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Polish DGPS System: 1995-2018 – Studies of Reference Station Operating Zones

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ABSTRACT: The operating zone of a radio navigation system is one of its main operating features. It determines the size of a water body in which the system can be used, while guaranteeing vessels' navigation safety.
The DGPS system in the LF/MF range is now the basic positioning system in coastal waters around the world, which guarantees not only metre positioning accuracy, but it is also the only one to provide navigators with signals on positioning reliability.
This paper describes and summarises over twenty years of studies dealing with the operating zone of the Polish DGPS reference station network. This paper is the fifth in a series of publications whose aim was to present in detail the process of installation, testing and long-term evaluation of the navigational parameters of the Polish DGPS system, launched in 1995. This paper includes the theoretical foundations of determination of the Dziwnów and Rozewie DGPS reference station operating zones in the years 1995-2018. Moreover, it presents the measurement results for the signal levels and the results of their analyses, which determine the station operating zones.

1 INTRODUCTION

The basic method of increasing the navigation safety is to ensure precision ship positioning by setting up navigation marking systems, including radio navigation systems accessible to all vessels [Czaplewski, K., 2018; Czaplewski, K., Goward, D., 2016; Jang, W.S. et al., 2018; Specht, C. et al., 2016]. The Differential Global Positioning System (DGPS) system in its marine version is the basic positioning system for coastal navigation and it is also widely used in hydrography, both marine and inland [Stateczny, A. et al., 2018], meeting all categories of requirements laid down in the International Hydrographic Organization (IHO) S-44 standard [IHO, 2008]. Moreover, DGPS system also has other applications, including offshore activities [Baptista, P. et al., 2008].

At the same time, methods of positioning improvement are applied both by such technical solutions as alternative positioning systems [Kelner, J.M. et al., 2016; Sadowski, J., Stefański, J., 2017], radar positioning [Stateczny, A. et al., 2019] and multi-GNSS (Global Navigation Satellite System) solutions [Specht, C. et al., 2019a; Yang, C. et al., 2016] using Kalman filtering [Xinchun, Z. et al., 2016].

Unlike various alternative positioning solutions mentioned here, the marine DGPS system dominated the vessel positioning process due to the following operational features:

– reference stations are placed at the same locations where radio beacons used to operate, which made it possible to use the existing transmission infrastructure,
– a typical range of a reference station is approx. 100 km, which makes it possible to cover most waters of coastal states,
– the positioning accuracy of approx. 1 m (p = 0.95) guarantees high navigation safety for vessels approaching ports, which is competitive against other commonly accessible systems [Specht, C. et al., 2019b],
– the ability of the DGPS system to transmit positioning reliability signals is unique among all the positioning systems worldwide.

Being a combined system, the marine DGPS system requires that the operating zone should be defined as a spatial product of the Global Positioning System (GPS) operating zone and the DGPS reference station operating zone. The GPS system operating zone is by definition regarded as global, but due to the dynamics of the satellite constellation system movement and a variable number of satellites visible above the required topocentric altitude, it can be alternatively defined as a function of time [Specht, C. et al., 2015]. In this case, it acquires a spatial-temporal dimension rather than being only water body-related. The availability of individual satellites in an area [Specht, C., Dąbrowski, P., 2017], their average number in a global approach and their geometric configuration, and in particular their constellation within a specific period of time, can be predicted analytically.

The following are the proposed precise definitions of both terms:
– a GPS operating zone is the percentage of time relative to its predefined interval, during which the required number of satellites is above the required topocentric altitude, thereby enabling users to determine position with a permissible error, at any point on or above the Earth,
– a DGPS reference station operating zone is a space referred to geographic coordinates of the DGPS reference station (φ, λ, h), in which telemetric transmission can be received with required reliability.

This paper presents the theoretical foundations of the DGPS operating zone determination and shows the findings of research on the Polish DGPS system in the years 1995-2018.

2 THE DGPS SYSTEM OPERATING ZONE – THEORETICAL FOUNDATIONS

Sending radio signals, associated directly with the system range and coverage, depends on a number of factors and circumstances. Propagation conditions vary depending on the place, time and frequency range. However, although the radio wave propagation theory is well developed, calculation results based on formulas and theoretical curves often deviate from reality [Enge, P. et al., 1992]. This is caused by an insufficiently strict approach to highly complex propagation phenomena, their insufficient explanation and practically unavoidable simplifications. Therefore, theoretical considerations regarding the coverage of an area by a radio navigation system must be verified practically, and the planned deployment of a DGPS reference station should take into account the real results of operating systems of this type.

Characteristic features of 300 kHz radio waves include different propagation conditions during the day and night, which is caused by the occurrence of the surface wave and the skywave at night. They can cause undesired interference (Figure 1), resulting in even signal disappearance. The DGPS-related experience so far shows that the effect of this interference is not significant (over distances under consideration) [Specht, C., 1997], although obviously it has to be considered at boundary ranges and its occurrence must be predicted even during the day in winter [Huuhka, E., Lehtoranta, V., 1995]. For this reason, radio wave propagation at this frequency should be considered mainly from the point of view of the surface wave propagation, particularly taking into account the effect of the ground and interference.

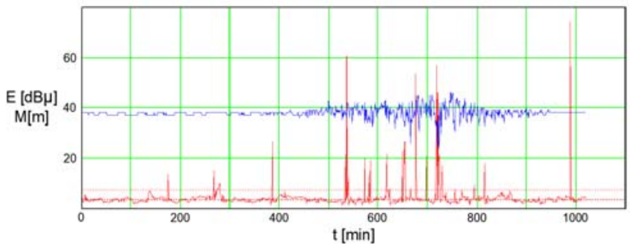

Figure 1. The signal strength - E [dBμ] (blue) of a Hoburg DGPS reference station and the mean positioning error - M (p = 0.95) (red) as a function of time. Recording: 24-05-1995 11:50 UTC – 25-05-1995 04:50 UTC, Gdynia, measurement frequency: 1 minute [Specht, C., 1997].

It is noteworthy that interference of the surface wave and skywave at night results in fluctuation of the Signal-to-Noise Ratio (SNR), which causes changes in the Bit Error Rate (BER) and, ultimately, damages Radio Technical Commission for Maritime (RTCM) messages. This results in increasing of the Age of Corrections (AoC) and, further, mean positioning error (M). According to the requirements for telemetric transmission of the DGPS system, the minimum SNR is 7 dB, with BER of 10^{-3}. It should be accepted that apart from the required signal strength (34 dBμ), the required SNR value is another factor which determines the DGPS reference station operating zone.

A DGPS reference station transmits signals within the range of: 283.5-325 kHz with Minimum-Shift Keying (MSK), at a transmission speed of (R): 50,100, 200 bd. In practice, it is accepted that the radio signal at distances larger than 70 Nm from a broadcasting antenna near the Earth surface is a field consisting of two types of waves: surface and ionospheric. Signals sent from a DGPS reference station basically reach a user on a surface wave. The signal strength depends mainly on the radio beacon transmitter power, the receiver-station distance and conductivity of the ground above which the radio wave propagates. The received signal strength for the ground of the ideal conductivity can be expressed with the formula:

$$E = 20 \cdot \log_{10}\left(\frac{3 \cdot 10^5}{d}\right) + 10 \cdot \log_{10}\left(\frac{P}{1000}\right), \tag{1}$$

where:
E – signal strength [dBµ],
P – radiated power [kW],
d – distance from transmitter [km].

This equation also describes approximate propagation conditions above the medium of variable conductivity, but it is true only for small ranges. With respect to the real conditions, the signal strength can be calculated from the following formula:

$$E_0 = \frac{3 \cdot 10^5 \cdot \sqrt{P}}{d} \cdot |F|, \tag{2}$$

where:
E_0 – signal strength [µV/m],
F – damping factor [-].

The value of $|F|$ for routes of non-uniform conductivity is calculated by the Millington method taking into account the electric properties of individual sections of the route. If a route consists of two sections of different electric properties, then:

$$|F| = \sqrt{\frac{F(\delta_1, d_1)}{F(\delta_2, d_1)} \cdot F(\delta_2, d) \cdot \frac{F(\delta_2, d_2)}{F(\delta_1, d_2)} \cdot F(\delta_1, d)}, \tag{3}$$

where:
$F(\delta_1, d_1)$ – damping factor calculated for a uniform route section of conductivity δ_1 and length d_1 [-],
d – sum of distances d_1 and d_2 [m].

The damping factor for routes of uniform conductivity can be calculated from Burrows graphs or from an approximate formula:

$$|F| \approx \frac{2 + 0.3 \cdot x_d}{2 + x_d + 0.6 \cdot x_d^{\,2}}, \tag{4}$$

where:

$$x_d = \frac{\pi \cdot d}{\lambda} \cdot \frac{\sqrt{(\varepsilon' - 1)^2 + (60 \cdot \lambda \cdot \delta)^2}}{(\varepsilon')^2 + (60 \cdot \lambda \cdot \delta)^2}, \tag{5}$$

assuming that:
x_d – distance number [-],
d – distance from the station [m],
ε' – relative permittivity [-],
λ – wavelength [m],
δ – ground conductivity [mS/m].

Another method of the surface wave signal strength determination uses Comité Consultatif International des Radiocommunications (CCIR) curves.

Skywave is another signal which reaches a DGPS receiver, especially at night. A radio wave from the DGPS station transmitter antenna reaches the ionosphere layer D, from which it is reflected and interferes with the surface wave, creating ionospheric interference. The condition of the ionospheric layer D is a function of: time of day and time of year, geomagnetic latitude. During the day, the sun is the basic ionization source, creating an effective reflection surface at 70 km (the sun at its zenith) and 75 km (at sundown). Solar ionization disappears at night and the effective reflection surface increases to 80-90 km.

The signal strength in a short vertical antenna can be described as:

$$E_{sky} = \frac{3 \cdot 10^5 \cdot \sqrt{P} \cdot \cos^2(\alpha) \cdot R_s \cdot D_j \cdot F_t \cdot F_r}{s}, \tag{6}$$

where:
E_{sky} – signal strength of skywave [µV/m],
α – angle between the direction of propagation and the horizon [rad],
R_s – ionospheric reflection coefficient [-],
D_j – ionospheric condition coefficient [-],
F_t – a coefficient characterising the transmitter antenna [-],
F_r – a coefficient characterising the receiver antenna [-],
s – total length of skywave [km].

Assuming the spherical shape of the Earth, the value of s can be expressed as:

$$s = 2 \cdot \left[(R_E + h)^2 + R_E^{\,2} - 2 \cdot R_E \cdot (R_E + h) \cdot \cos\left(\frac{\psi}{2}\right)\right]^{\frac{1}{2}}, \tag{7}$$

where:
R_E – Earth radius [km],
h – effective reflection altitude [km],
ψ – central angle between the transmitter and the receiver [rad],

therefore:

$$\cos(\alpha) = \frac{2 \cdot (R_E + h) \cdot \sin\left(\frac{\psi}{2}\right)}{s}. \tag{8}$$

Figure 2 presents signal strength curves. The signal strength for the surface wave and skywave as a function of the time of day and time of year, distance from the reference station for the frequency of 300 kHz and EPR of 1 kW.

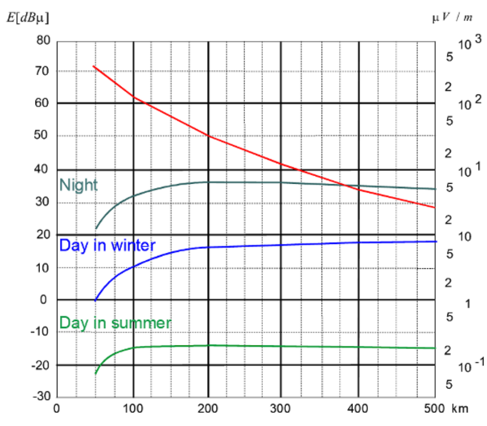

Figure 2. The signal strength for the surface wave and skywave as a function of the time of day and time of year, distance from the reference station for the frequency of 300 kHz and EPR of 1 kW. The red line denotes the signal strength for the surface wave [IALA, 1996].

3 TESTING THE POLISH DGPS SYSTEM OPERATING ZONE

3.1 *Study in the years: 1995-1996*

The implementation work conducted during the process of launching the Polish DGPS system in 1995-1996 focused on establishing two basic characteristics of the system: positioning accuracy and the operating zone. Since no software for determining the system operating zone was available, it was decided to conduct the measurements directly in the sea. The energy measurements (signal strength) for the DGPS reference station were conducted multiple times and simultaneously with other system studies in summer and winter (1995-1996).

Figure 3 shows the operating zones – signal strength for both DGPS reference stations (Dziwnów and Rozewie).

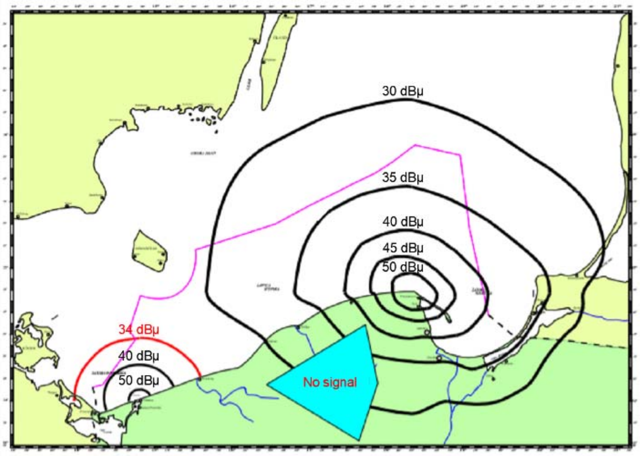

Figure 3. The Dziwnów and Rozewie DGPS reference station operating zones in 1996 [Specht, C., 1997].

The signal level of 50 µV/m is regarded as the operating zone border value, which means that the Polish DGPS system operating range was 60 and 100 km for the Dziwnów and Rozewie DGPS reference stations.

Table 1 shows the planned and real (based on the measurements) operating zones for both DGPS reference stations (Dziwnów and Rozewie).

Table 1. Radiated power measurements results with source data for Polish DGPS systems [Specht, C., 1997].

Station name	Geographic coordinates	Nominal range (50 µV/m) source data [km]	Nominal range (50 µV/m) actual data [km]	ERP [W]
Dziwnów	54°01'N 14°44'E	90	55 120*	0.1 0.5*
Rozewie	54°49'N 18°20'E	90	100	0.4

*for simulated data

3.2 *Study after system modernisation in 2002*

Opinions on the need to use the DGPS system appeared in the literature in the late 1990s. It turned out that the close (local) monitoring does not meet the system users' expectations. There were situations in which the DGPS system was not available at a considerable distance from the reference station (several dozen kilometres) and the local monitoring did not generate an alarm. Therefore, it was decided to set up additional monitoring stations in the most dangerous areas for navigation. A monitoring station in the Port of Gdynia was launched for the Rozewie DGPS reference station, and one in Szczecin – for the Dziwnów DGPS reference station.

In 2002, under an agreement between the maritime offices, a decision was taken to hand over the technical infrastructure of the Dziwnów DGPS reference station to the Maritime Office in Gdynia. It resulted in a system which is controlled by one station in Gdynia. Reconnecting the systems of Dziwnów and Rozewie DGPS reference stations and handing over the coordination of running the whole DGPS system should be regarded as justified and in line with international standards. The essence of the modernisation lay in replacement of the transmitting antennas in both stations, resulting in a considerable increase in the system operating range. Figure 4 shows the new transmitting antennas in the station. Replacement of the antenna in the Dziwnów DGPS reference station was of particular importance because its grounding failed to meet the required technical standards.

Figure 4. The transmitting antennas in the Dziwnów (left) and Rozewie (right) DGPS reference stations, modernised in 2002.

These changes resulted in a considerable increase in the operating range of both stations. Tests conducted in 2002 showed that the operating range of the Rozewie DGPS reference station was 300 km, and that of the Dziwnów DGPS reference station – 150 km. The operating ranges of both stations are shown in Figure 5.

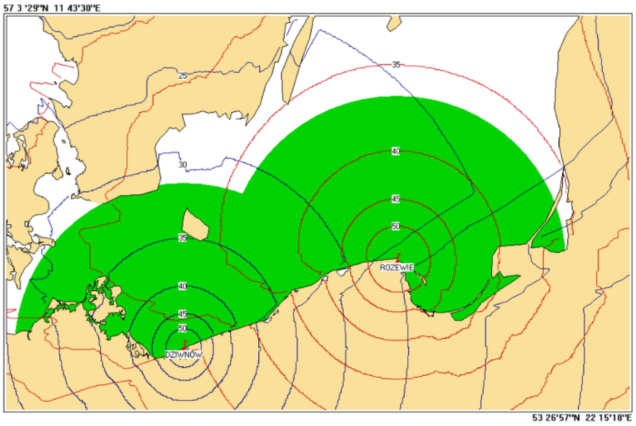

Figure 5. The Dziwnów and Rozewie DGPS reference station operating zones in 2003 [Specht, C. et al., 2016].

3.3 *Study after system modernisation in 2007*

The system modernisation started in 2007. The first to be modernised by the Gdynia Maritime Office was the Rozewie DGPS reference station and the Central Control Station (CCS) in Gdynia. The modernisation work at the Dziwnów DGPS station was completed in July 2008, and at the Rozewie DGPS station – in April 2011 [Dziewicki, M., Specht, C., 2009].

As part of the National Maritime Safety System, thorough modernisation of the Polish DGPS system was completed in April 2011. It is currently part of the integrated navigation marking system of the Maritime Office in Gdynia. Owing to a subsidy from the European Union (EU), worn equipment and software at the DGPS stations was replaced with a new generation of devices; it included old systems of antenna masts and GPS receivers. The new system organisation is shown in Figure 6.

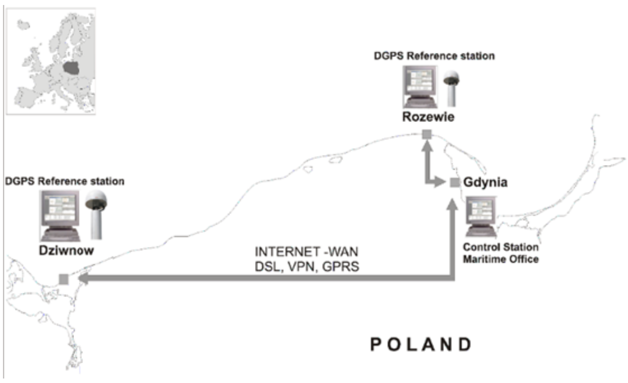

Figure 6. Organisation of the Polish DGPS system after the modernisation in 2007-2011 [Specht, C., 2011].

The aim of the DGPS transmitting infrastructure modernisation plan was mainly to improve the state of maritime safety; it was developed for the coastal navigation and navigation marking services, hydrographic services, search services, marine engineering, etc. Operation of both stations is monitored from Gdynia. Now each station has two modern receivers and two transmitters, which react to changes in atmospheric conditions, adjusting the radiated power accordingly. The old, run-down AGA antennas, made of steel, had been in use for 50 years and the mast guy wires absorbed part of the radiated energy. They were replaced with modern, effective and durable, plastic rod antennas. This unique solution was implemented by Elecom-Mastertech of Gdynia as the last stage of the comprehensive modernisation of the National Maritime DGPS Network. The Rozewie DGPS reference station operating zone is shown in Figure 7.

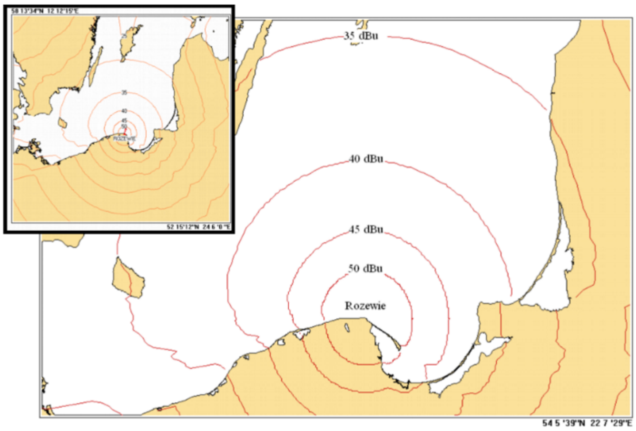

Figure 7. Signal strength level in dBμV/m for the Rozewie DGPS reference station [Specht, C., 2011].

Based on the signal strength level measurements, ERP was calculated as a 4.02 W for the transmitter of the Rozewie DGPS reference station. Presented coverage of the modernised Rozewie DGPS reference station (Figure 7) guarantee maximum range for the system as 200 km (for 34 dBμV/m).

4 CONCLUSIONS

The Polish DGPS system is now the main positioning system in the water bodies of the Republic of Poland. It is used mainly to ensure navigation safety for vessels and in hydrography. In terms of its technical equipment, the Polish DGPS system is at the highest level. Owing to the equipment modernisation in 2002-2003 and in 2007-2011, the operating range has increased two-fold and the positioning accuracy has increased nearly five-fold. These modernisation works were taken in accordance with the guidelines for e-Navigation [Urbański, J. et al., 2008], whose principles were formulated by International Maritime Organization (IMO) and are implemented by carrying out the Efficient, Safe and Sustainable Traffic at Sea (EfficienSea) project co-financed from the funds of the Interreg Baltic Sea Region Programme.

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