Analysis of Applying the EGNOS System in APV-1 and LPV-200 Operations

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Abstract. The EGNOS satellite system was created, inter alia, to support air operations. In May 2016, the first LPV-200 landing approach in Europe was implemented at the Paris airport. The article presents the results of research on the quality of the EGNOS system, carried out in various places in Poland. Data obtained in real time and in post-processing mode were used for analyses. 24-hour observational data recorded in 2015 using the Polish TPI NETpro network were used. Research includes a period of low and high ionospheric activity. All data used in the work has been developed for APV-1 and LPV-200 applications. The algorithms described in the documentation characterizing the possibilities of using satellite systems in aviation were used in the work. The calculations were performed in the professional PEGASUS software, which is intended for testing the GPS / SBAS positioning quality in Europe. It was also necessary to use proprietary software - PP_SBAS_Analyzer. Summing up the results of research carried out at selected TPI NETpro network points located in Poland, it can be concluded that the quality of GPS / EGNOS positioning depends on the location of the observation. The basis for conducting a more thorough analysis should be weak results obtained for the territory of Poland in the extreme south, where, according to the results of experiments, it is not possible to implement procedures compatible with APV. Noteworthy are the significantly different results of the positioning quality test at some points located only about 100 km apart. Therefore, prior to the application of the EGNOS system in aviation, it seems necessary to conduct local monitoring of the system's operation. The results of the conducted research prove that the quality of positioning using the EGNOS system has significantly improved in recent years and can meet the requirements of satellite air navigation in accordance with APV-1 and even LPV-200.

1. Introduction

GNSS (Global Navigation Satellite Systems) is currently one of the most popular navigation techniques. It is successfully used in air, road, pedestrian and water traffic. GPS (Global Positioning System) is currently the most popular navigation system, however, positioning using other elements of the GNSS group is also becoming more common and effective [1, 2]. Air transport is an attractive alternative to other means of communication [3]. In recent years, the number of registered civil aircraft has increased, which can easily use small airports [4]. However, a common problem is the poor technical infrastructure, which is equipped with both small aircraft and ground facilities. An excellent solution could be the use of a navigation system based on GNSS, which does not require any additional devices at the airport. Navigation is carried out with the use of a suitable satellite receiver included in the aircraft's equipment. It is then possible to use GPS system, but only for horizontal navigation. To enable simultaneous application of vertical indications, it is necessary to support GPS positioning with systems from the
SBAS group (Satellite Based Augmentation Systems). One of them is the European EGNOS (European Geostationary Navigation Overlay Service). It can be stated that the process of its implementation in Polish aviation is just beginning [5].

The most important quality parameters of GPS / SBAS positioning are accuracy, integrity, continuity and availability. Integrity means the probability that can be assigned to the correctness of information provided by the navigation system [6]. HPL (horizontal protection level) and VPL (vertical protection level) are used to express the level of integrity in real time. HPL is the radius of a circle with the center in the real position that corresponds to the area containing the position calculated by the system. The VPL, on the other hand, is the length of the middle axis of the roller with the center in the true position, which corresponds to the area containing the vertical position calculated by the system [7]. It is assumed that the integrity is met when the XPL (HPL and VPL) values do not exceed the alarm limits defined for a given stage of the flight. MI (misleading information) occurs when the erroneous solution of the position is affected by a large positioning error exceeding the values of protection levels, while HMI (Hazardous Misleading Information) is MI leading to extremely critical situations.

The quality of the EGNOS system in Poland has been studied many times. The most frequently analyzed parameter is system accuracy [8]. However, the key role in navigation is the integrity of positioning, on the basis of which it is possible to increase the safety of navigation [9, 10, 11, 12].

The results of EGNOS performance analyses should improve over time with the development of the system infrastructure and systematic changes in algorithms related to its operation. Until recently, the area of north-eastern Poland was considered as the boundary of the system by means of the RIMS (Ranging and Integrity Monitoring Station) located in Warsaw, as the most eastern one. However, the latest research conducted in Ukraine indicates a significant improvement of EGNOS activities in eastern Europe [13].

The aircraft navigation systems can use SBAS, which theoretically comply with defined requirements. NPA (Non-Precision Approach) allows the use of navigation based on satellite systems only for horizontal solutions [14]. Whereas, using the APV (Approach with Vertical Guidance) and LPV (Localizer Performance with Vertical Guidance) procedures, vertical and horizontal GNSS positioning can be used.

Table 1 presents the required values of positioning quality parameters based on the EGNOS system [15, 16].

| type of operation | accuracy | integrity | continuity | availability |
|-------------------|----------|-----------|------------|--------------|
|                  | horizontal (95 %) | vertical (95 %) | Horizontal Alert Limit (HAL) | Vertical Alert Limit (VAL) |                      |
| "en route" oceanic/continental low density | 3.7 km | N/A | 7.4 km | N/A | 1 - 1x10^-4 /h to 1 - 1x10^-3 /h | 0.99 to 0.99999 |
| "en route" continental | 0.74 km | N/A | 1.85 km | N/A | 1 - 1x10^-4 /h to 1 - 1x10^-3 /h | 0.99 to 0.99999 |
| "en route" terminal | 0.74 km | N/A | 3.7 km | N/A | - | - |
| NPA | 220 m | N/A | 556 m | N/A | 1 - 8x10^-6 /15 s to 1 - 1x10^-3 /h | 0.99 to 0.99999 |
| APV-1 | 16 m | 20 m | 40 m | 50 m | 1 - 8x10^-6 /15 s | 0.99 to 0.99999 |
| CAT-1 (LPV-200) | 16 m | 6 m | 40 m | 35 m | 1 - 8x10^-6 /15 s | 0.99 to 0.99999 |

The main objective of the work is to assess the quality of GPS / EGNOS positioning in north-eastern Poland (in relation to the rest of the country) in the aspect of application in APV and LPV procedures.
2. Description of the experiments
The aim of the research is to examine the functioning of the EGNOS system in selected places in Poland. For this purpose, the values of parameters characterizing the accuracy and integrity of positioning were examined. TPI NETpro, a nationwide network of GPS/GLONASS reference stations, was used for this task [17]. This choice was made, because almost all stations included in the system are equipped with the same model of the receiver (Topcon NET-G3A, TPSCR.G5 TPSH). 24-hour observational data recorded using TPI NETpro on 05/03/2015, 18/03/2015, 23/03/2015 and 22-hour sessions from 17/03/2015 were recorded (data were not fully available). The interval of recorded data is 1 s. On 05/03/2015 and on 23/03/2015, the Kp coefficients reached low values, indicating the low level of activity of the Earth's electromagnetic field. On March 17, 2015 and March 18, 2015, their values reached almost 8 units. The obtained data was used to analyze in post-processing mode using the SDK Septentrio Post Processing software, the proprietary software PP_SBAS_Analyzer and the PEGASUS tool set (according to the diagram shown in Figure 1). Based on observation and navigation files in the RINEX format (independent receiver exchange format) and data containing information transmitted by EGNOS geostationary satellites (recorded at the Dajtki-Olsztyn GNSS station), it was possible to try to determine the GPS / EGNOS position for each measurement epoch. SBAS data in the RINEX format was filtered in the PP_SBAS_Analyzer application because the messages sent by the SDCM (System for Differential Corrections and Monitoring) system generated errors during analyses made in the PEGASUS and Septentrio Post Processing SDK software. Due to interruptions in the observations obtained from TPI NETpro network, it was also necessary to filter this data.

[Diagram of the post-processing algorithm]

3. Results and discussions
Measurement points were selected in such a way that it would be possible to study the functioning of the EGNOS system at the edges of Poland (north, south, east, west). In addition, data collected in chosen cities of the north-eastern part of Poland were analyzed. Figure 2 contains the approximate location of the points for which the quality parameters of the EGNOS system have been determined (accuracy and integrity).
Figure 2. TPI NETpro network stations used in research.

Figure 3 presents the analyses of the accuracy made for horizontal and vertical results of 05/03/2015 (calm state of the ionosphere).

Based on this data, it can be concluded that the best horizontal results were obtained at points: SULE (HPE 95% = 0.62 m), BRAN (HPE 95% = 0.64 m) and OSTD (HPE 95% = 0.66 m). Whereas the worst horizontal results of positioning are characterized by KRYN point (HPE 95% = 0.91 m), OSTO (HPE 95% = 0.83 m) and GARW (HPE 95% = 0.81 m). In the case of vertical analyses, the POZN point is the best (VPE 95% = 1.40 m), KRYN (VPE 95% = 1.42 m) and OSTD (VPE 95% = 1.43 m). The worst performers are: SEJN (VPE 95% = 1.63 m), BRAN (VPE 95% = 1.56 m) and OSTO (VPE 95% = 1.53 m), however, these results can also be considered satisfactory for aircraft applications.

Figure 4 shows the results of the accuracy analyses carried out for the data on 17/03/2015, in which the ionosphere was characterized by very high activity.
In Figure 4, the best horizontal results were obtained on the basis of data from the BRAN point (HPE 95% = 1.66 m), OSTD (HPE 95% = 1.73 m), SEJN (HPE 95% = 1.79 m) and SZCT (HPE 95% = 1.81 m). The worst results of horizontal analyses were obtained on the basis of data from SULE (HPE 95% = 2.36 m), KRYN (HPE 95% = 2.30 m), GARW and POZN (for each of the HPE points 95% = 2.26 m).

Vertical analyses show the best results for the SULE point (VPE 95% = 3.15 m), KLES (VPE 95% = 3.16 m) and OSTO point (VPE 95% = 3.24 m). The worst results were obtained in the case of data from the BRAN point (VPE 95% = 3.44 m), GARW (VPE 95% = 3.36 m), OSTD, PISZ, POZN and SEJN (for each of the points VPE 95% = 3.27 m). However, it should be noted, that the VPE values obtained for all tested points reach a similar level. Figure 5 presents the results of the accuracy analyses carried out for the data of 18/03/2015, in which the ionosphere was characterized by increased activity.

The best horizontal results of GPS / EGNOS positioning on 18/03/2015 were obtained at SULE (HPE 95% = 0.75 m), POZN (HPE 95% = 0.84 m) and OSTD (HPE 95% = 0.85 m). The worst results are characterized by the KRYN (HPE 95% = 1.03 m) point. The remaining points present values at a satisfactory level (HPE 95% <1 m). Vertical analyses show the best results also for SULE points (VPE 95% = 1.44 m), POZN (VPE 95% = 1.57 m) and OSTD (VPE 95% = 1.63 m). The worst results were obtained for data from SEJN (VPE 95% = 1.93 m), GARW (VPE 95% = 1.91 m), KLES (VPE 95% = 1.85 m) and OSTO (VPE 95% = 1.85 m). Figure 6 shows the results of the accuracy analyses carried out for the data of 23/03/2015, when the ionosphere was characterized by moderate activity.
Figure 6. Positioning errors for horizontal (left figure) and vertical analyses (right figure), determined for the session of 23/03/2015.

In Figure 6, the best horizontal results were obtained on the basis of data from SULE (HPE 95% = 0.63 m), OSTD (HPE 95% = 0.66 m) and BRAN, POZN, SZCT (HPE 95% = 0.73 m). The worst results of horizontal analyses were obtained once again based on data from the point KRYN (HPE 95% = 0.93 m). The vertical analyses show the best results for the SULE point (VPE 95% = 1.37 m) and KRYN (VPE 95% = 1.38 m). The worst values were obtained for data from SEJN (VPE 95% = 1.72 m) and PISZ (VPE 95% = 1.68 m).

Analyses presented in Figures 7-14 present extreme values of parameters characterizing the quality of GPS / EGNOS positioning based on TPI NETpro network points.

Figure 7. Maximum values of positioning errors and the corresponding HPL and VPL for horizontal (left figure) and vertical (right figure) components, determined for the session on 05/03/2015.

Figure 8. Minimum HPL and VPL values and corresponding positioning errors for horizontal (left figure) and vertical (right figure) components, determined for the session on 05/03/2015.
In figure 7 (data from 05/03/2015) it can be seen that in the case of the KRYN point, the maximum values of HPE and VPE are not much smaller than the corresponding HPL and VPL designations. The HSI value (horizontal security index) calculated on their basis of formula presented in [18] is 0.74, which almost indicates the risk of misleading information about the quality of positioning (MI). The results of the analyses of the maximum VSI = 0.97 indicate a high risk of such a case. The results obtained in the remaining points are much better. Analysis of the minimum values of HPL and VPL together with the corresponding HPE and VPE, does not show any abnormalities in the functioning of the integrity model.

The results presented in Figure 8 describing the minimum HPL and VPL values (data from 05/03/2015), show that their respective relationship is maintained together with the corresponding positioning errors for each tested point.

![Figure 9](image1.png) **Figure 9.** Maximum values of positioning errors and the corresponding HPL and VPL for horizontal (left figure) and vertical analyses (right figure), determined for the session of 17/03/2015.

![Figure 10](image2.png) **Figure 10.** Minimum HPL and VPL values and corresponding positioning errors for horizontal (left figure) and vertical analyses (right figure), determined for the session of 17/03/2015.

The analysis of the maximum positioning errors received on 17/03/2015 shows that HPE > HPL and VPE > VPL occurrence for PISZ. The GARW point is characterized by very large HPL (179.10 m) and VPL (358.86 m) values corresponding also to the increased results of the accuracy analysis. Despite the very high activity of the ionosphere, the results obtained in the remaining points and the results of the analysis of the minimum values of HPL and VPL do not show any anomalies in the operation of the integrity algorithm.
Figure 11. Maximum values of positioning errors and the corresponding HPL and VPL for horizontal (left figure) and vertical analyses (right figure), determined for the session of 18/03/2015.

Figure 12. Minimum HPL and VPL values and corresponding positioning errors for horizontal (left figure) and vertical analyses (right figure), determined for the session on 18/03/2015.

The results of the analysis of the maximum values of positioning errors and minimum HPL and VPL values determined on the basis of data from 18/03/2015 do not present any MI risk. Noteworthy however, are the results of the study of maximum HPE and VPE obtained at KRYN (horizontal and vertical results) and PISZ (horizontal results). The HPL and VPL values determined are much higher than those obtained for the remaining points.

Figure 13. Maximum values of positioning errors and the corresponding HPL and VPL for horizontal (left figure) and vertical analyses (right figure), determined for the session of 23/03/2015.
Figure 14. Minimum HPL and VPL values and corresponding positioning errors for horizontal (left figure) and vertical analyses (right figure), determined for the session from 23.03.2015

Figures 13 and 14 also present satisfactory results of the analysis (23/03/2015) of the maximum HPE, VPE and the corresponding HPL, VPL. Again, higher values (than results obtained at other points) of HPL and VPL corresponding to the maximum positioning errors obtained at KRYN (horizontal and vertical results) can be observed.

4. Conclusions

Summing up the results of parallel research carried out at selected TPI NETpro network points located in Poland, it can be concluded that the quality of GPS / EGNOS positioning depends on the location of the observation. It should not be said that the eastern part of the country is characterized by unsatisfactory results (they meet the requirements of APV-1 and even LPV-200). The few points (OSTD, SZCT) presents a comparable quality of EGNOS positioning with stations localized in western Poland (e.g. SULE). The basis for conducting a more thorough analysis should be weak results obtained for the territory of the extreme south of Poland (KRYN), where, according to the obtained results of experiments, it is not possible to implement procedures compatible with APV. Noteworthy are the significantly different results of the positioning quality test at some points located only about 100 km apart. Therefore, prior to the application of the EGNOS system in aviation, it seems necessary to conduct local monitoring of the system's operation.

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