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THE ACCURACY OF EGNOS (ESTB) IN POLAND - THE SYSTEM PERFORMANCE TESTS IN THE POSITION DOMAIN

ABSTRACT In the year 2005 the EGNOS enters the Operational Readiness Review phase becoming available for users in its almost full capability. It may be expected that very soon EGNOS will find significant interest among many users and will find many applications all over the Europe. The paper presents the summary of the tests of satellite positioning with using EGNOS (ESTB) signal conducted by author in the area of the Polish coast of the Baltic Sea during several years since 2001 till now. The results of conducted tests show the EGNOS (ESTB) performance at the edge of the nominal system coverage, verifying, in the experimental way, the predicted system accuracy and the efficiency of WADGPS EGNOS algorithms in this area. Additionally, the comparison of the results obtained during the subsequent years of the system development shows the gradual improvement in system performance coming with increased number of RIMS and the evolution from the EGNOS System Test Bed to the fully capable EGNOS.

INTRODUCTION

The European Geostationary Navigation Overlay Service (EGNOS) is designed to provide the regional augmentation to GPS and GLONASS services by delivering to users the following types of services:

- R-GEO (GEO Ranging) – GPS-like signal retransmitted via geostationary satellite which could be additional source of pseudorange measurements;
- GIC (GNSS Integrity Channel) – additional signal transmitted via GEO satellite giving users online information about actual system performance and integrity;
- WAD (Wide Area Differential) – transmission of wide area differential corrections calculated from measurements collected from the network of reference stations. The set of differential corrections includes satellite clock error corrections, satellite orbit error corrections and ionosphere signal delay error corrections.

The above services are to improve the users positioning abilities in the context of accuracy, availability, continuity and to secure the safety of navigation for aeronautical, maritime and land users. EGNOS performance requirements are determinate by the positioning demands of the aircraft that is approaching to landing in conditions defined as APV 1 or APV 2 (approach with vertical guidance). To meet these requirements EGNOS is expected to:

- improve the GNSS positioning accuracy to about 5 meters vertical and 2 meters horizontal through the broadcast of wide-area differential (WAD) corrections;
- deliver the GNSS positioning integrity both through the high degree of redundancy in the system and by alerting users within 6 seconds if something goes wrong with EGNOS, GPS or GLONASS (Vertical Alert Limit – 20 m, integrity risk – 10^{-7});
- improve the GNSS positioning availability by broadcasting GPS look-alike signals from three geostationary satellites.

The main components of the EGNOS ground infrastructure are: 4 Master Control Centers (MCC), 6 Navigational Land Earth Stations (NLES), 34 Reference Integrity Monitoring Stations (RIMS), 2 support processing facilities.

The EGNOS space segment is composed of three geostationary satellites: Inmarsat AOR-E (15,5°W) (PRN 120), Inmarsat F5 (IOR–W)(25°E) (PRN 126), ESA ARTEMIS (21,5°E) (PRN 124).

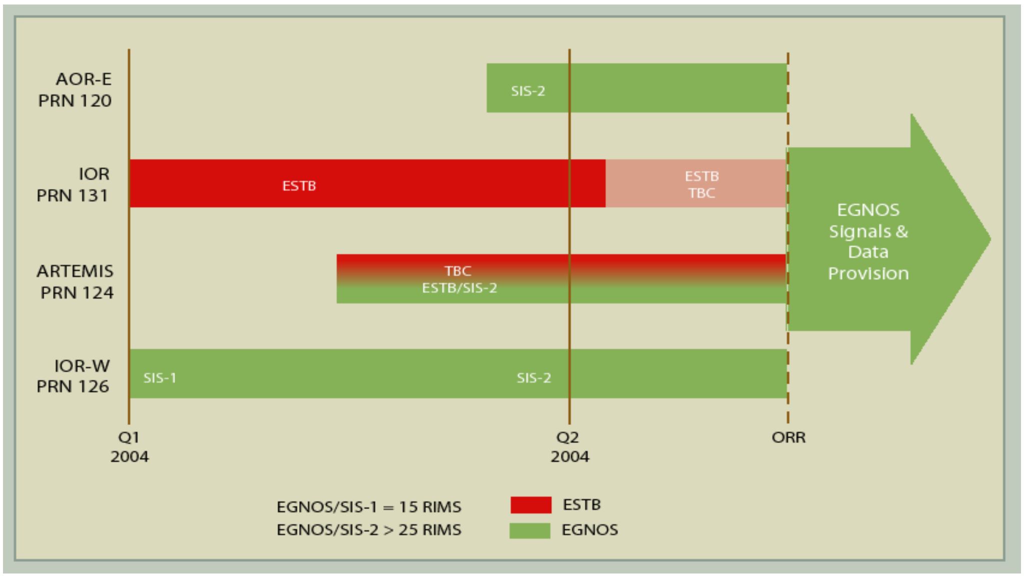


Fig.1. The phases of the transition from ESTB to EGNOS [ESA, 2003].
(**SIS 0** – 6RIMS, 1MCC, 1NLES; **SIS-1** 10-15 RIMS, 1 MCC, 1 NLES;
SIS 2 - > 25 RIMS, 2MCCs, 2 NLES)

The EGNOS signal format complies with RTCA DO 229C standard which was chosen as the common format for all SBAS components of GNSS-1: EGNOS, WAAS and MSAS. RIMS are deployed to monitor the satellite constellation satellites. Each satellite has to be monitored by multiple RIMS before correction and integrity messages are generated. MCC process data from these RIMS to generate the WAD corrections and integrity messages for each satellite. Only one of these MCCs is active and operational, the other MCCs are hot spares that can be activated if a problem occurs.

Stations NLES upload the corrections and integrity messages to the satellites, for onward broadcast to the users. The system will deploy two NLESs (one primary and one backup) for each of the three geostationary satellites, and a further NLES for test and validation purposes. EGNOS enters his Operational Readiness Review phase in fourth quarter of 2004. In this phase the full system infrastructure and all signals will be available to users and the verification and validation procedures will be conducted [Basker et al., 2003]

Before EGNOS become fully operational in 2005, during the last couple of years, the users of GNSS had the sample of the future EGNOS by using the signal of the EGNOS System Test Bed (ESTB). In Fig. 1 the timetable of the ESTB transition to EGNOS is presented. ESTB test signal is available for navigation demonstration and service trials since February 2000 via Inmarsat AOR-E geostationary satellite (PRN 120). Later, since early 2002, the ESTB signal became available via Inmarsat IOR satellite (PRN 131). The infrastructure of ESTB is only a fraction of those planned for EGNOS. The ESTB, as the prototype of the EGNOS system, provides its services with real time elements enabling different user experiments or tests, however the system is developed over limited area and the ESTB functions complexity and performances are reduced to an order of magnitude from the EGNOS system, principally concerning the availability, the robustness and redundant facilities. Due to the limited infrastructure and the test, pre-operational nature of the service, the ESTB operational range do not fully cover the ECAC (European Civil Aviation Control) area which is declared as the EGNOS operational domain. However, in spite of all those limitations the ESTB give potential users the opportunity to assess the performance of the future EGNOS [ESTB, 2000], [Basker et al, 2003].

THE SCOPE OF EXPERIMENTS AND THEIR OBJECTIVES

The paper presents the summary of the tests of satellite positioning with using EGNOS (ESTB) signal conducted by the author in the area of the Polish coast of the Baltic Sea during several years since July 2001 till May 2004. When the new system appears it always raises the interest and doubts as well. The questions are always about that how good is it and is it good enough. These questions become worthy to answer especially while talking about the Wide Area DGPS solution, which is highly dependent on the errors modeling over large areas. The area of Poland is located on the eastern edge of nominal EGNOS coverage and there is a possibility that the EGNOS accuracy in this region may be somehow degraded than that, what is observed in the areas better covered by RIMS network.

The majority of the described below tests were based on the ESTB signal as the only available at these times. During this period of operation the ESTB was the subject of the several modifications that had the influence on the general system performance. Those modifications included [EGNOS, 2004]:

- the increase in the number of RIMS stations (10 RIMS in July 2001, 16 RIMS in May 2004);
- the extension of Iono Grid Points (IGP) area of coverage;
- the modification of ionoalgorithms used to calculate the Grid Iono Vertical Errors (GIVE) and Grid Iono Vertical Delays (GIVD);
- the changes in transmission formats (from RTCA DO-229A to RTCA DO-229C with MT 0/2 implemented);
- the verification of the RIMS positions accuracy.

Therefore the subsequent tests enable to monitor the changes in the system achievements in this particular region since early stages of the system developments till its almost full capability phase.

During the subsequent years, the objectives of the conducted tests were as follows:

- to get the measure of EGNOS (ESTB) performance in the area of Polish Coast;
- to compare EGNOS (ESTB) performance with other GPS-based methods of satellite positioning, such as maritime DGPS and standalone GPS;
- to compare accuracy parameters of EGNOS (ESTB) working in different operational modes and different day periods (day, night, sunrise, sunset);
- to compare the EGNOS (ESTB) performances observed in different locations on the edge of system nominal coverage.

In their basic idea, the conducted experiments were focused on the verification of EGNOS (ESTB) performance in the context of maritime applications of the system. So this is why, the EGNOS (ESTB) accuracy is referred to maritime DGPS performance and the tests took place on the Polish Coast and offshore - on vessel. However, in general they give the picture of the EGNOS (ESTB) accuracy in this particular area for any other applications as well. The main interest of the author was the system performance in position domain so most of the results and comparisons are made referring to the position accuracy parameters.

The dates and the scopes of the subsequent tests, covered by this paper, carried out to verify the EGNOS (ESTB) performance were as follows:

- July 2001 – first tests in Gdynia – measurements in static conditions; the experiment focused on the comparison of ESTB performance with other GPS-based methods of satellite positioning, such as maritime DGPS and standalone GPS;April 2002 – tests in Gdynia (East Coast) and Dziwnów (West Coast) –

measurements in static conditions; the experiment focused on the comparison of ESTB performances observed in different locations on the edge of system nominal coverage;August 2003 – maritime tests; measurements in dynamic conditions;
the experiment conducted at sea, in the area of Gdańsk Bay within traffic separation scheme established on the approach waters to Gdynia and Gdańsk Harbours;

- May 2004 – the latest tests in Gdynia – measurements in static conditions; the experiment conducted to compare the actual system performance to the previous years results and to verify the potential performance improvements observed at the last months of the system testing stage before ESTB transition to EGNOS.

The common assumption for all static tests was that the experiments were performed with receivers antennas located in known, precisely surveyed positions. Such assumptions enabled to refer obtained measurements to known locations and to verify the absolute system accuracy in the area of tests. Additionally, for all comparative tests, the data were logged simultaneously in several, differently configured receivers (EGNOS with and without ionocorrections; maritime DGPS – various reference stations; GPS) and for different locations (Gdynia – eastern Polish Coast; Dziwnów- western Polish Coast). During the dynamic tests conducted in the area of Gdansk Bay the vessel positions obtained with using EGNOS (ESTB) signal were referred to the results of RTK GPS positioning. In all experiments the EGNOS (ESTB) measurements were performed with using TOPCON “Legacy-E” receivers upgraded to WAAS/EGNOS option.

The following sections give the brief description of the all above experiments and the summaries of the obtained results. The more comprehensive reports on some of those tests may be found in the specified references, as they were already the subjects of the presentations given by author at various conferences and congresses during the previous years [Cydejko, Oszczak, 2001][Cydejko, Oszczak, 2002][Cydejko, Oszczak, 2003].

THE STATIC TESTS - JULY 2001, APRIL 2002

The experiments conducted in July 2001 and April 2002 were focused on two issues. The objective of the first tests (July 2001) was to compare the different methods of satellite positioning, including ESTB, GPS, and DGPS. In this case all measurements were taken in one location at Gdynia [Cydejko, Oszczak, 2001]. The second static experiment (April 2002) was focused on the comparison of ESTB performance in two different locations. During this test the data were logged in Gdynia and Dziwnów at the same time [Cydejko, Oszczak, 2002]. The test location was selected taking into consideration the predicted ESTB performance, in the way that one of them (Dziwnów) supposes to be inside the nominal ESTB range and the other (Gdynia) located outside or on the edge of the system coverage. In both experiments the satellite positioning with using ESTB signal was executed with TOPCON Legacy –E receiver. During all tests the antennas of the receivers located in known, precisely determined positions and the data were logged simultaneously in several receivers and for different locations.

The results of the test conducted in July 2001, focused on the comparison of different methods of satellite positioning are presented in Fig. 2 and Fig. 3. The statistical measures of accuracy, such as average positions and standard deviations, are presented for different period of measurements. Each set of data considers 2 hours observation within specific periods of day when various statuses of ionosphere can be expected. The results of the test conducted in April 2002 and focused on the comparison of ESTB performance observed simultaneously in two different locations in the area of Poland are presented in Fig. 4 and Fig 5.

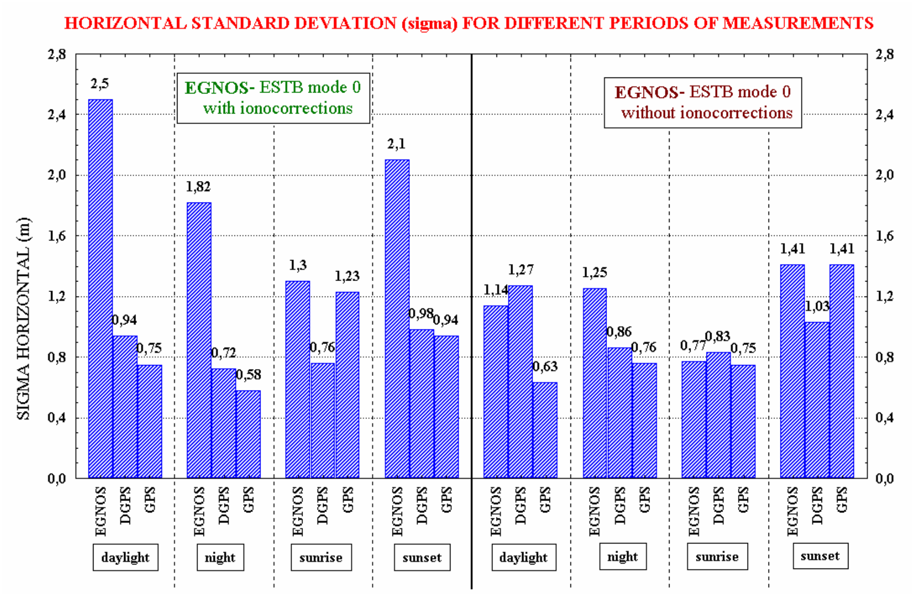


Fig. 2. The comparison of EGNOS, DGPS and GPS horizontal standard deviation (sigma) of observed positions for different periods of measurements (daylight, sunset, night and sunrise) – first static tests (July 2001)

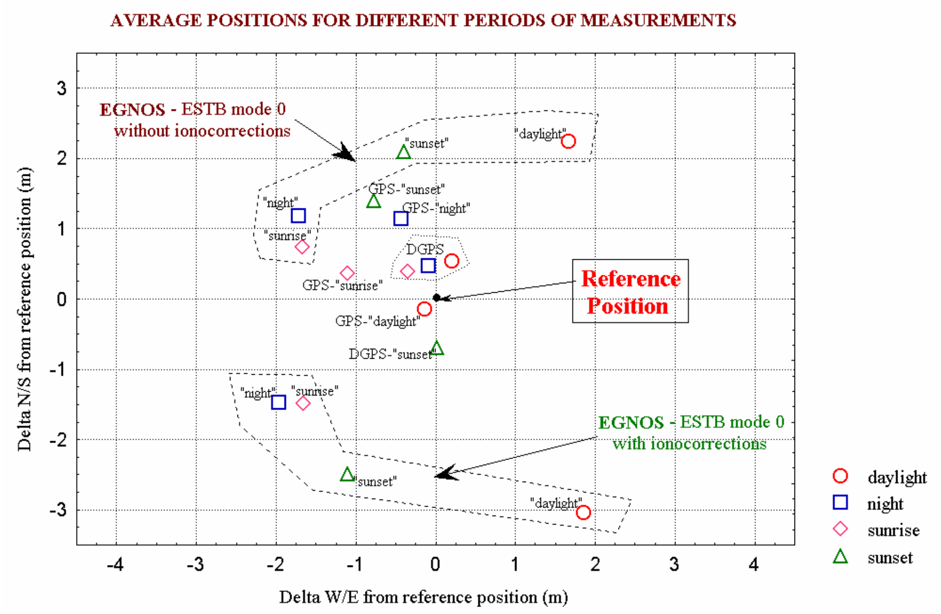


Fig. 3. The comparison of EGNOS, DGPS and GPS average positions for different periods of measurements (daylight, sunset, night and sunrise) – first tests (July 2001).

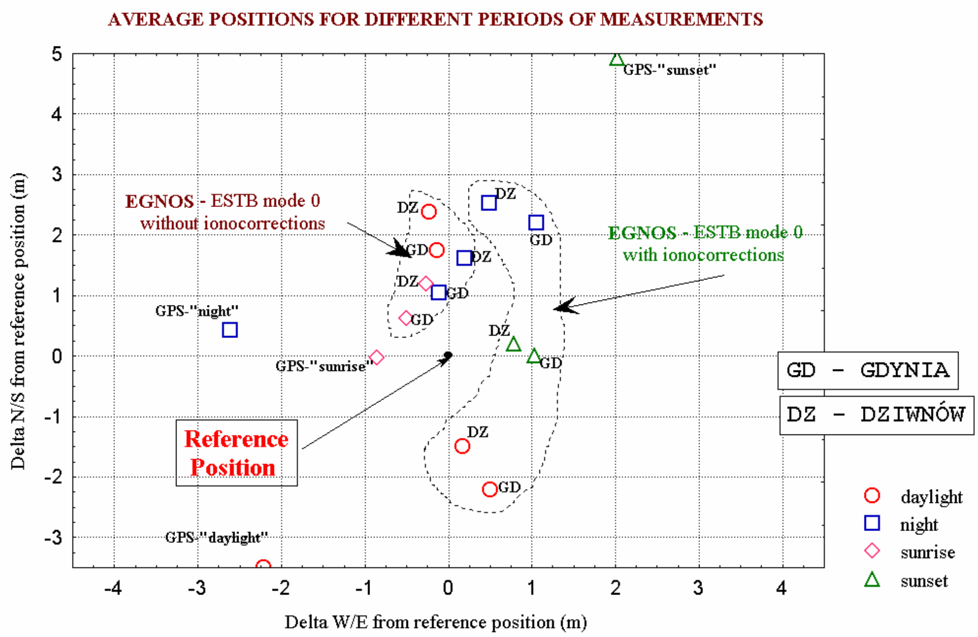


Fig. 4. The comparison of EGNOS and GPS average positions for different locations and during various periods of measurements (daylight, sunset, night and sunrise) – second static tests - April 2002

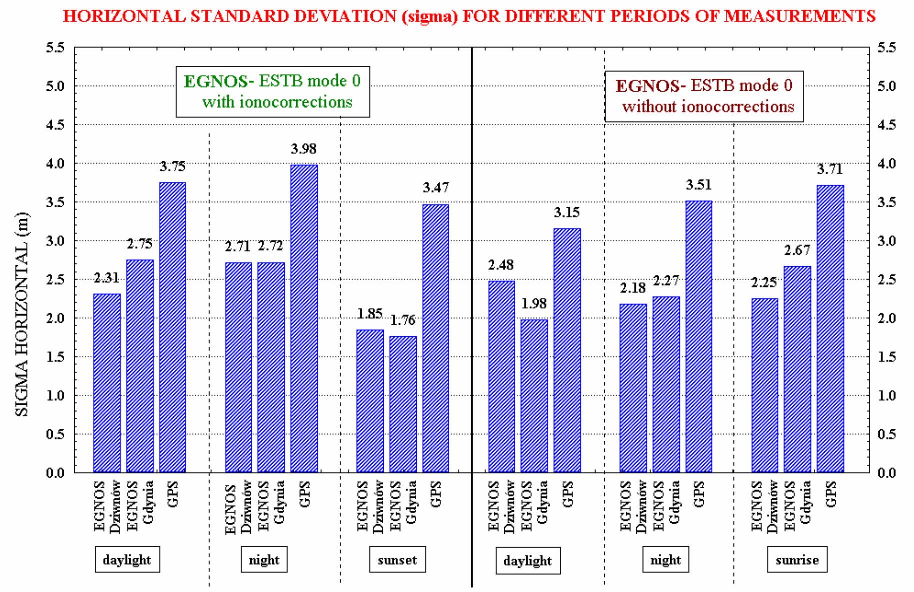


Fig. 5. The comparison of EGNOS and GPS horizontal standard deviation (sigma) of observed positions for different locations and during various periods of measurements (daylight, sunset, night and sunrise)- April 2002.

After this first assessment of the ESTB performance in the area of Poland the several items were worth to be pointed out. The following conclusions were the most important among them:

a) ESTB positions have 2-4 meters offset from precisely determined position used as reference point. The maximum offsets are observed during daylight and become significantly minimized during night observations.
b) There are the periods, especially during the first phase of measurements (July 2001), while the ESTB performance is worse than DGPS and GPS
c) The second phase of tests (April 2002) shows general improvement in ESTB performance either for long and short period observations
d) The second phase of tests (April 2002) shows that such ESTB performance parameters as: horizontal and vertical standard deviation, 2DRMS are less dependent on time of observation (daylight, night etc.) and significantly better than GPS parameters observed at the same time;
e) As expected, the performance of ESTB in western part of Poland (Dziwnów) is better than in more eastern part (Gdynia) but the differences are not big.

In general, those measurements showed that on the edge of the nominal ESTB operational range the performance of the system may be significantly degraded due to the lack of the proper ionosphere modeling which appears as the result of limited number of RIMS. However the comparison of the accuracy parameters obtained in 2001 and in 2002 showed that the modification of the ESTB operational parameters (ionoalgorithms, accuracy of RIMS coordinates), what took place during time separating these two test periods [EGNOS, 2004], may improve the system performance even without significant changes in the ESTB infrastructure.

THE MARITIME TESTS - AUGUST 2003

The maritime tests of the ESTB performance in Poland took place on 29th of August 2003 [Cydejko, Oszczak 2003]. During the period of tests the ESTB was working in mode 2 (fast corrections and ionocorrections plus Ranging). All tests were conducted on the survey vessel "Tucana" owned by Maritime Office in Gdynia. The vessel was navigating in the area of The Gdańsk Bay within traffic separation scheme established on the approach waters to Gdynia and Gdańsk harbors. For all tests, the common assumption was that the vessel positions obtained with using ESTB signal were referred to the results of RTK GPS positioning. The RTK GPS reference station was established in the area of the Gdynia harbour. The RTK GPS solution was executed with the position update rate of 1Hz at the baseline of 2-12 km. With such an arrangement the RTK positioning accuracy was estimated as 2-5 cm (horizontal RMS). Such the test arrangement enabled to compare the kinematical ESTB measurements with the highly precise reference system and to verify the absolute system accuracy in the area of tests. Because the scope of the experiment includes the comparison of the ESTB performance with GPS and DGPS, these kind of equipment was installed on vessel as well, ready for the simultaneous data logging.

The chart presented in Fig. 6 shows the area where the experiment was conducted. The main measurement sessions took place in Gdynia harbour approach fairway, where the survey vessel made several subsequent passages inward and outward the port entrance maintaining her position on the fairway centerline marked by the leading lights. During those several passages all receivers were logging data with the rate of 1 second and the total time of experiment was 2 hours. The ESTB positioning performance was tested in two modes: with and without implementing the ionocorrections (1 hour session with the receiver working in each mode).

In Fig. 7 and Fig. 8 the results of the positioning observed simultaneously with ESTB, DGPS and GPS receivers installed onboard the survey vessel are presented in the comparative way. In each epoch simultaneously observed GPS RTK position estimations were considered as the absolute true reference and all positioning errors of ESTB, DGPS and GPS were determined with respect to them.

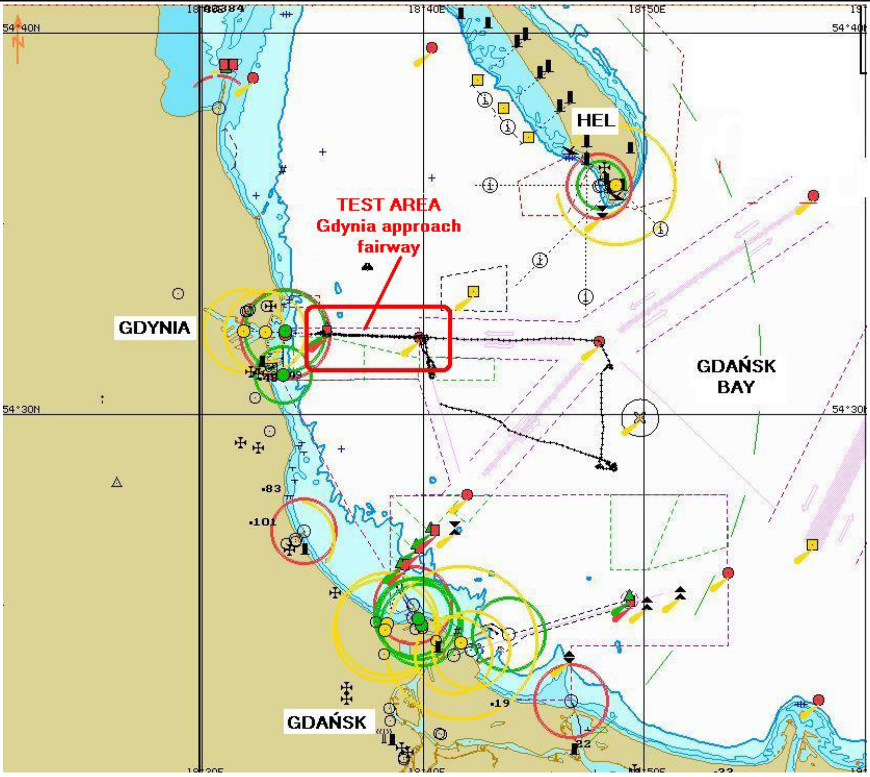


Fig. 6. Test area of EGNOS System Test Bed (ESTB) in Gdańsk Bay.

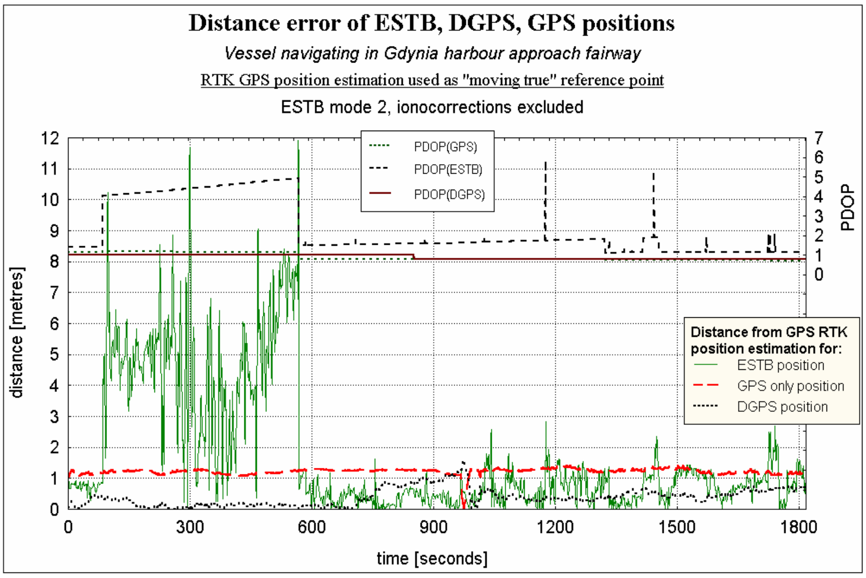


Fig. 7. The ESTB maritime tests. Distance error of ESTB, DGPS and GPS positions with respect to GPS RTK. ESTB performance without implementing the ionocorrections.

Fig. 7 presents the distance error with respect to RTK GPS observed simultaneously for ESTB, DGPS and GPS position estimations. These graphs visualize the changes in the position accuracy over the time. Because during the measurements the ESTB receiver was recording the significant changes in PDOP value, the distance errors changes are presented together with the graph of PDOP changes over the time. This enables to notice that most of the ESTB positions „jumps" are associated with the deterioration of the PDOP parameter. The high values of PDOP for the ESTB were directly associated with the significantly lower number of satellites available for differential positioning (GPS, DGPS – average 10; ESTB – average 6), which was directly caused by the lack of the ESTB corrections for the full satellite constellation visible in the area of the experiment.

The scatter plots presented in Fig. 8 show the distribution of the position estimations around the point assumed as the true reference. Because during the kinematical measurements the true reference position has to be established for each epoch, for the purpose of these tests, the GPS RTK position estimation was considered as "moving" true reference. The X and Y coordinates of dots representing ESTB, DGPS and GPS positions in Fig. 8 reflects the adequate differences in the coordinates observed between RTK GPS positions and simultaneously determined ESTB, GPS or DGPS positions (for all comparisons the adequate corrections due to the antennas offsets were implemented).

Such the data presentation of the kinematical test results is similar to that obtained after the static tests and makes easier to compare the system position accuracies obtained during both experiments.

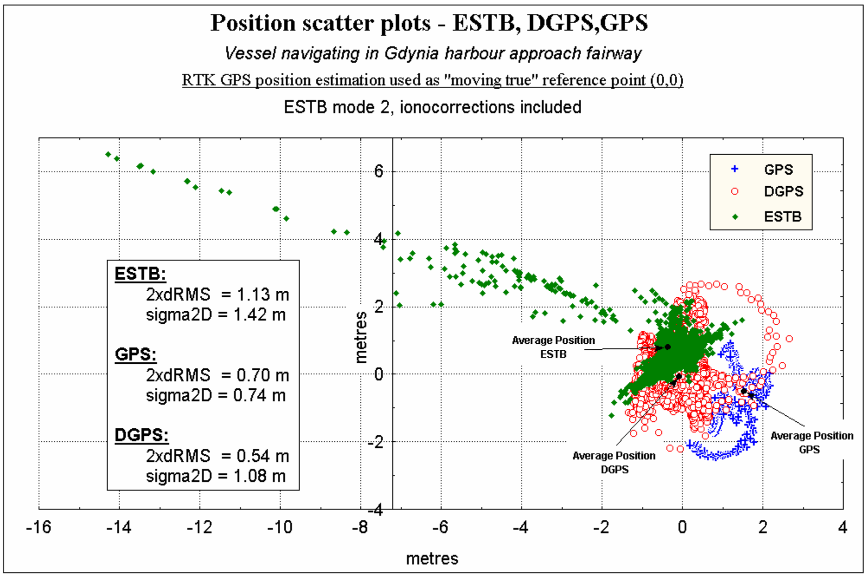


Fig. 8. The ESTB maritime tests. Position scatter plots of ESTB, DGPS and GPS with respect to GPS RTK. ESTB performance with implementing the ionocorrections.

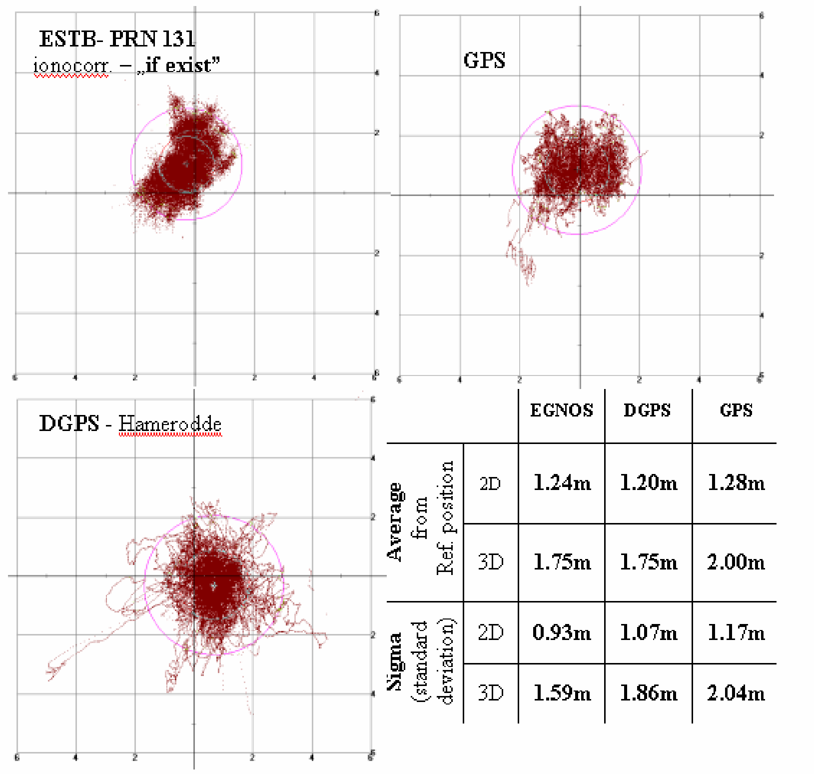
The conducted tests were the next step in the assessing the ESTB performance in the area of Polish Coast. In comparison with the results from previous years, some improvement was noticed due to the ESTB modifications carried out meanwhile. The results of the maritime tests may be summarized as follows:

a) The average ESTB position calculated from the set of data recorded during the tests has the 1 –1.5 m offset from the reference point; In this aspect the ESTB error is less than the one observed for GPS but significantly worse than the DGPS one;
b) The magnitude of the average ESTB position offset observed during the maritime tests in August 2003 is lower than the analogous value observed during the tests conducted in previous years showing the improvement in ESTB performance in this aspect;
c) The ESTB accuracy, considered in terms of system repeatability and expressed by the distance root mean square error (dRMS) or the horizontal standard deviation (sigma2D), appears worse than DGPS and GPS accuracy and is significantly degraded by the selected periods of the ESTB positions "jumps";
d) The "unstable" ESTB position estimations and the degraded accuracy of ESTB positioning was directly associated with the deteriorations of PDOP parameter observed in the receiver and caused by the lack of the ESTB corrections for the full satellite constellation visible in the area of the experiment;

In general, at this stage of tests, the ESTB performance was not good enough to deliver the maritime users the service with the positioning accuracy comparative to that, what was available with the existing local maritime DGPS.

THE LATEST EXPERIMENT – STATIC TESTS – MAY 2004

The latest tests of ESTB performance, covered by this paper, were conducted in May 2004 in Gdynia. This period of time was chosen intentionally to do a final check of the EGNOS prototype accuracy at the last moment, before its transition to fully capable system, which was originally planned to happen during the third quarter of 2004. By the date of this last test, the system was working with 16 RIMS and was the most of the developments listed in the first section of this paper had taken place already. So it was expected, that at this stage the ultimate estimate of the EGNOS test version could be achieved.



		EGNOS	DGPS	GPS
Average from Ref. position	2D	**1.24m**	**1.20m**	**1.28m**
	3D	**1.75m**	**1.75m**	**2.00m**
Sigma (standard deviation)	2D	**0.93m**	**1.07m**	**1.17m**
	3D	**1.59m**	**1.86m**	**2.04m**

Fig. 9. Static tests – May 2004. Position scatter plots for GPS, DGPS and EGNOS System Test Bed – all day measurements. EGNOS receiver option for ionocorrections- “use if exists”.

During the test the ESTB was working in mode 2 (fast corrections and ionocorrections plus Ranging) and the augmentation signal was being received from Inmarsat IOR satellite (PRN 131). The set up of test were similar to the static experiments, which took place 2 and 3 years ago. By creating the similar experiment set up and by executing the same data evaluation it was easier to notice any changes, improvements or degradations in the system performance. In Fig. 9 the 24-hours position scatter plots of the simultaneously observed ESTB, maritime DGPS and GPS positions are shown. All plots are referred to true value and the statistical measures are summarized in the table.

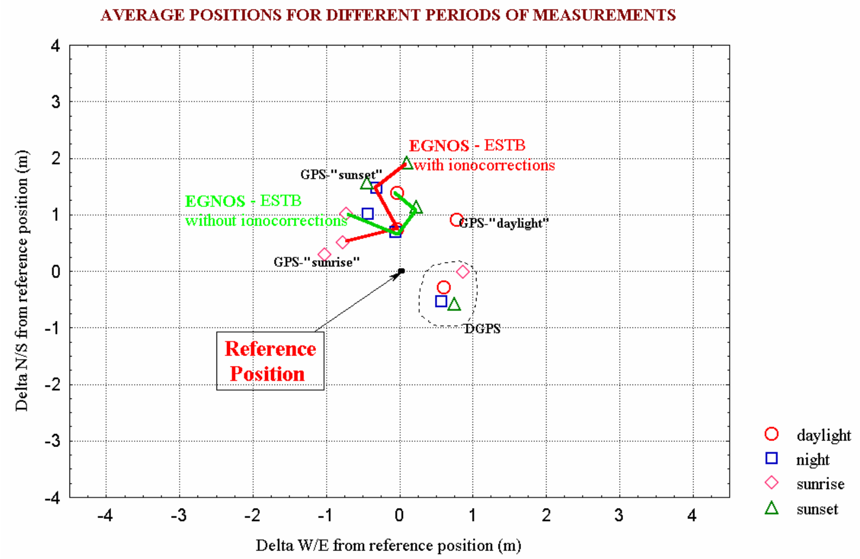


Fig. 10. The comparison of EGNOS, DGPS and GPS average positions for different periods of measurements (daylight, sunset, night and sunrise) – static tests - May 2004.

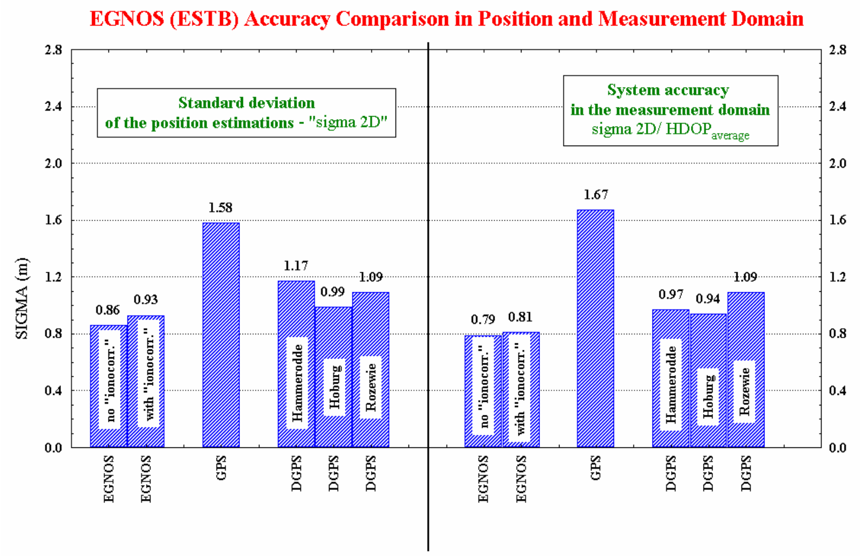


Fig. 11. The comparison of EGNOS, GPS and maritime DGPS (various stations) horizontal standard deviations (sigma) of observed positions and accuracy estimates of various systems in measurements domain – static tests - May 2004.

In Fig. 10 the average positions obtained for different period of measurements are presented. Each set of data considers 2 hours observation within specific periods of day while various statuses of ionosphere can be expected. Finally the Fig. 11 gives the summary of the standard deviation measures obtained for various systems. The same figure gives the comparison of the estimations of the systems accuracies in measurements domain, which was calculated as the quotient of sigma 2D and the average value of HDOP factor observed during the test.

Next section is summarizing the results obtained at this stage of tests in comparison to the observation made in the previous years. The easy to read visualization of the changes in the ESTB accuracy is presented in Fig. 12, where the position scatter plots observed at each stage of system testing are gathered and compared.

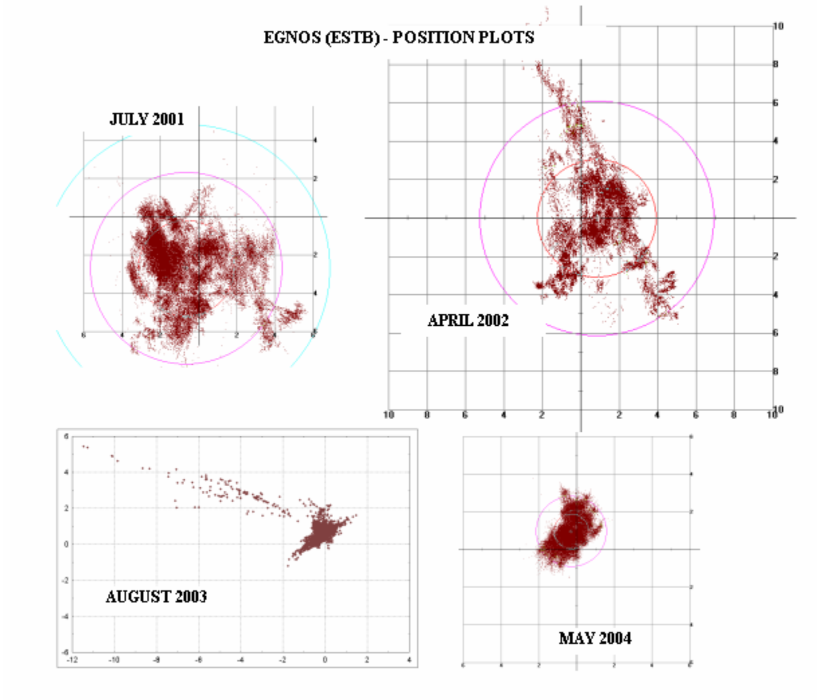


Fig. 12. The comparison of the EGNOS System Test Bed position scatter plots observed at various stages of the system performance assessment in Poland.

FINAL CONCLUSIONS

The results of the latest experiment allowed to phrase the final conclusions, which are describing the actual EGNOS prototype achievements with reference to the system performance observed during the previous years and are giving the summary of the EGNOS (ESTB) performance assessment in Poland. At the final stage of experiments the further improvement in the EGNOS System Test Bed accuracy has been noticed.

The horizontal ESTB position accuracy in Poland estimated during the 24-hour static test has reached the following values:

- standard deviation (sigma 2D) - 1.2 to 1.5 meters;

- average position offset from true location – 1.5 to 2.2 meters.

The EGNOS (ESTB) accuracy parameters are better than observed simultaneously GPS performance in 2D position domain. The EGNOS (ESTB) at the current stage of development delivers the comparable positioning accuracy as the maritime DGPS service. It was observed that the EGNOS performance in 2D position domain was better than maritime DGPS in all this cases, while the distant (~ 300 km) reference stations (Hoburg, Hammerode) were used. However the EGNOS (ESTB) positioning is less accurate while compared with maritime DGPS performance based on closed differential station (Rozewie ~ 40 km).

The minor influence of the ionocorrections implementation on the EGNOS (ESTB) positioning performance was noticed (see positioning results with and without ionocorrections). However, this statement is true only when the 2D positioning domain is considered. In the 3D position domain the lack of ionocorrections causes 4-5 meters errors in the altitude estimations.

The EGNOS (ESTB) position estimations are obtained with the higher (worse) value of HDOP factor than simultaneously observed DGPS positions. So, because the final performances of both systems in position domain are comparable, it may be stated that the EGNOS (ESTB) reaches better than DGPS accuracies in measurement domain (average standard deviation of pseudorange measurements).

Summarizing, it may be stated that, during the years of the ESTB tests in Poland, the gradual improvement in the system performance was observed. All those improvements were directly associated with the progressive development of the system infrastructure and the modification of the signal processing methods. The latest performance assessment of the EGNOS prototype shows that this Satellite Based Augmentation System is able to deliver users the service, which gives the comparable positioning accuracy as actually utilized maritime DGPS. The transition from test version to fully capable EGNOS may be only beneficial for users. Additionally, having in mind that EGNOS is providing to users the integrity channel and improves the satellite positioning availability, there are no doubts that together with EGNOS, the new quality of the navigational safety appears.

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