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NEW STRATEGY THE FOR DESIGNATION OF THE INTEGRITY PARAMETER IN SBAS POSITIONING IN AIR TRANSPORT

Summary. The article shows the results of a study on the determination of SBAS satellite positioning integrity parameters as a HPL and VPL protection levels. To this end, a modified algorithm was developed to determine the HPL and VPL protection levels from a common aircraft position navigation solution based on EGNOS and SDCM augmentation systems. The developed mathematical scheme was verified on real GNSS kinematic data recorded by two onboard Septentrio AsterRx2i and Trimble Alloy receivers installed on a Diamond DA 20-C aircraft. Based on the conducted tests, it was found that the HPL parameter does not exceed 12.24 m, while respectively the VPL does not exceed 18.01 m. In addition, in the course of the study it was found that the proposed EGNOS+SDCM solution

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improves the HPL/VPL integrity determination in relation to the EGNOS solution by 8÷66%. The mathematical scheme used in the study was also applied to designation the HPL/VPL terms for the UAV platform. The obtained results of the HPL/VPL values for the positioning of the aircraft and the UAV platform show a high efficiency of the developed algorithm for improving the integrity parameter.
Keywords: SBAS, integrity, EGNOS, SDCM

1. INTRODUCTION

Reinforcement of plates by rod systems is widely used in engineering, especially in aircraft Four basic parameters were applied to assess the quality of GNSS positioning in aviation, namely: availability, accuracy, integrity, and continuity [1]. For SBAS systems, the most important and also key parameter is the integrity of aircraft positioning [2]. According to ICAO Annex 10, integrity term is defined as: a measure of confidence in the accuracy of the information provided by the system. Integrity includes the ability of the system to provide the user with timely and appropriate warnings (alerts) when the system should not be used for a particular operation (or phase of flight) [3]. There are the following types of warnings [4]:

- AL (Alert Limit), denoting that the error must not be higher than a given value X without issuing a warning,
- PL (Protection Level) - a statistical error set to ensure that the probability of an absolute position error exceeding this figure is less than or equal to the target integrity risk. When the protection level exceeds the required alert limit during flight, the aircraft may not use the GNSS system for navigation,
- time to alarm - maximum permissible time from the start of the navigation system beyond tolerance until the period when the device issues a warning,
- integrity risk - indicates a degree of likelihood that at any point in time an error in the position will reach an alert limit.

The integrity of positioning of augmentation systems is determined on the basis of the HPL/VPL terms, which express the levels of technical safety using the GNSS sensor in the conducted flight operations [3, 5]. The HPL parameter relates to the horizontal plane and is defined by the radius of the circle as the base of the cylinder figure in which the position of the aircraft in the horizontal plane is determined at a confidence level of 95% [6, 7]. The VPL parameter, on the other hand, relates to the vertical plane and determines the height of the cylinder figure in which the determined aircraft position is located in the vertical plane for a confidence level of 95% [6, 7]. In addition, limit alerts have been set for both the HPL and VPL parameters, informing of the acceptable limits for position errors in the vertical and horizontal planes. A HAL parameter was defined for the HPL and a VAL parameter for the VPL [8]. In accordance with the ICAO Annex 10 for the SBAS APV-I approach procedure, a HAL boundary alert is specified of 40 m and a VAL vertical boundary alert of 50 m. For the SBAS APV-II approach procedure, the HAL is 40 m and the VAL is 20 m, respectively [9]. Table 1 shows a summary of the HAL and VAL parameters for both the SBAS APV approach procedures. It is worth noting that in both SBAS APV approach procedures, the value for the K_H factor equals 6.00 and for the K_v factor, it is equal to 5.33.

Tab. 1

Values of HAL and VAL term for both the SBAS APV approach procedures [9]

Parameter	SBAS APV-I	SBAS APV-II
Integrity	40 m for horizontal axes	40 m for horizontal axes
	50 m for vertical axis	20 m for horizontal axis

2. SCIENTIFIC KNOWLEDGE ANALYSIS

SBAS satellite augmentation systems are an essential feature in improving the quality of GNSS positioning in aviation. By determining the parameters of quality of the SBAS satellite signal, it is possible to improve the determination of the aircraft position. These attributes of the augmentation systems have contributed to a rapid increase of commonly available SBAS systems in the global market. Chapter Two presents the state of expertise with regard to determining HPL/VPL protection levels carried out in Poland and abroad.

Experiments relating to the determination of the HPL/VPL protection levels have been carried out in air transport. Scientific articles [6, 7] have proposed the use of EGNOS to define HPL/VPL protection levels during a flight test. In particular, paper [10] investigates the possibility of determining the HPL/VPL terms using the SBAS augmentation system for a single GNSS reference station. The research experiment was conducted for a GNSS reference station mounted in the vicinity of Rzeszów Airport. The protection levels were calculated in specialist Pegasus software using GPS observations and differential corrections from EGNOS satellites. Similar studies were also carried out over a different period of time at Dęblin and Olsztyn Dajtki airfields [7, 11].

Studies on the integrity of EGNOS positioning as an SBAS augmentation systems have also been carried out in Europe and North Africa. Scientific articles [12, 13, 14, 15, 16] deal with aerial research tests on the positioning of the EGNOS augmentation system over Europe. For example, article [14] investigates the positioning quality parameters of a GPS+EGNOS solution during an approach procedure in Amsterdam. Based on the obtained findings, the authors of the study stress that the integrity requirements have been met for the SBAS APV approach. For studies conducted in North Africa, research papers [17, 18] analyse EGNOS positioning in Algeria. Articles [17, 18] observe that by using a GPS+EGNOS solution, there is a significant improvement in positioning quality parameters, including integrity. In addition, the implementation of RIMS stations in Algeria has the potential to significantly improve EGNOS correction coverage across North Africa. Moreover, paper [17] emphasizes the fact that, for the moment, in Algeria, the EGNOS augmentation system can be applied to implement the SBAS APV procedure.

Based on the literature review, it can be stated that:

– most of the air research determining the integrity of positioning in Poland has been conducted using the EGNOS system,
– the subject of SBAS positioning lies in the scope of interest of numerous Polish and foreign research institutions,
– the HPL/VPL protection levels were calculated in static GPS measurements and kinematic measurements during a flight test.

Therefore, currently there are insufficient data in research regarding the determination of HPL/VPL protection levels based on a joint solution from EGNOS and SDCM systems as a SBAS systems. According to an analysis of the available literature in Poland and Europe, experiments were conducted which considered only one type of SBAS augmentation systems, mainly EGNOS. Thus, the paper proposes a navigation solution to improve the integrity of SBAS positioning through their interoperability. For this purpose, a modified formula was applied to determine the integrity of HPL/VPL positioning using a combination of EGNOS+SDCM navigation solution. The proposed model is a new approach to designation of the HPL/VPL protection levels. The authors' contribution to the article is as follows:

- development of a modified algorithm for determining the integrity of HPL/VPL during a flight test for the needs of air transport,
- the application of integrity computing strategy using navigational data from two SBAS systems, not merely on one system as previously,
- demonstrating the validity of improving the integrity determination from the EGNOS+SDCM solution with respect to the EGNOS results,
- checking and testing the developed algorithm in UAV positioning.

The article is divided into seven chapters, with an attached list of scientific literature at the end.

3. RESEARCH METHOD

The basic mathematical equation for computing the integrity parameters can be expressed as follows [2, 3, 19]:

$$\begin{cases} HPL = K_H \cdot \sqrt{dB^2 + dL^2} \\ VPL = K_V \cdot dh \end{cases} \tag{1}$$

where:
K_H – coefficient limiting the horizontal position of the user with a probability of 10^{-9} (for en-route navigation: $K_H = 6.18$; however, for a precise approach $K_H = 6.00$),
K_V – limiting factor for the vertical position of the user with a probability of 0.5×10^{-7} ($K_V = 5.33$),
(dB, dL, dh) – position errors for the designated aircraft coordinates from the EGNOS+SDCM solution,
HPL – horizontal protection level,
VPL – vertical protection level.

Equation (1) shows only the protection levels determination for a single SBAS system. In the case of integrity determinations from several SBAS systems, position errors (dB, dL, dh) may be expressed as follows:

$$\begin{cases} dB = B_m - B_{ref} \\ dL = L_m - L_{ref} \\ dh = h_m - h_{ref} \end{cases} \tag{2}$$

where:
(B_m, L_m, h_m) – aircraft position from the EGNOS+SDCM solution,
$B_m = \frac{w_E \cdot B_E + w_S \cdot B_S}{w_E + w_S}$ – B-coordinate of the aircraft position, determined from the weighted average model,
$L_m = \frac{w_E \cdot L_E + w_S \cdot L_S}{w_E + w_S}$ – L-coordinate of the aircraft's position, determined from the weighted average model,
$h_m = \frac{w_E \cdot h_E + w_S \cdot h_S}{w_E + w_S}$ – h-coordinate of the aircraft position as determined from the weighted average model,
w_E – linear coefficient from the EGNOS solution computed as a function: $w_E = \frac{1}{N_E}$,
w_S – linear coefficient from the SDCM solution computed as a function: $w_S = \frac{1}{N_S}$,
N_E – total number of GPS satellites for which EGNOS corrections were determined,
N_S – total number of GPS satellites for which SDCM corrections were determined,
(B_E, L_E, h_E) – flight aircraft coordinates from the EGNOS solution,
(B_S, L_S, h_S) – flight aircraft coordinates from the SDCM solution,
$(B_{ref}, L_{ref}, h_{ref})$ – flight aircraft references position from the RTK-OTF solution.

Equation (1) can therefore be transformed to its initial form:

$$\begin{cases} HPL = K_H \cdot \sqrt{(B_m - B_{ref})^2 + (L_m - L_{ref})^2} \\ VPL = K_V \cdot (h_m - h_{ref}) \end{cases}, \tag{3}$$

and then into its final form:

$$\begin{cases} HPL = K_H \cdot \sqrt{(\frac{w_E \cdot B_E + w_S \cdot B_S}{w_E + w_S} - B_{ref})^2 + (\frac{w_E \cdot L_E + w_S \cdot L_S}{w_E + w_S} - L_{ref})^2} \\ VPL = K_V \cdot (\frac{w_E \cdot h_E + w_S \cdot h_S}{w_E + w_S} - h_{ref}) \end{cases}. \tag{4}$$

The HPL/VPL terms from equation (4) determine the levels of integrity for performing flight operations in the horizontal and vertical planes, respectively. HPL and VPL values in accordance with ICAO requirements are given in metres [2].

4. RESEARCH EXPERIMENT

The research experiment was conducted as part of the implementation of a test flight using the Diamond DA 20-C aircraft on the Olsztyn-Suwałki-Olsztyn route. The purpose of the flight was to determine the quality of SBAS positioning in air transport in the area of north-eastern Poland. The starting and finishing point of the route was the civil airport EPOD (Olsztyn Dajtki). The airfield has had GNSS approach procedures since 2014 [20]. Two dual-frequency geodetic receivers were mounted on board the aircraft: Septentrio AsterRx2i and Trimble Alloy, with an accuracy class of 1-2 m for the SBAS positioning module. The onboard receivers recorded GPS satellite data in RINEX format with an interval of 1 second. The SBAS corrections from the EGNOS and SDCM systems were downloaded from the real-time server: ftp://serenad-public.cnes.fr [21]. The acquired GNSS satellite data were applied to calculate the aircraft coordinates, next to determine the SBAS positioning accuracy and finally to determine the HPL/VPL integrity parameters according to equations (1-4). The RTKLIB v.2.4.2 programme [22], available at http://rtklib.com [23], was used to determine the aircraft coordinates using the Single Point Positioning method. In turn, the accuracy and integrity of SBAS positioning was calculated in Scilab v.6.0.0 programming language [24] using the authors' own commands in script. It should be added that navigational calculations were made only for the approach stage of the aircraft at EPOD airfield. The results for the HPL/VPL parameters calculated according to the mathematical equations (1-4) will be presented in Chapter 5.

5. RESULTS

Figure 1 presents the results of the HPL levels for the EGNOS+SDCM solution for the Septentrio AsterRx2ireceiver during the approach procedure, i.e., from 11:38:31 (41911 s) to 11:55:59 (42959 s) according to GPS Time. HPL and VPL values in accordance with ICAO requirements are expressed in metres. HPL results ranged from 0.55 m to 11.71 m, with an average HPL of 5.26 m. In addition, in accordance with ICAO standards, the HAL boundary alert was not exceeded during the approach procedure [3].

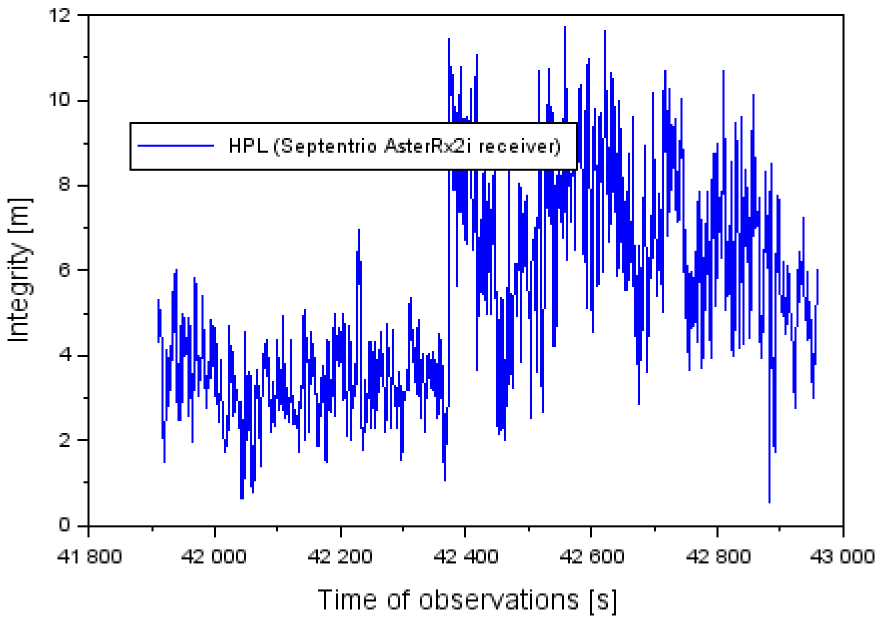

Fig. 1. Integrity of HPL positioning of the solution EGNOS+SDCM from the Septentrio AsterRx2i receiver

In contrast, Fig. 2 shows the integrity findings in the form of the VPL parameter during an approach to landing. VPL values ranged from 2.41 m to 18.01 m, with an average value of 11.63 m. As with the HPL parameter, the VPL integrity values do not exceed the VAL horizontal alarm limit, whose values are 50 m for the SBAS APV-I procedure and 20 m for the SBAS APV-II procedure, respectively [3]. Therefore, the integrity of the SBAS meets the required standards, making it suitable for supporting approach operations. In Figures 1 and 2, a rapid change in the HPL/VPL integrity values can be seen, especially around epoch 42400 s.

This is due to the change in positioning accuracy of aircraft coordinates. According to equation (4), a change in positioning accuracy affects the level of integrity. Based on Figures 1 and 2, it should be statement that the application of the EGNOS+SDCM mathematical model made it possible to achieve the highest HPL/VPL values of approximately 18 m. This means that, with the EGNOS+SDCM mathematical model, it is possible to increase the level of safety in ongoing flight operations.

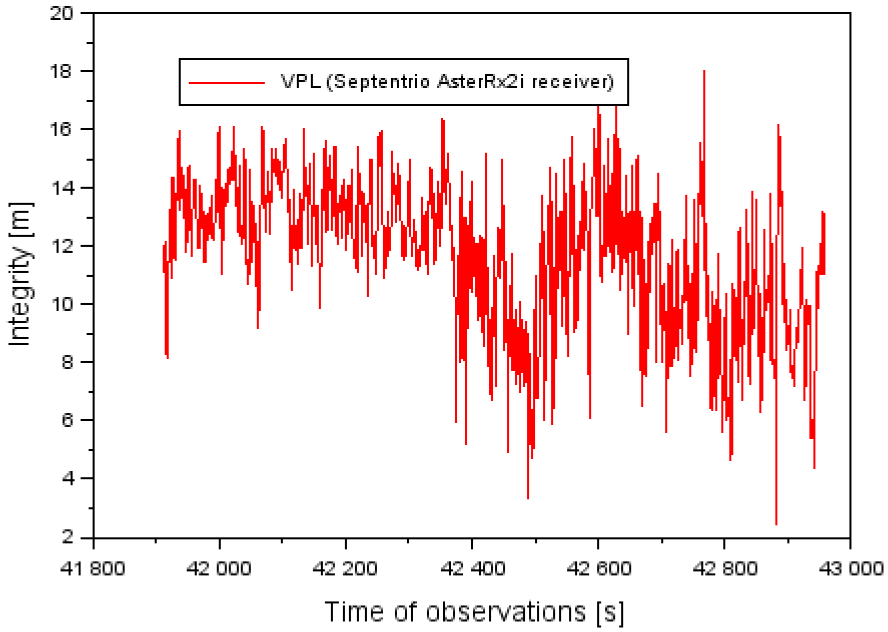

Fig. 2. Integrity of VPL positioning from the solution EGNOS+SDCM from the Septentrio AsterRx2i receiver

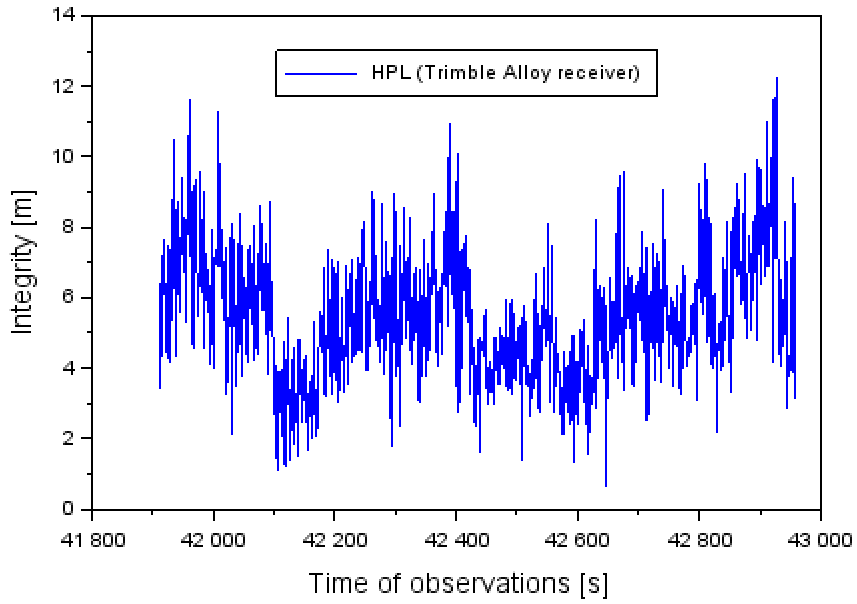

Fig. 3. Integrity of HPL positioning based on solution EGNOS+SDCM from the Trimble Alloy receiver

Figure 3 presents the values of the HPL parameters for the EGNOS+SDCM solution during an approach procedure for the Trimble Alloy receiver. The HPL results ranged from 0.64 m to 12.24 m, with an average HPL of 5.46 m. The obtained HPL integrity results from the Trimble Alloy receiver are at a similar level to the results obtained from the Septentrio AsterRx2i receiver.

In turn, Fig. 4 shows the integrity results obtained from the EGNOS+SDCM mathematical algorithm in the form of the VPL parameter during an approach to landing from the Trimble Alloy receiver. The VPL values ranged between 0.05 m and 15.04 m, with an average value of 5.50 m. Comparing the results of the integrity of VPL positioning for both receivers, it can be concluded that the integrity of determining the VPL parameter is 51% higher for the Trimble Alloy receiver than the Septentrio AsterRx2i. This is connected with the fact that the accuracy of ellipsoidal height determination is higher for the Trimble Alloy receiver than for the Septentrio AsterRx2i.

In summary, the HPL/VPL integrity results did not exceed ICAO technical standards for both SBAS APV procedures. The leaps in the HPL/VPL integrity in Figures 3 and 4 are due to the change in the aircraft positioning accuracy value according to equation (2). Furthermore, with reference to equation (2), an increase in the value of position errors results in an increase in the level of integrity of HPL/VPL.

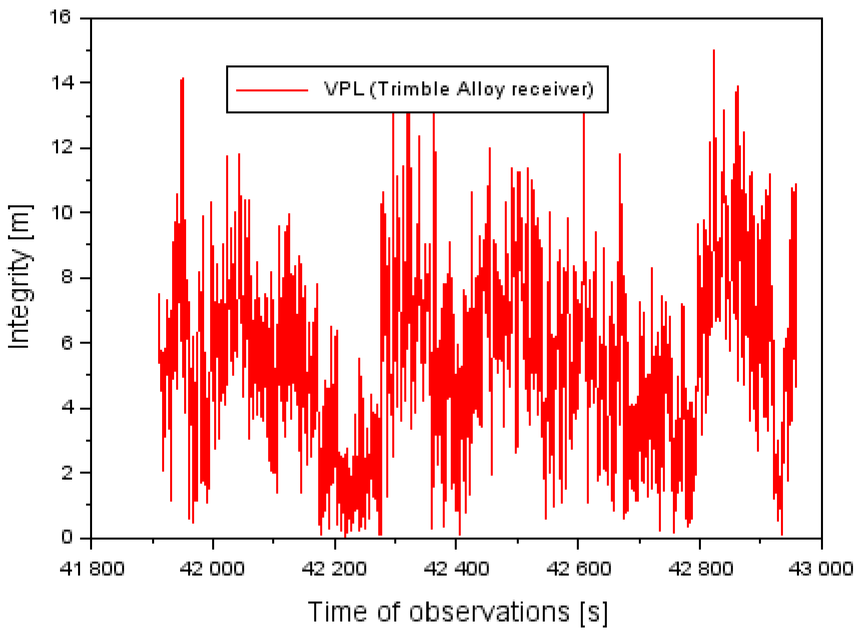

Fig. 4. Integrity of VPL positioning based on solution EGNOS+SDCM from the Trimble Alloy receiver

6. DISCUSSION

Chapter 6 presents a discussion of the presented research method and the obtained research results. In the first step of the discussion, the results of the obtained HPL and VPL protection levels from EGNOS+SDCM solution were compared to a single SBAS solution, e.g., only to EGNOS system. The HPL and VPL results from the EGNOS+SDCM mathematical scheme were calculated using equation (4), while the EGNOS solution used the equation (1) for a single SBAS system. Table 2 lists the obtained comparative HPL/VPL findings.

Tab. 2

Comparison of HPL/VPL values based on EGNOS+SDCM and EGNOS solutions only

Integrity parameter	Receiver	EGNOS+SDCM solution [m]	EGNOS solution [m]	Conclusions
HPL	Septentrio AsterRx2i	0.55 ÷ 11.71	0.88 ÷ 12.74	HPL from EGNOS+SDCM positioning model improved by 8÷36% compared to EGNOS solution
VPL	Septentrio AsterRx2i	2.41 ÷ 18.01	7.20 ÷ 22.18	VPL from EGNOS+SDCM positioning model improved by 18÷66% compared to EGNOS solution
HPL	Trimble Alloy	0.64 ÷ 12.24	0.78 ÷ 14.42	HPL from EGNOS+SDCM positioning model improved by 15÷18% compared to EGNOS solution
VPL	Trimble Alloy	0.05 ÷ 15.04	0.10 ÷ 17.87	VPL from EGNOS+SDCM positioning model improved by 16÷50% compared to EGNOS solution

The HPL parameter value from the EGNOS+SDCM solution was improved from 8÷36% for the Septentrio AsterRx2i receiver and from 15÷18% for the second Trimble Alloy receiver with regard to the EGNOS solution. Furthermore, the VPL value from the EGNOS+SDCM solution was improved from 18÷66% for the Septentrio AsterRx2i receiver and from 16÷50% for the second Trimble Alloy receiver relative to the EGNOS solution. The presented algorithm in equation (4) is therefore valid in the analysis of positioning integrity using several SBAS systems in navigation. The integrity results obtained for the HPL and VPL safety parameters enable to formulate a conclusion that the implementation of the EGNOS+SDCM positioning model is more efficient than in the case of using an EGNOS solution.

In the following discussion, a summary of the of HPL/VPL levels based on EGNOS+SDCM solution is presented in relation to an analysis of the available expertise. The results obtained for the HPL/VPL integrity parameters are lower or on a similar level as in the research papers [2, 6, 9, 14, 15, 16, 17]. This only proves the correctness of the proposed mathematical algorithm for equations (2-4). This is of particular significance as the research papers [2, 6, 9, 14, 15, 16, 17] used a single SBAS, i.e., the EGNOS augmentation system. In addition, the lower the integrity level of the HPL/VPL, the higher is the accuracy of SBAS positioning, which translates into position error values.

The paper also calculates the resultant HPL/VPL integrity values for the two Septentrio AsterRx2i and Trimble Alloy receivers used in the discussed air test. For this purpose, the HPL/VPL levels were determined from a mathematical relationship:

$$\begin{cases} HPL_{res} = \frac{HPL_{SEPT}+HPL_{TRIM}}{NR} \\ VPL_{res} = \frac{VPL_{SEPT}+VPL_{TRIM}}{NR} \end{cases}, \tag{5}$$

where:
HPL_{res}– resultant HPL positioning integrity value based on the EGNOS+SDCM mathematical algorithm for both GNSS receivers,
VPL_{res}– resultant VPL positioning integrity value based on the EGNOS+SDCM mathematical algorithm for both GNSS receivers,
HPL_{SEPT} – integrity of HPL positioning based on the EGNOS+SDCM mathematical algorithm for first the Septentrio AsterRx2i receiver,
HPL_{TRIM} – integrity of HPL positioning based on the EGNOS+SDCM mathematical algorithm determined for the second Trimble Alloy receiver,
VPL_{SEPT} – integrity of VPL positioning based on the EGNOS+SDCM mathematical algorithm for the first Septentrio AsterRx2i receiver,
VPL_{TRIM} – integrity of VPL positioning based on the EGNOS+SDCM mathematical algorithm determined for the second Trimble Alloy receiver,
NR– number of GNSS receivers used in the flight test, $NR = 2$.

Table 3 presents the results of the resultant protection levels for the two Septentrio AsterRx2i and Trimble Alloy receivers. Within the implemented flight test, the resultant integrity value of HPL_{res} ranges from 0.59 m to 11.98 m. On the other hand, the resultant integrity value of VPL_{res} ranges from 1.23 m to 16.53 m.

Tab. 3

Resultant values of HPL/VPL integrity based on EGNOS+SDCM solution for both GNSS receivers

Integrity parameter	Minimum value [m]	Maximum value [m]
HPL_{res}	0.59	11.98
VPL_{res}	1.23	16.53

The final discussion focused on the reproducibility of the presented research method. Therefore, equation (4) was used to determine the integrity levels of HPL/VPL during a flight test executed with a UAV platform. The flight test was performed in 2020 nearby Warsaw. An AsteRx-m2 UAS receiver was mounted on the UAV vehicle to record GNSS navigation data. This made it possible to implement a mathematical algorithm (2-4) for integrity calculations within the EGNOS+SDCM positioning method. Figure 5 presents the values of the HPL parameter for the EGNOS+SDCM solution during the UAV test flight. HPL values changed between 0.16 m and 9.94 m. The average HPL result was 4.46 m.

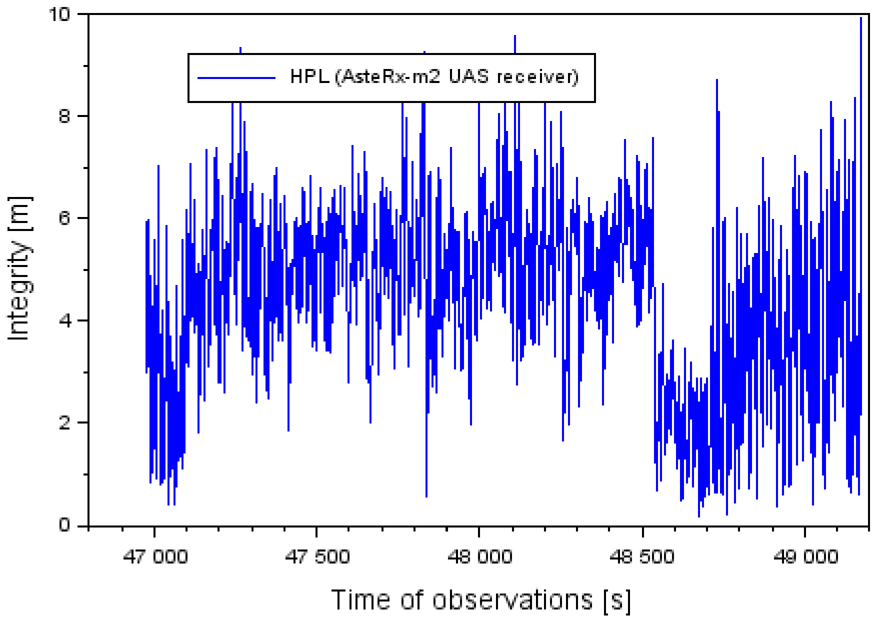

Fig. 5. Integrity of HPL positioning from the solution EGNOS+SDCM for the AsteRx-m2 UAS receiver

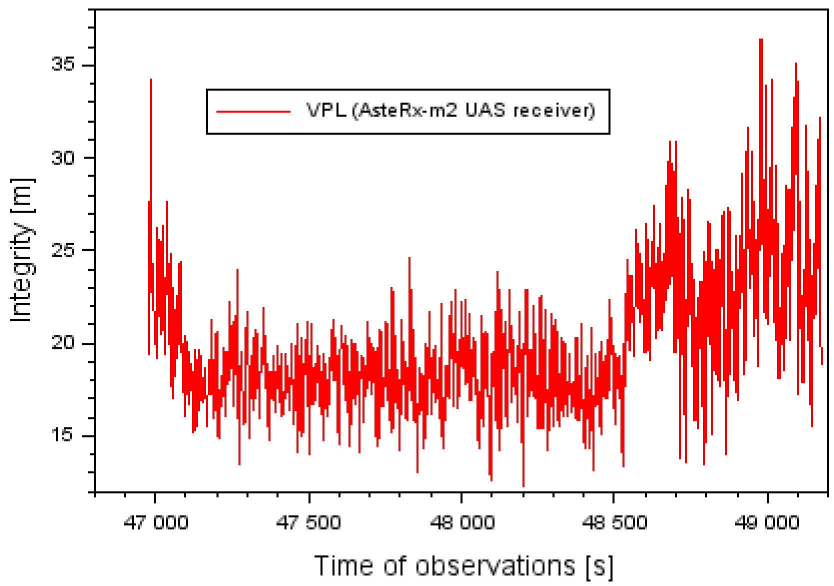

Fig. 6. Integrity of VPL positioning from the solution EGNOS+SDCM for the AsteRx-m2 UAS receiver

In turn, Fig. 6 shows the VPL values for the EGNOS+SDCM solution for the UAV platform. The VPL results changed between 12.21 m and 36.49 m, and the average VPL value was 19.93 m. For the HPL parameter, similar results were obtained as in the case of both the GNSS receivers. In contrast, the VPL values for UAV flight are higher than the integrity levels obtained for both the GNSS receivers. This is due to the position errors results for the ellipsoidal height, according to equation (2). If the positioning accuracy decreases, the level of integrity increases, according to equation (4).

7. SUMMARY AND CONCLUSIONS

The article shows the values of a study on the determination of the HPL/VPL integrity parameters of HPL/VPL in an air experiment. The paper modifies the basic algorithm for determining HPL/VPL parameters based on a combination of a position navigation solution using two SBAS systems, e.g., EGNOS and SDCM augmentation systems. This is crucial since the integrity parameters have so far been determined for a single SBAS augmentation system. The study uses GPS observation and navigation data recorded by two onboard GNSS receivers: Septentrio AsterRx2i and Trimble Alloy were installed on board a Diamond DA 20-C aircraft. In addition, the study makes use of corrections from EGNOS and SDCM satellites. Based on the performed tests, it was statement that the HPL parameter does not exceed 12.24 m, while the VPL does not exceed 18.01 m, respectively. In addition, the study proved that the proposed EGNOS+SDCM solution improves the HPL/VPL integrity determination rather than the EGNOS solution by 8÷66%. The paper also calculates the resultant HPL/VPL integrity values for the two Septentrio AsterRx2i and Trimble Alloy receivers for the discussed air test. The mathematical algorithm developed for the purpose of the examinations was also used to determine the integrity of HPL/VPL positioning for the UAV platform. The obtained findings of the HPL/VPL values enable the potential and practical use of the developed algorithm to determine the integrity of HPL/VPL for air transport.

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