sciendo

POLISH MARITIME RESEARCH 2 (102) 2019 Vol. 26; pp. 15-21
10.2478/pomr-2019-0021

POLISH DGPS SYSTEM: 1995–2017 – STUDY OF POSITIONING ACCURACY

Cezary Specht
Leszek Smolarek
Jan Pawelski
Mariusz Specht
Paweł Dąbrowski
Gdynia Maritime University, Poland

ABSTRACT

This paper is the fourth in a series of publications presenting the process of installation, testing and long-term assessment of the navigational parameters of the Polish DGPS system. This series of publications intends to present – to the general public – the accomplishments of teams of Polish scientists who have been working for years to make the DGPS the main positioning system used in the Polish sea areas. A considerable part of the materials presented in this paper has never been published.
The article presents changes in the position accuracy of the Polish DGPS system over 20 years. Both dynamic tests performed on vessels as well as static measurements campaigns were analysed. The publication contains selected results achieved in its installation and testing in 1995–1997 supplemented with the results of studies conducted in the years: 2006, 2010, 2014, 2017. During this period the position accuracy increased from 2–8 m (1996) to approx. 1–2 m (2010) due to three reasons: turning – off the Selective Availability (2000), technical modernization of reference stations (2010) and continuous – over many years – reducing GPS signal-in-space pseudorange errors, which results in increased position accuracy in all GPS augmentation systems.

Keywords: Polish DGPS system, positioning accuracy, position accuracy measures

INTRODUCTION

To make oneself aware of the importance of the DGPS system implementation in the Polish sea areas in the 1990s, one has to make an assessment of the condition of maritime radio navigation systems available on the Polish coast during the period in question.

The beginnings of radio navigation in Poland date back to the 1950s, when a network of circular (non-directional) radiobeacons was set up on the Polish coast to cover the Polish Exclusive Economic Zone (EEZ). The deployment of the beacons was supposed to enable positioning (conducting at least two radio direction findings) at any place within it. A complex process of computation and placing the results on a map was considerably improved after installation (1970) of the OA chain of the Decca-Navigator system on the Swedish coast [14]. It became the main system of positioning for civil (Mark series receivers) and military ships (Russian Pirs receivers) until the early 1990s when first Transit receivers appeared.

The systems of radio navigation operating on the Polish coast, which are of particular interest included: the AD-2 phase-location system – developed in the 1970s in the Bay of Gdańsk and intended for tankers entering the Gdansk north port [21] and Syledis – intended for maritime pilotage and hydrography in the Szczecin-Świnoujscie harbour complex [9].

Launching the DGPS system on the Polish coast in 1995–1997was of fundamental importance for navigation in the South Baltic Sea. The DGPS system is a positioning solution supporting the GPS in navigation. Like other supporting systems: EGNOS or GNSS geodetic networks [16], it has a particular feature which involves the emission signals of service reliability, which is of particular importance in every type of navigation.

Unlike the GPS, which is used in open sea (oceanic) navigation, the DGPS is used mainly in navigation when approaching ports – on coastal maritime highways [2]. The system is also used in precision hydrographic measurements, both in sea [7] and inland waters [13].

It is noteworthy that positioning accuracy can be improved by modernisation of existing positioning systems, launching new ones and developing reserve ones [8]. Alternatively, this can be achieved with a range of other solutions. The most frequently applied solutions include: Kalman filter [23], data fusion from various sensors [24] or using satellite network and multi-constellation solutions [15]. Other methods that cannot be ignored include: comparative ones [11], advanced methods employing adjustment computations in coastal navigation, positioning algorithms alternative to existing ones [12] or, increasingly popular, employing neural networks. However, despite being highly advanced, these numerical methods will never replace a modern radio navigation positioning system, such as DGPS.

CONCEPT STUDY OF THE POLISH DGPS SYSTEM IN 1995–1997

Unlike other positioning solutions of a local range in the South Baltic Sea, the DGPS was a national system covering the entire Polish coast. During the initial stage of its implementation in 1995–1997 a number of studies were conducted to determine the accuracy of position, range and availability of the system. The implementation work was carried out in two directions: an assessment of the actual range of operation as well as positioning accuracy and availability. It is beyond doubt that the Institute of Navigation and Hydrography of the Polish Naval Academy was the leader in the implementation process. The team led by prof. Kopacz, together with another led by prof. Oszczak of the Academy of Agriculture and Technology in Olsztyn as well as with the Maritime Office in Gdynia, conducted the core accuracy measurements of the Rozewie reference station (RS) and determined the range of operation of both stations. Stationary studies enabling to assess the accuracy and range of operation were conducted between April 1995 and May 1996. Tab. 1 shows all of the measurement campaigns completed at the time.

In terms of the area the tests covered virtually the entire Polish coastal area. The positioning accuracy in the stationary measurements was assessed by examining both Polish stations and those whose range of operation covered the Polish EEZ (Hammerodde, Hoburg, Wustrow). The core accuracy measurements were conducted on the coast, whereas the area of operation of both stations was measured inland using a mobile measurement station (a car with a Leica MX9212 receiver).

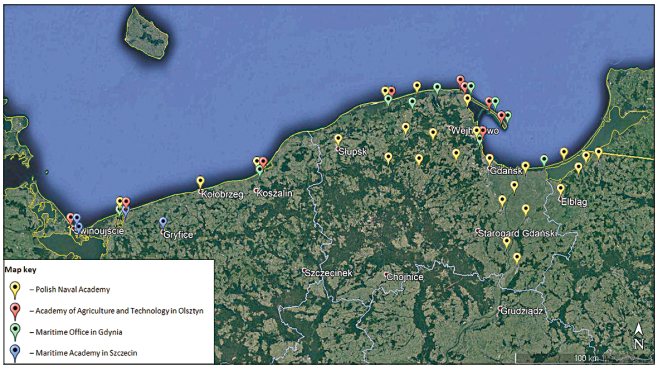


Fig. 1. Location of measurements conducted in the seaside areas. Acc. these authors' study based on [10]

Tab. 1. A list of the stationary tests and measurements conducted in the seaside areas as part of the calibration and start-up process of the DGPS on the Polish coast [10]

No.	Measurement contractor	Date of measurements	Place of measurements	Tested DGPS reference stations
1.	Polish Naval Academy	13–14.04.1995	Braniewo, Elbląg, Frombork, Jarosławiec, Kołobrzeg, Słupsk	Hammerodde, Hoburg, Rozewie, Wustrow
2.	Polish Naval Academy	23–26.05.1995	Gdynia	Hammerodde, Hoburg, Rozewie
3.	Polish Naval Academy	26–27.05.1995	Pomerania coast	Hoburg, Rozewie
4.	Polish Naval Academy	03–09.02.1996	Dziwnów, Gdynia	Dziwnów, Rozewie
5.	Academy of Agriculture and Technology in Olsztyn	18–19.08.1995 27–28.08.1995 20–21.08.1995 14.10.1995	Dziwnów, Hel, Jarosławiec, Jastarnia, Łeba, Rozewie, Świnoujście, Władysławowo	Dziwnów, Hammerodde, Hoburg, Rozewie, Wustrow
6.	Maritime Academy in Szczecin	22–28.05.1996	Szczecin Lagoon	Dziwnów, Hammerodde, Wustrow
7.	Maritime Office in Gdynia	12–13.06.1995	Hel, Jastarnia, Łeba, Władysławowo, Żarnowiec	Rozewie

MEASUREMENTS OF POSITIONING ACCURACY IN 1995–1997

Positioning accuracy is the most frequently quoted criterion of a navigation system evaluation, which is commonly regarded as a measure of its quality. However, other features of operation are often disregarded, which makes this approach superficial. Before presenting the individual quality features of a system, let us analyze briefly the position accuracy measures whose understanding helps to interpret correctly these values. The term positioning accuracy is understood as the extent of conformity of statistics (distribution) of measured (determined) position coordinates either with the real values or those taken as real. It is noteworthy that accuracy of a position is measured as its error which can be assessed in reference to any dimension of a space or planes – horizontal error, vertical error.

The study involved conducting a range of measurement campaigns in 1995–1997 to determine the positioning accuracy. The most representative (lasting many days without a break) stationary studies included measurements with the use of two receivers: Leica MX9212+MX51R and Magnavox MX200+MX50R. The receivers were put at the Rozewie reference station (Leica MX9212+MX51R) and at the Gdynia Polish Naval Academy monitoring station (Magnavox MX200+MX50R). The below presented graphs show the measurement results. The measurement sessions being part of static studies included 1000 to 500000 measurements (Polish Naval Academy, on 03–09.02.1996) of position coordinates as well as a number of other parameters.

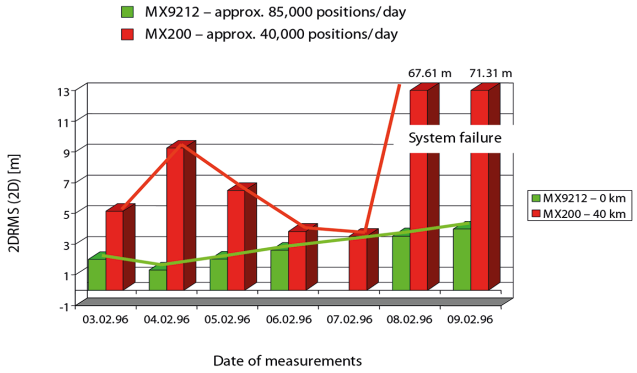


Fig. 2. Position error (determined every 24 h) for two DGPS receivers operating in parallel. Corrections were obtained from the DGPS station in Rozewie [10]

In Fig. 3 a typical position distribution around the mean value is shown for the Polish DGPS reference stations at Rozewie and Dziwnów. The DGPS system had a considerable effect on the possibility of obtaining highly accurate position coordinates in the Polish sea areas. For comparison, Fig. 3 (on the right) shows a position distribution of the Decca Navigator system determined during a campaign conducted in Jarosławiec in 1995.

The accuracy of the DGPS system was tested periodically in successive years of the system operation. The experience gained during the measurement campaign of 1994–1996 provided the basis for a strategy which involved regular

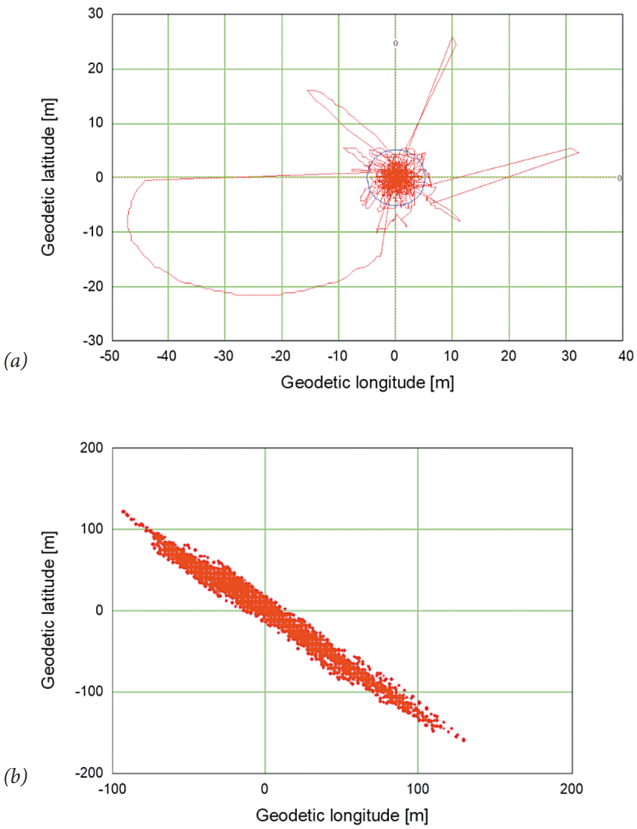


Fig. 3. A position distribution around the mean value for the DGPS system; (a) – Rozewie DGPS reference station, measurement on 03.02.1996, number of measurements approx. 50 000; [10] and the Decca Navigator system in 1995 (b) – acc. these authors' study

testing of the Polish DGPS system in measurement campaigns of 1–2 million measurements [5]. The results of campaigns in the years 2006, 2009 and 2014 show that the DGPS-PL system increased its positioning accuracy year after year (Fig. 4).

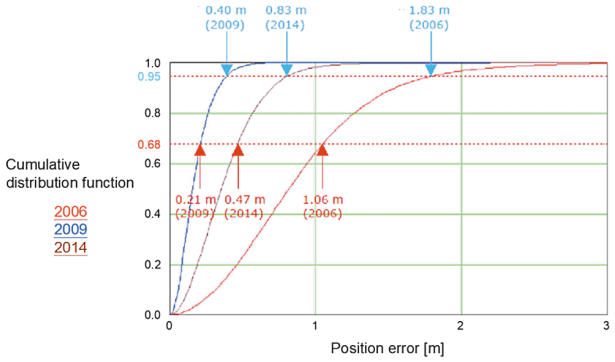


Fig. 4. The cumulative distribution functions of the 2D position errors for the DGPS-PL system (Rozewie) determined in 2006, 2009, 2014 based on 1–2 million measurements per campaign

Consideration of the causes of the increased accuracy of the Polish DGPS system shows that the most important of them includes: turn-off the Selective Availability (SA) in the GPS, change of the emission of RTCM messages from No. 1 to message No. 9–3 [22] which considerably increases the availability of highly accurate position [19] as well as technical

modernisation of both Polish stations, in the same way as it has been done in many other countries [6]. It is noteworthy that the positioning accuracy of the GPS is also improving [18], which also results in improved positioning accuracy of all the supporting systems, including DGPS.

DYNAMIC MEASUREMENTS OF THE DGPS SYSTEM

The first sea trials of the DGPS system in Poland were conducted in the Bay of Gdańsk in 1993 [3], where the telemetric connection in the very high frequency (VHF) range was used instead of the DGPS reference station in the low-/medium-frequency (LF/MF) bands [4]. Studies have shown that accuracies of several metres can be achieved, clearly indicating that the idea of transmission of differential corrections for the GPS system can be applied in marine navigation. Dynamic measurements were a very important part of the DGPS implementation project carried out in 1994–1996. Dynamic measurements were the most difficult part of the project from the technical point of view and in regard to the involved resources. Measurements in motion were conducted three times during the project by the teams coming from four universities (Polish Naval Academy, Academy of Agriculture and Technology in Olsztyn, Maritime Academy in Gdynia, Maritime Academy in Szczecin) and the Maritime Office in Gdynia [10]:

- the team of Polish Naval Academy (leader) – during a voyage of the ORP Wodnik on: 03–09.02.1996;
- the team of Polish Naval Academy (leader) – a voyage of the hydrographic cutter on: 16.10.1996;
- the team of Maritime Academy in Szczecin (leader) – dynamic measurements: July 1996.

The main measurements of the Polish DGPS system in the Bay of Gdańsk and in the middle of the Polish Baltic coast were conducted (on 03–09.02.1996) by the measurement team of the Institute of Navigation and Hydrography at the Polish Naval Academy, with the assistance of a team of the Academy of Agriculture and Technology in Olsztyn. The following DGPS receivers were used in the measurements:

- Leica MX9212+MX51R – measurement receiver;
- Magnavox MX200+MX50R – monitoring receiver;
- Magnavox MX300+MX51R – measurement receiver;
- Ashtech MDXII – reference receiver.

The dynamic measurements included eight trials (circulation and a figure of eight). The figure below shows an example of a full trial consisting of a circulation and figures of eight in the Bay of Gdańsk on 03.02.1996 at: 09:57–10:30 (Fig. 5, left). When the results were worked out it turned out that the positions of the reference receiver (Ashtech) and the measurement receiver (MX9212+MX51R) recorded at the same time (as shown by the receivers) are shifted relative to each other by a time constant.

An analysis showed that the geodetic receiver presented time on the GPS scale, whereas the measurement receiver operated according to the UTC scale. After adjusting the

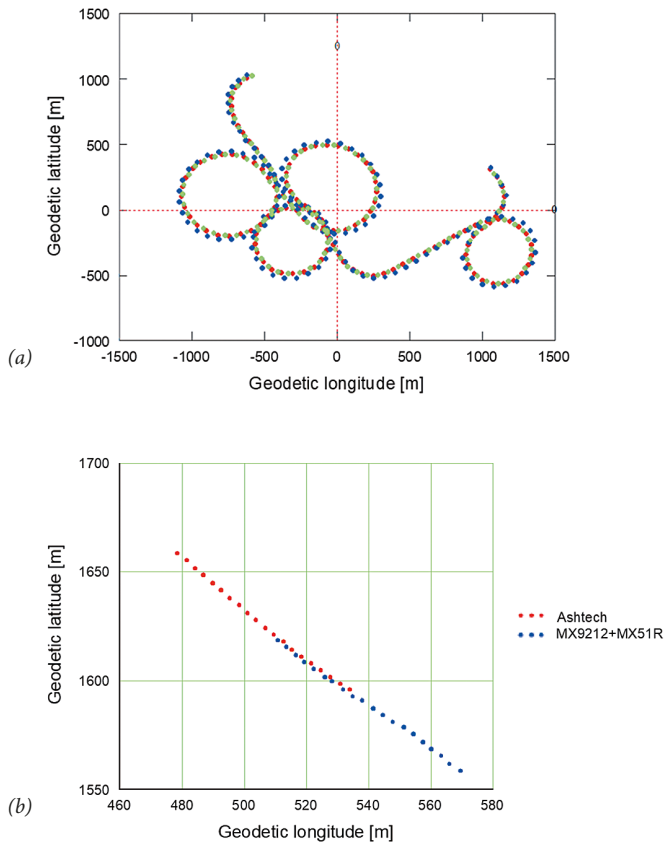


Fig. 5. The trajectories obtained from Ashtech and DGPS receivers in the dynamic trials (a) and indications of the receiver position without taking into consideration the synchronisation of the UTC and GPS times (b) [10]

time shift, the error of the DGPS position error (Rozewie RS), represented by the shift between the indications of the Ashtech (standard) receiver and MX9212+MX51R, was between 1 and 4 m (Fig. 6), showing that the system calibration (coordinates of the reference station antennas) was done properly.

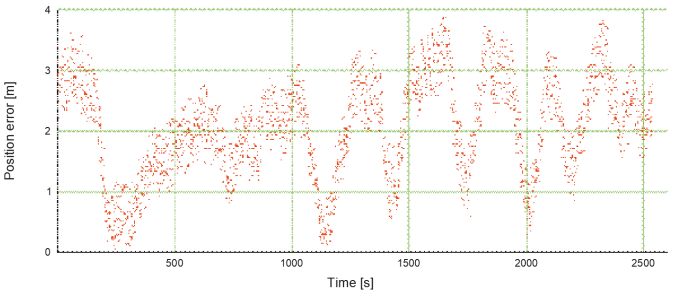
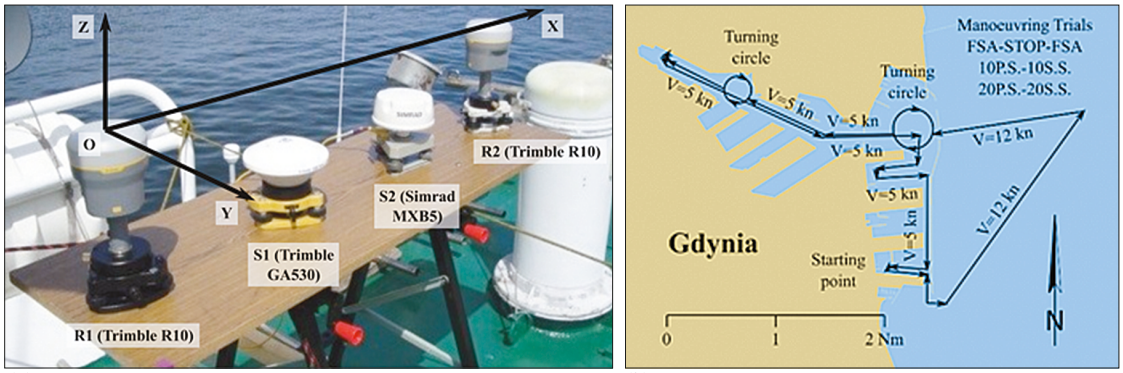


Fig. 6. Position error in function of time of dynamic measurements of the DGPS system on 03.02.1996 [10]

This project also involved examination of the accuracy and range of operation of the Dziwnów DGPS RS by the team from the Maritime Academy in Szczecin [1]. The results were very similar to those presented in the study carried out at the Polish Naval Academy.

In 2017, dynamic measurements were conducted again; their aim was to verify the accuracy of the DGPS system and



(a) *(b)*

Fig. 7. Position of antennas and receivers during dynamic measurements of the DGPS system in 2017 (a) and the ship's route (b)

a comparative assessment of the results relative to the EGNOS system. The measurements were conducted at the roadstead of the Port of Gdynia. The results of these measurements will be published in another paper, but it is noteworthy that the positioning methodology of a DGPS antenna was changed compared to the 1996 study because it was placed between two RTK receivers which used the GNSS geodetic networks (Fig. 7, a), whose expected accuracy in stationary measurements was 1–2 cm (2DRMS) [20]. On the other hand, in dynamic measurements (conducted at 20 Hz frequency), the estimated accuracy was approx. 1–2 cm [17].

The following statistics of positioning accuracy were obtained in the dynamic measurements of 2017.

Tab. 2. Position accuracy statistics of the DGPS system in the dynamic measurements of 2017

Values of DGPS parameters	Statistics
Number of fixes	11697
Average	0.614 m
Standard deviation	0.404 m
Coefficient of variation	65.7928%
Minimum	0.008 m
Maximum	8.621 m
Range	8.613 m

CONCLUSIONS

The Polish DGPS system was examined and thoroughly tested during the start-up phase. An assessment of the positioning accuracy made in stationary and dynamic measurements was one of key elements of such tests and examinations. The stationary measurements conducted in 1994–1996 showed that the accuracy positioning ensured by the Polish systems ranged from 2 to 8 m (2DRMS). It was also noted that an error increase could be caused by a low signal-to-noise ratio (SNR) which may result from insufficient power beamed by the reference station or from high industrial or inter-channel interference. Due to Selective Availability in the GPS (before 2000), in the 1990s it was proposed that the data transmission speed in the DGPS-PL stations should be increased to 200 bauds and that the emission of RTCM 9–3 messages should be started as soon as possible. In fact, the transmission speed has never been changed, and the RTCM 9–3 messages were not broadcasted until 2010.

Regular tests of the Polish DGPS system accuracy were conducted in 2006, 2009, 2014 and 2017. They showed a steady increase in position accuracy. Currently, the position accuracy of the Polish DGPS system is 1–2 m (2DRMS). The increase is basically due to three reasons: turning-off the Selective Availability (2000), technical modernization of reference stations (2010) and continuous – over many years – reducing GPS signal-in-space (SIS) pseudorange errors, which results in increased position accuracy of all GPS augmentation systems.

REFERENCES

1. Banachowicz A., Bober R., Wolski A., Banachowicz G.: *Statistical Research into GPS and DGPS Measurements in West Pomerania in the years 1996–2004,* Reports on Geodesy, No. 2, 2005, pp. 331–335.

2. Beškovnik B.: *Possibilities for Motorways of the Sea Development in the Eastern Part of the Adriatic Sea.* Polish Maritime Research, Vol. 20(1),2013, pp. 87–93.

3. Cydejko J., Wawruch R.: *Examination of Operating Parameters of the Local Differential GPS System in Static Conditions* (in Polish). Gdynia Maritime Academy Publishing House, Gdynia 1993.

4. Cydejko J., Wawruch R.: *Preliminary Assessment of the DGPS System for Determining the Position and Manoeuvring Parameters of the Ship During Maritime Trials* (in Polish). Proceedings of the 9th International Scientific and Technical Conference on the *„Role of Navigation to Protect the Human Activity in Sea"*, Gdynia, 1994, pp. 21–33.

5. Dziewicki M., Specht C.: *Position Accuracy Evaluation of the Modernized Polish DGPS.* Polish Maritime Research, Vol. 16(4), 2009, pp. 57–61.

6. Ferguson K., Albright M., Remondi B.W., Cleveland A., Parsons M.: *NDGPS Reference Station and Integrity Monitor*

Architecture Modernization. Proceedings of the 60th Annual Meeting of the Institute of Navigation, Dayton, 2004, pp. 729–740.

7. Grządziel A., Felski A., Wąż M.: *Experience with the Use of a Rigidly-Mounted Side-Scan Sonar in a Harbour Basin Bottom Investigation.* Ocean Engineering, Vol. 109, 2015, pp. 439–443.

8. Kelner J.M., Ziółkowski C., Nowosielski L., Wnuk M.: *Reserve Navigation System for Ships Based on Coastal Radio Beacons.* Proceedings of the 2016 IEEE/ION Position, Location and Navigation Symposium (PLANS), Savannah, 2016.

9. Kopacz Z., Mor aś W., Pawłowski P. et al.: *Modernization of the SYLEDIS Radio-Navigation System in the Pomeranian Bay* (in Polish). Research project under the code name „SYLEDIS-3", 2001.

10. Kopacz Z., Specht C. et al.: *Radio-navigation Service in the Polish Sea Areas* (in Polish). Research project report, Polish Naval Academy, Gdynia 1996.

11. Naus K., Wąż M.: *Precision in Determining Ship Position Using the Method of Comparing an Omnidirectional Map to a Visual Shoreline Image.* Journal of Navigation, Vol. 69(2), 2016, pp. 391–413.

12. Oszczak B.: *New Algorithm for GNSS Positioning Using System of Linear Equations.* Proceedings of the 26th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS+ 2013), Nashville, 2013, pp. 3560–3563.

13. Popielarczyk D.: *RTK Water Level Determination in Precise Inland Bathymetric Measurements.* Proceedings of the 25th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS 2012), Nashville, 2012, pp. 1158–1163.

14. Proc J. (2014): *Hyperbolic Radio-navigation Systems* (in Polish). http://www.jproc.ca/hyperbolic/index.html, Accessed on 30 April 2018.

15. Przestrzelski P., Bakuła M., Galas R.: *The Integrated Use of GPS/GLONASS Observations in Network Code Differential Positioning.* GPS Solutions, Vol. 21(2), 2017, pp. 627–638.

16. Sitnik E., Oszczak B., Specht C.: *Availability Characteristics Determination of FKP and VRS Techniques of ASG-EUPOS System.* Proceedings of the 14th International Multidisciplinary Scientific GeoConference & EXPO SGEM2014, Albena, 2014, pp. 97–104.

17. Specht C., Koc W., Smolarek L., Grządziela A., Szmagliński J., Specht M.: *Diagnostics of the Tram Track Shape with the Use of the Global Positioning Satellite Systems (GPS/GLONASS) Measurements with a 20 Hz Frequency Rate.* Journal of Vibroengineering, Vol. 16(6), 2014, pp. 3076–3085.

18. Specht C., Mania M., Skóra M., Specht M.: *Accuracy of the GPS Positioning System in the Context of Increasing the Number of Satellites in the Constellation.* Polish Maritime Research, Vol. 22(2), 2015, pp. 9–14.

19. Specht C., Rudnicki J.: *A Method for the Assessing of Reliability Characteristics Relevant to an Assumed Position-Fixing Accuracy in Navigational Positioning Systems.* Polish Maritime Research, Vol. 23(3), 2016, pp. 20–27.

20. Specht C., Specht M., Dąbrowski P.: *Comparative Analysis of Active Geodetic Networks in Poland.* Proceedings of the 17th International Multidisciplinary Scientific GeoConference & EXPO SGEM2017, Albena, 2017, pp. 163–176.

21. Specht C., Weintrit A., Specht M.: *A History of Maritime Radio-Navigation Positioning Systems Used in Poland.* Journal of Navigation, Vol. 69(3), 2016, pp. 468–480.

22. Ward N.: *Future of IALA DGNSS.* Proceedings of the 2006 National Technical Meeting of the Institute of Navigation, Monterey, 2006, pp. 184–187.

23. Xinchun Z., Ximin C., Dongkun Y.: *Application of Modified Kalman Filtering Restraining Outliers Based on Orthogonality of Innovation to Track Tester.* Proceedings of the 2016 IEEE International Conference on Mechatronics and Automation (ICMA), Harbin, 2016, pp. 171–175.

24. Yang C., Mohammadi A., Chen Q.-W.: *Multi-Sensor Fusion with Interaction Multiple Model and Chi-Square Test Tolerant Filter.* Sensors, Vol. 16(11), 2016, pp. 1835.

CONTACT WITH THE AUTHORS

Cezary Specht
e-mail: c.specht@wn.am.gdynia.pl

Leszek Smolarek
e-mail: leszsmol@am.gdynia.pl

Jan Pawelski
e-mail: j.pawelski@wn.am.gdynia.pl

Mariusz Specht
e-mail: m.specht@wn.am.gdynia.pl

Paweł Dąbrowski
e-mail: p.dabrowski@wn.am.gdynia.pl

Gdynia Maritime University
81–87 Morska Str., 81–225 Gdynia
Poland