakia. The use of EGNOS resulted in an improvement in positioning accuracy to ±3–15 m in relation to the GPS solution. Publication [54] shows the results of EGNOS positioning accuracy in relation to the double difference (DD) solution of GPS phase observations. The EGNOS positioning accuracy was 1.1–2.2 m. The article [55] showed the results of WAAS positioning accuracy in air navigation. During the research, it was noted that the accuracy of WAAS positioning is affected by measurement noise, the multi-track effect and change in the number of tracked GNSS satellites. The obtained WAAS positioning accuracy is up to ±2.5 m. The flight tests in works [56,57] were carried out under the EGNOS System Test-Bed (ESTB) program. The paper [56] shows the results of EGNOS positioning accuracy during a flight test in Portugal. The accuracy of EGNOS positioning was 1.5–2.4 m. On the other hand, paper [57] showed the results of EGNOS positioning accuracy in a flight experiment in Lugano (Switzerland). The EGNOS positioning accuracy was 1.1–1.3 m.

Comparing the results of the study presented in this paper with reference to publications [14–17,21,52–57], it can be seen that:

- The positioning accuracy of the presented work was higher than in works [14–16,52,53,55],
- In contrast, the average positioning accuracy of the presented work was comparable to the work of [21,54,56,57],
- Similarly to the presented work, publications [16,17] have used at least two GNSS receivers in EGNOS research,
- Similarly to the presented work, the publications [21,53,56,57] compare the achieved accuracy performance in the context of ICAO technical recommendations,
- Similarly to the presented work, the publications [14–17,21,53,54,56,57] show the results of SBAS/EGNOS positioning accuracy,
- Whereas the difference is that the presented work uses two SBAS (i.e., SDCM and EGNOS), while the work [14–17,21,52–57] uses only one SBAS (EGNOS or WAAS or GAGAN).

Nevertheless, the topic of testing the accuracy of SBAS positioning is relevant to air navigation and should be further addressed in research work. The proposed algorithm in general is designed to improve the accuracy of GNSS positioning in aviation. The algorithm was previously tested and verified for the SPP positioning method and the differential GPS (DGPS) technique, as was demonstrated in scientific papers [58,59]. Therefore, the performance of the algorithm was examined and validated for the absolute and differential GNSS positioning methods. As shown by the results in publications [58,59], the performance of the applied algorithm is satisfactory, and most crucially, the algorithm is proven to work correctly when several GNSS receivers (at least two) are used in an aerial experiment. This paper and achieved results confirm the valid performance of the algorithm also for different SBAS augmentation systems using two GNSS receivers in air navigation.

6. Conclusions

The paper shows the results of research on the determination of the resultant accuracy parameter with the SDCM augmentation in air navigation. For this purpose, original navigation solutions were proposed by determining the resultant accuracy of SDCM positioning for two GNSS satellite receivers. The mathematical algorithm scheme was based on the SDCM positioning accuracy parameter calculated separately for each GNSS receiver and a weighting factor combining the determined single SDCM accuracy. The weighting factor was dependent on the number of GNSS satellites tracked by each receiver. The verification of the algorithm was tested on GNSS kinematic data recorded by two satellite receivers: Trimble Alloy and Septentrio AsterRx2i, placed on a Diamond DA 20-C1 aircraft. A test flight was performed in north-eastern Poland in 2020. For each receiver, the positioning accuracy in BLh ellipsoidal coordinates was determined and then the proposed algorithm was applied to calculate the resultant accuracy value. The resultant positioning accuracy was compared with a single position error solution separately for each GNSS receiver. On the basis of the performed tests and numerical analysis, it was found that the proposed algorithm for the SDCM system allows us to improve the determination of the resultant accuracy value by 56–80% in relation to the individual results of position errors from a single GNSS receiver. Additionally, the proposed algorithm was checked in terms of functionality for the system European Geostationary Navigation Overlay Service (EGNOS), and in this case, the improvement in the accuracy parameter was in the range of 69–89%. Therefore, the algorithm has even better improved the accuracy parameter in the EGNOS system. It should be mentioned that the obtained results of the resultant accuracy parameter from the SDCM and EGNOS solution meet the ICAO certification requirements for SBAS systems in air navigation. The presented algorithm has shown to be extremely effective for SDCM and EGNOS augmentation systems. In the future, the authors plan to extend their research to also include the GAGAN augmentation system. This approach based on three SBAS augmentation systems would be an interesting navigation solution for GNSS satellite data integration.

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