POLISH MARITIME RESEARCH 3 (99) 2018 Vol. 25; pp. 5-13
10.2478/pomr-2018-0091

THE IMPACT OF RADAR DISTANCE MEASUREMENT ACCURACY ON THE ACCURACY OF POSITION FIXING IN VTS SYSTEMS

Krzysztof Czaplewski[1]
Sambor Guze[1]
Sławomir Świerczyński[2]
[1] Gdynia Maritime University, Poland
[2] Polish Naval Academy, Gdynia, Poland

ABSTRACT

The main source of information on the situation across the sea basins used by operators of shipping monitoring systems is a network of coastal radar stations. Presently, it is possible to gather navigational information from many individual radar stations simultaneously, which may be used for improving the accuracy of vessel position fixing. However, without making other estimates, we obtain an inconsistent image comprising multiple echoes of the same ship, and as such it is impossible to say which echo presents the vessel on the move. Another problem is the method of performing radar observations, which significantly affects the accuracy of position fixing. The estimated radar distance is encumbered with a gross error in the case of large vessels, as the position of a large vessel is not the same as the position of the edge of the radar echo to which the estimation is made. In this paper, the authors present a method to adjust the measured radar distance. The proposed method may be automated easily, which would significantly enhance VTS positioning processes.

Keywords: radar, VTS, navigation, navigation automation, mathematical methods

INTRODUCTION

The main source of information on the situation across the sea basins supporting the work of operators of shipping monitoring systems is a network of coastal radar stations. The coastal radar stations located along the shores of basins under supervision of VTS systems may convey navigational information from one or more radars. VTS systems also use the information from the Automatic Identification System, which uses the information from satellite systems [Urbański, Morgaś, Specht 2008; Czaplewski, Goward 2016; Dziewicki Specht 2009]. However, this information area is not considered in this article.

Navigational information may be simultaneously obtained from many individual radar stations [Świerczyński, Czaplewski 2012, 2013], and used to improve the accuracy of estimating vessel positions. However, the information obtained simultaneously from all coastal stations produces an inconsistent image of the ship generated by multiple echoes, in which case it is difficult to determine which echo represents the vessel on the move [Świerczyński 2017].To eliminate this problem and correct the fixing, modern observation adjustment methods, known in geodesy and presented in [Czaplewski, Świerczyński 2015], among other publications, may be used. Greater ship positioning accuracy translates into improved navigational safety and the possibility of giving an early warning, which is especially important in the case of enclosed waters where the risk of collision is relatively high [Guze et al., 2016]. Another research problem is the adequate use of observations (bearings, range) obtained from coastal radar stations. Good maritime practice requires that in the case of a radar bearing, a watchman performs the bearing to the centre of the radar echo, whilst in the case of radar distance measurements, the observation should be made to the nearest edge of the echo, and not to the echo centre. In the case of vessels of small dimensions (length, width), the measurement error is not considerable, but for large vessels (such as MAERSK container ships) the observations may be encumbered by gross errors, depending on the position of the vessel in relation to the radar station. The authors of this paper present the results of their studies and propose to automate the process of adjusting distances measured by coastal radar stations. The studies were performed in the basin covered by the Gulf of Gdansk VTS system.

RADAR SUB-SYSTEM IN THE GULF OF GDANSK VTS SYSTEM

The radar sub-system provides for early detection and accurate tracking of targets to prevent vessel collisions and environmental threats. The National Maritime Safety System (KSBM) is a monitoring and control system committed to ensuring maritime navigation safety and protection of maritime environment. As part of KSBM's development (KSBM-I – 2014), the facilities managed by Maritime Offices in Gdynia, Słupsk and Szczecin, and by the Maritime Search and Rescue Service were modernized. The VTS system in Gdynia is contained within the organisational structure of KSBM, providing services for the territory of jurisdiction of Gdynia Maritime Office. The Gulf of Gdansk VTS system was upgraded as part of stage 1 of KSBM's development. Five radar stations were modernised and other five were put into operation. Presently, there are ten operational radar stations. The location of nine coastal radar stations is presented in Fig. 1. Additionally, one radar station was built on the PetroBaltic platform [UMG, 2016c].

Fig. 1. Location of coastal stations operating in the system of Gulf of Gdansk VTS

The coordinates of radar station antennas are presented in Table 1.

While retaining the same functional scope, the modernisation of the Gulf of Gdansk VTS system has brought about increased efficacy. Software and hardware was upgraded, operators' stands were modernised, new sensors were installed, and data transmission was provided to a central application. The integration of all components is implemented through the Maritime Safety Information Exchange System (SWIBŻ) and high-speed communication networks of KSBM centres in Gdynia, Ustka and Szczecin.

RADAR DISTANCE DETERMINATION MODEL ACCOUNTING FOR THE SHAPE OF VESSEL

In radar navigation, the reciprocal position of ships is characterised by the angle between the true course of the observed vessel and the bearing taken from the observed object on the own vessel [Chrzanowski, et al. 2010]. This angle is called aspect. For the description of a radar cross-section, we use the term "aspect" defined as the angle at which the object is inclined toward the incoming radar wave [Chrzanowski, et al., 2010; Wei, et al. 2010]. In this article, the angle between the course of the vessel observed in the VTS system and the bearing taken on the ship from the coastal radar station (Fig. 2) will be called the aspect (α_A).

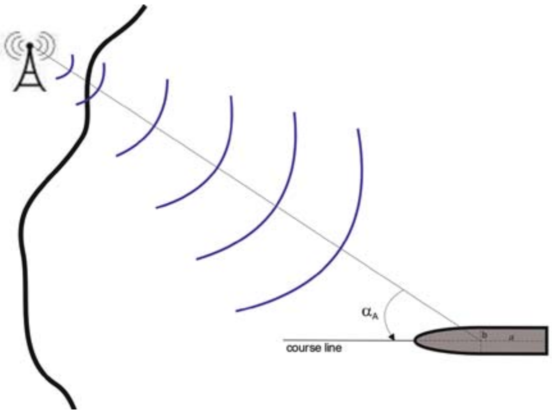

Fig. 2. Graphic presentation of the aspect

Tab. 1. Coordinates of radar station antennas in the Gulf of Gdansk VTS system

Symbol	Location	Geographic coordinates		Cartesian coordinates	
		φ	λ	X	Y
Władysławowo	Władysławowo Harbour	54°47.809' N	018°25.281'E	6075231.55	334234.35
Hel_L	Hel Lighthouse	54°36.003' N	018°48.771'E	6052486.06	358713.75
HEL_SB	Hel, South Breakwater	54°35.985' N	018°48.058' E	6052476.63	357945.55
Gdynia_WQ	Gdynia, Wenda Quay	54°31.739' N	018°33.576' E	6045119.44	342083.22
Gdynia_HMO	Gdynia, Harbour Master's Office	54°32.021' N	018°32.841' E	6045669.81	341309.47
Gdańsk_HMO	Harbour Master's Office, Gdańsk North Harbour	54°23.987' N	018°41.778' E	6030447.63	350457.03
Gdańsk_NH	Gdańsk, New Harbour	54°24.405' N	018°39.658' E	6031298.79	348189.74
GZ_RT	Górki Zachodnie, Radar Tower	54°22.229' N	018°46.734' E	6027017.31	355714.79
KM_L	Krynica Morska, Lighthouse	54°23.123' N	019°27.046' E	6027506.85	399392.32

Among all radar observations, bearing and distance measurements are the most common. With regard to radar bearing, good maritime practice recommends that the observation be performed toward the centre of the radar echo for better quality of its final determinations. On the other hand, the distance measurement is to be made to the "closest" boundary of echo created by RCS. For small sailing vessels, such a measurement technique is not encumbered by a big error that could grossly affect final determinations. The situation is dramatically different when a radar band "delivers echo" for large and very large vessels. The site of measurement is significantly different from the centre of the radar echo, which grossly affects the final determination of the coordinates of a ship at sea [Bole et al., 2005].

The factor that heavily affects the accuracy of position fixing is the vessel's course in relation to the measuring radar. Coastal radar stations are located along the costal line around the basin. Each radar can "see" the sailing vessel at a different angle, at a different bearing. This angle affects the accuracy of fixing the distance or bearing by the radar [Curry, 2004].

The accuracy of position fixing is also affected by the shape of a vessel, which can be different depending on its type and designed use. However, its radar image is usually similar to the shape of an ellipse, and the position of a ship is assumed to be at its centre. In the analyses presented further in this paper, we will assume that the coordinates of the centre of an ellipse are the coordinates of the vessel at sea; the sailing vessel will be represented by a flat figure being a combination of an ellipse and a rectangle (Fig. 2). Such a figure will provide a more precise representation of the actual shape of the hull for the purpose of the model proposed in this article.

Let us assume that the aspect (α_A) takes values from the range $\alpha_A = \langle 000°, 180° \rangle$ in the system of horizon half-division. The α_A angle depends on the true bearing taken from the position of the radar antenna on the vessel and the course of the vessel, which may be illustrated by the following formula:

$$\begin{cases} \alpha_A = NR^R - KR + 180° & \text{for } \left(NR^R - KR\right) < 000° \\ \alpha_A = 180° & \text{for } \left(NR^R - KR\right) = 000° \\ \alpha_A = 000° & \text{for } \left(NR^R - KR\right) = -180° \\ \alpha_A = NR^R - KR - 180° & \text{for } \left(NR^R - KR\right) > 000° \end{cases} \tag{1}$$

where:

NR^R – is the true bearing taken from the radar on the ship,

KR – is the true course of the ship.

Assuming that the model of the bow of the ship is a half ellipse and the value of the aspect is within the range of $\alpha_A \in (000°, 090°)$, then the measurement structure of interest will take the shape presented in Fig. 3.

Moreover, the following parameters were introduced: a is a half of the vessel's length (semi-major axis of the ellipse), and b is half of the vessel's width (semi-minor axis of the ellipse). In Fig. 3, the measured radar distance (d_R) was marked together with the distance (d_P) by which the d_R distance should be adjusted in accordance with the assumption that the centre of the ellipse marks the position of the sailing vessel. The VTS operator is interested in the actual position of the vessel, therefore, the navigational observation obtained from the radar distance measurement should be specified as follows:

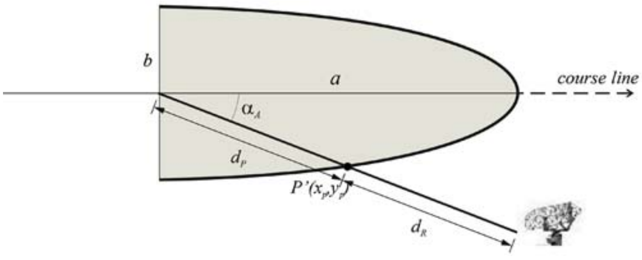

Fig. 3. Measurement structure for the adjustment of radar distance d_R measured up to the bow

$$d_C = d_R + d_P \tag{2}$$

where:

d_C is the actual distance between the radar station and the ship position.

To determine the distance d_P by which the radar distance (d_R) should be adjusted, the ellipse equation needs to be used. Using a local coordinate system with the centre at the ellipse centre, the equation of the ellipse will take the following form [Yates, 1974]:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \rightarrow b^2 \cdot x^2 + a^2 \cdot y^2 = a^2 \cdot b^2 \tag{3}$$

Assuming that the radar beam bounces off the hull at point P', then its polar coordinates (x_p, y_p) may be written down as:

$$\begin{cases} x_p = d_p \cdot \cos\alpha_A \\ y_p = d_p \cdot \sin\alpha_A \end{cases} \tag{4}$$

Upon substituting the formula (4) for (3), the following is obtained:

$$b^2 \cdot d_P^2 \cdot \cos^2\alpha_A + a^2 \cdot d_P^2 \cdot \sin^2\alpha_A = a^2 \cdot b^2 \tag{5}$$

And after transformations:

$$d_p^2 = \frac{a^2 \cdot b^2}{b^2 \cdot \cos^2\alpha_A + a^2 \cdot \sin^2\alpha_A} \rightarrow$$
$$\rightarrow d_p = \frac{a \cdot b}{\sqrt{b^2 \cdot \cos^2\alpha_A + a^2 \cdot \sin^2\alpha_A}} \tag{6}$$

Using the geometrical formula $\sin^2\alpha_A + \cos^2\alpha = 1$, a formula is finally obtained that can be used to determine the adjustment to the measured radar distance:

$$d_p = \frac{a \cdot b}{\sqrt{b^2 + \left(a^2 - b^2\right) \cdot \sin^2\alpha_A}} \tag{7}$$

The formula (7) is valid for the angle's value $\alpha_A \in (000°, 090°)$.

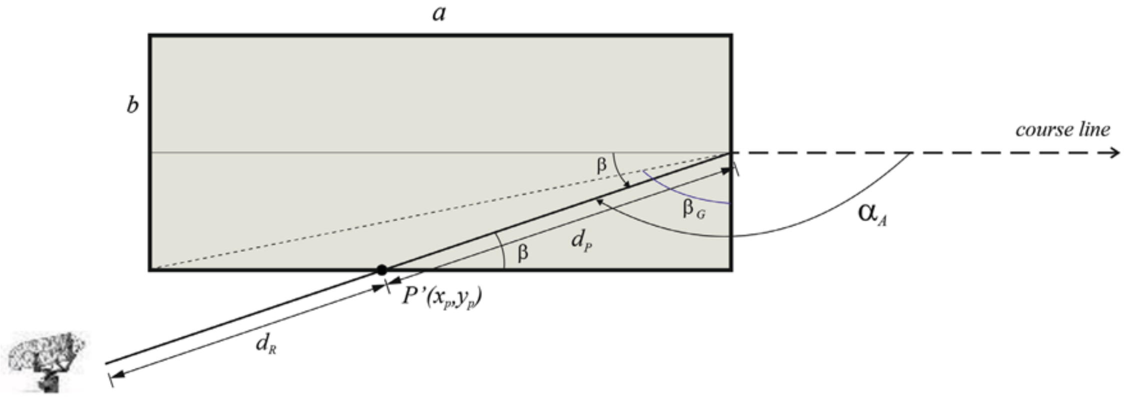

Fig. 4. Model of stern part of a ship presented as a rectangle – radar beam falling on the ship's broadside

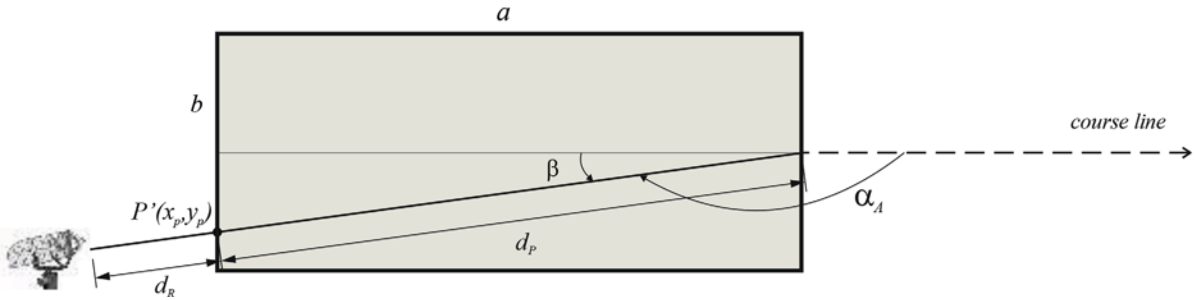

Fig. 5. Model of stern part of a ship presented as a rectangle – radar beam falling on the ship's stern

Assuming that the model for the stern is a rectangle with sides equal to a half of the ship's length (a) and width (b), the measurement structure takes the form shown in Fig. 4.

Then, two cases have to be considered: when the radar beam falls on the ship's broadside (Fig. 4) or on the stern part (Fig. 5).

In the first case (Fig. 4), let the β angle be $\beta < 180° - \alpha_A$, then, after application of the law of sines, we receive:

$$\frac{b}{d_p} = \sin(180° - \alpha_A) \rightarrow d_p = \frac{b}{\sin(180° - \alpha_A)} \quad (8)$$

For the distance measurement performed to the vessel's stern (Fig. 5), the law of cosines is used. The use of the law of cosines is justified by the determination of the β_G angle value (Fig. 4). The value of this angle can be determined using the formula:

$$\beta_G = arc\ tg \frac{a}{b} \quad (9)$$

Then, it may be assumed that the threshold value of aspect (α_G) above which the law of cosines should be used takes the form:

$$\alpha_A = \alpha_G = \beta_G + 90° \quad (10)$$

For this case, the angle $\beta < 180° - \alpha_A$ (Fig. 5), and the value of the corrected distance is calculated with the use of the law of cosines. Finally:

$$\frac{a}{d_p} = \cos(180° - \alpha_A) \rightarrow d_p = \frac{a}{\cos(180° - \alpha_A)} \quad (11)$$

As a result, we obtain a mathematical model of (d_p) distance by which the measured radar distance should be adjusted, as a function of sailing vessel dimensions, determined with the following formulas:

$$\begin{cases} d_P = a & \text{for} \quad \alpha_A = 000° \quad i \quad \alpha_A = 180° \\ d_p = \dfrac{a \cdot b}{\sqrt{b^2 + \left(a^2 - b^2\right) \cdot \sin^2 \alpha_A}} & \text{for} \quad \alpha_A \in \left(000°, 090°\right) \\ d_P = b & \text{for} \quad \alpha_A = 090° \\ d_P = \dfrac{b}{\sin(180° - \alpha_A)} & \text{for} \quad \alpha_A \in \left(090°, \alpha_G\right) \\ d_P = \dfrac{a}{\cos(180° - \alpha_A)} & \text{for} \quad \alpha_A \in \ \alpha_G, 180°\right) \end{cases} \quad (12)$$

Where:
a – is half of the vessel's length
b – is half of the vessel's width

VALIDATION TEST

Built in 2007, the Deepsea Container Terminal Gdansk (DTC) has been handling one of the world's largest container vessels of E Maersk Line class, which regularly calls there every week, since 2011. In their research, the authors have used the actual registrations performed at the Gulf of Gdansk VTS Centre in Gdynia. The test presented below uses the measurement structure that involved four coastal radar stations (Hel_L, Gdynia_HMO, Gdańsk_HMO, GZ_RT) and the ship m/s MADISON MAERSK (Fig. 6). In the test the registration of the ship's passage which took place on 06/18/2017 at 06.20 – 06.35 UTC is used. The container ship sailed to approach the channel to the Port of Gdansk, at the height of the special mark BY ZS with speeds 12 – 9.2 kn. The vessel was moving through the courses 205° – 227°. Hydro-meteorological conditions prevailing during the registration were as follows:

- visibility: 9 Nm,
- air temperature: 14°C,
- state of the sea: 2,
- wind direction: S.

The coordinates of the coastal radar stations that performed the observations are presented in Table 1. Taking the vessel's dimensions $(L = 399 \text{ m}, B = 59 \text{ m})$ into account, the formula $a = L/2 = 199{,}50 \text{ m}$, $b = B/2 = 29{,}50 \text{ m}$ was applied for further calculations.

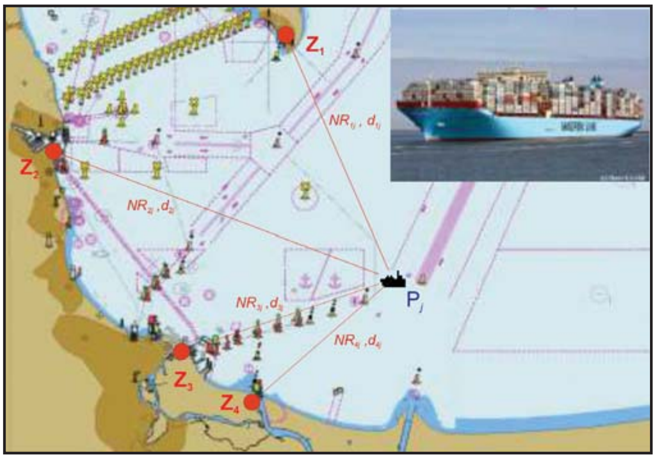

Fig. 6. Measurement structure used in testing

Four distances were measured from the coastal radar stations (Table 2) to the vessel positioned at $\varphi^o = 54°26.748'\text{N}$, $\lambda^o = 018°56.154'\text{N}$, $(X^o_P = 6035084.50, X^o_P = 366158.25)$. The position was registered in the AIS system.

The test presents the moment when the vessel was on course $KR = 221°$.

Tab. 2. Measured distances from the coastal radar stations to the vessel

Coastal radar stations	Observations d_i^R [m]
Hel Lighthouse (Hel_L)	$d_1^R = 18885.00$
Gdynia, Harbour Master's Office (Gdynia_HMO)	$d_2^R = 26975.00$
Harbour Master's Office, Gdańsk North Harbour (Gdańsk_HMO)	$d_3^R = 16310.00$
Górki Zachodnie, Radar Tower (GZ_RT)	$d_4^R = 130655.00$

Further, in order to determine the aspect (α_A), true bearings were taken from the coastal radar stations on the ship (Table 3).

A simplified graphical presentation of the measurement structure allowing for the foregoing input data is presented in Fig. 7.

Tab. 3. Bearings taken by the coastal radar stations on the ship

Coastal radar stations	Observations NR_i^R [°]
Hel Lighthouse (Hel_L)	$NR_1^R = 155.2$
Gdynia, Harbour Master's Office (Gdynia_HMO)	$NR_2^R = 110.8$
Harbour Master's Office, Gdańsk North Harbour (Gdańsk_HMO)	$NR_3^R = 072.3$
Górki Zachodnie, Radar Tower (GZ_RT)	$NR_4^R = 050.7$

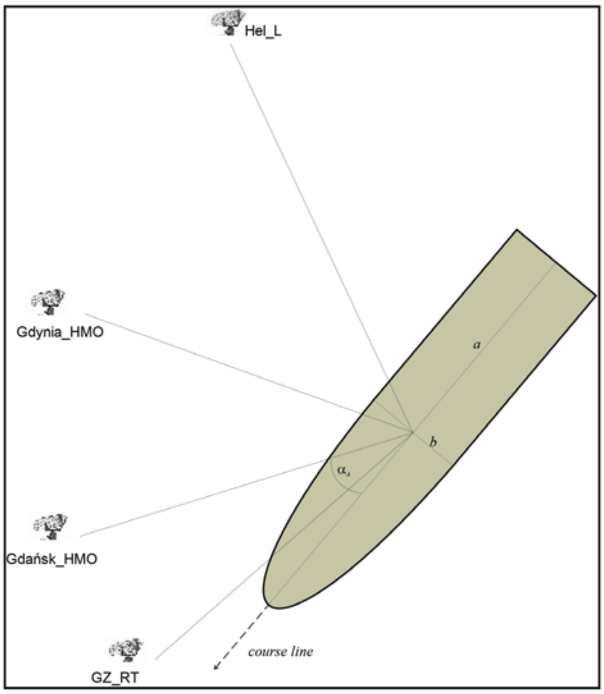

Fig. 7. Simplified graphic presentation of the measurement structure used in testing

First, angle α_A values in the half-division horizon system should be determined. Given the formula (1) and Fig. 7 the conclusion is summarised that:

- the aspect for Hel L radar station is:
  $\alpha_A = 155.2° - 221.0° + 180° = 114.2°$,
  because $(NR_1^R - KR) < 0$
  in the system of half-division horizon $\alpha_A = 114.2°$ p.b.
- the aspect for Gdynia_HMO radar station is:
  $\alpha_A = 110.8° - 221.0° + 180° = 069.8°$,
  because $(NR_2^R - KR) < 0$
  in the system of half-division horizon $\alpha_A = 069.8°$ p.b.
- the aspect for Gdańsk_HMO radar station is:
  $\alpha_A = 072.3° - 221.0° + 180° = 031.3°$,
  because $(NR_3^R - KR) < 0$
  in the system of half-division horizon $\alpha_A = 031.3°$ p.b.
- the aspect for GZ_RT radar station is:
  $\alpha_A = 050.7° - 221.0° + 180° = 009.7°$,
  because $(NR_4^R - KR) < 0$
  in the system of half-division horizon $\alpha_A = 009.7°$ p.b.

Then, in accordance with formula (12), adjustments are made to the measured distances for particular values of the aspect:

- $\alpha_A \in (000°, 090°)$

Since aspect $\alpha_A = 009.7°$ p.b. for GZ_RT station, in accordance with (7) the distance adjustment equals as follows:

$$d_p = \frac{a \cdot b}{\sqrt{b^2 + \left(a^2 - b^2\right) \cdot \sin^2 \alpha_A}} = \frac{199.50 - 29.50}{\sqrt{\left(29.50\right)^2 + \left[\left(199.50\right)^2 - \left(29.50\right)^2\right] \cdot \sin^2 009.7°}} = 132.41 \text{ [m]}$$

For Gdańsk_HMO station, where the aspect $\alpha_A = 031.3°$ p.b., in accordance with (7) the distance adjustment equals as follows:

$$d_p = \frac{a \cdot b}{\sqrt{b^2 + \left(a^2 - b^2\right) \cdot \sin^2 \alpha_A}} = \frac{199.50 - 29.50}{\sqrt{\left(29.50\right)^2 + \left[\left(199.50\right)^2 - \left(29.50\right)^2\right] \cdot \sin^2 031.3°}} = 55.17 \text{ [m]}$$

And for Gdynia_HMO station, where aspect $\alpha_A = 069.8°$ p.b., in accordance with (7) the distance adjustment equals as follows:

$$d_p = \frac{a \cdot b}{\sqrt{b^2 + \left(a^2 - b^2\right) \cdot \sin^2 \alpha_A}} = \frac{199.50 - 29.50}{\sqrt{\left(29.50\right)^2 + \left[\left(199.50\right)^2 - \left(29.50\right)^2\right] \cdot \sin^2 069.8°}} = 31.39 \text{ [m]}$$

- $\acute{a}_A \in (090°, \alpha_G)$

The aspect calculated for Hel_L station is contained within the sector of stern angles; therefore, a threshold value of the aspect angle should be specified in order to determine which formula, (8) or (11), is to be used:

$$\alpha_G = \beta_G + 090° = 081.59° + 090° = 171.59°$$

where:

$\beta_G = arc\ tg \frac{a}{b}$ – in accordance with (9)

Then, the value of measured distance adjustment will be calculated with the use of (11).
Since the aspect for Hel_L station is $\alpha_A = 114.2°$ p.b., the value of measured distance adjustment in accordance with (8) is:

$$d_P = \frac{b}{\sin(180° - \alpha_A)} = \frac{29.50}{\sin(180° - 114.2°)} = 32.34 \text{ [m]}$$

The final values of the adjusted radar distances measured by coastal radar stations of the VTS system are presented in Table 4.

Tab. 4. Measured distances from the coastal radar stations to the vessel

Coastal radar stations	Observations d_i^R [m]
Hel Lighthouse (Hel_L)	$d_1^R = 18885.00$
Gdynia, Harbour Master's Office (Gdynia_HMO)	$d_2^R = 26975.00$
Harbour Master's Office, Gdańsk North Harbour (Gdańsk_HMO)	$d_3^R = 16310.00$
Górki Zachodnie, Radar Tower (GZ_RT)	$d_4^R = 130655.00$

The adjusted distances (d_i^C) are different from the measured values, in extreme cases by 31.39 [m] (for Gdynia_HMO) and by 132.41 [m] (for GZ_RT).

The proposed model for adjusting radar distances measured by VTS system stations provides for a more effective way of using the observations made in the proposed methodology. With the use of the model, the adjustments to the observations may be made more accurately. Eventually, the position of m/s MADISON MAERSK was fixed with the use of adjustment calculus described in [Czaplewski, Świerczyński 2015]:

$$\left.\begin{array}{ll}\mathbf{V}=\mathbf{A}\hat{\mathbf{d}}_X+\mathbf{L} & \text{functional model}\\ \mathbf{C_X}=\sigma_0^2\mathbf{Q_X}=\sigma_0^2\mathbf{P}^{-1} & \text{original statistical model}\\ \hat{\mathbf{C}}_\mathbf{X}=\sigma_0^2\hat{\mathbf{Q}}_\mathbf{X}=\sigma_0^2\hat{\mathbf{P}}^{-1} & \text{equivalent statistical model}\\ \hat{\mathbf{P}}=\mathbf{T}\left(\overline{\mathbf{V}}\right)\mathbf{P} & \text{equivalent weights}\\ \Psi\left(\hat{\mathbf{d}}_X\right)=\mathbf{V}^T\mathbf{P}\mathbf{V}=\mathbf{V}^T\mathbf{T}\left(\overline{\mathbf{V}}\right)\mathbf{P}\mathbf{V}=\min & \text{adjustment criterion}\\ \mathbf{V}^T\mathbf{T}\left(\overline{\mathbf{V}}\right)\mathbf{P}\mathbf{V}=\hat{\mathbf{V}}^T\mathbf{T}\left(\hat{\overline{\mathbf{V}}}\right)\mathbf{P}\hat{\mathbf{V}} & \text{adjustment criterion}\end{array}\right\}\qquad(13)$$

where:

$\hat{\mathbf{P}}=\mathbf{T}(\overline{\mathbf{V}})\mathbf{P}$ – is the equivalent weight matrix,
$\hat{\mathbf{C}}_\mathbf{X}$ is the equivalent covariance matrix,
$\hat{\mathbf{Q}}_\mathbf{X}$ is the equivalent cofactor matrix,
$\mathbf{T}(\overline{\mathbf{V}})$ is the diagonal attenuation matrix.

In this paper, the authors have skipped the determination of adjustment calculus (13) as the principles of the surveying methods of robust M-estimation and the Danish damping function are broadly described in literature, see [Wiśniewski 2016; Czaplewski K., Wąż M. 2017] for instance, and were the subject of research described in [Czaplewski, Świerczyński 2015]. It has been assumed that the error was the same for the observations of all distances and amounted to $m_{d_i}=10$ [m] ($i=1,\ldots,4$) [UMG, 2016a, 2016b]. The adjusted distances significantly affected the free term vector (L):

- before the measured distances were adjusted:

$$\mathbf{L}=\begin{bmatrix}18927.09-18885.00\\27009.45-26975.00\\16371.59-16310.00\\13196.42-13065.00\end{bmatrix}=\begin{bmatrix}42.09\\34.45\\61.59\\131.42\end{bmatrix}_{[m]}$$

- and with the use of the method proposed in this paper:

$$\mathbf{L}=\begin{bmatrix}18927.09-18885.00-32.34\\27009.45-26975.00-31.39\\16371.59-16310.00-55.17\\13196.42-13065.00-132.41\end{bmatrix}=\begin{bmatrix}9.75\\3.06\\6.42\\-0.99\end{bmatrix}_{[m]}$$

Finally, this has an influence on the estimated position of the ship:

- before the measured distance was adjusted

$$\hat{\mathbf{X}}_P=\mathbf{X}_P^o+\hat{\mathbf{d}}_\mathbf{X}=\begin{bmatrix}6035084.50\\366158.25\end{bmatrix}+\begin{bmatrix}-29.48\\-82.58\end{bmatrix}=\begin{bmatrix}6035055.02\\366075.67\end{bmatrix}=\begin{bmatrix}\hat{X}_P\\\hat{Y}_P\end{bmatrix}$$

for which the mean error of the fix was $m_\mathrm{x}=53.16$ [m]

- with the use of the measured distance adjustment method:

$$\hat{\mathbf{X}}_P=\mathbf{X}_P^o+\hat{\mathbf{d}}_\mathbf{X}=\begin{bmatrix}6035084.50\\366158.25\end{bmatrix}+\begin{bmatrix}6.28\\-4.80\end{bmatrix}=\begin{bmatrix}6035090.78\\366153.45\end{bmatrix}=\begin{bmatrix}\hat{X}_P\\\hat{Y}_P\end{bmatrix}$$

for which the mean error of the position fix was $m_\mathrm{x}=4.21$ [m]

SUMMARY

The radar is a fundamental tool used in sea navigation due to its ability to provide visualisation of the surroundings, which is especially indispensable in high-traffic waters monitored by VTS systems. The development of technology has made it possible to obtain information about moving objects from several radar stations simultaneously. This gives an opportunity to improve the safety of navigation in congested waters. However, the use of "unprocessed" radar observations generates ambiguous results. Therefore, there is a need to create analytical solutions that can be applied easily in the process of automation to address and solve this problem of ambiguity.

The studies presented in the article have enabled the creation of an analytic method to improve the measured radar distances. Good maritime practice requires that radar observations be performed up to the closest edge of the echo under observation. In the case of large vessels, the position of the echo's edge is not the same as the position of the vessel, therefore, the measured distances should be adjusted in accordance with the assumptions of the method used to adjust them.

In order to be able to use the proposed method for correcting the measured distances in future sea navigation, further research should be carried out for other ship hull shapes and other configurations of coastal radar stations. Furthermore, an interesting problem is a possibility of correcting radar bearing acquired in VTS systems. Therefore, the authors undertake further research in this area, the effects of which will be the subject of subsequent scientific publications.

Adjustment of navigational observations coupled with the application of modern surveying methods of adjusting observations allows for a more accurate position fix, which is of crucial importance for waters where VTS systems are established. The ways in which surveying methods can be used for observation adjustments were described by the authors in [Czaplewski K., Świerczyński S. 2015; 2015b; Świerczyński S., Czaplewski K. 2012, 2013].

REFERENCES

1. Bole A., Dineley B., Wall A., 2005: *Radar and ARPA Manual (Second Edition)*, Elsevier Butterworth-Heinemann Linacre House, Oxford

2. Curry R., 2004 *Radar System Performance Modeling, Second Edition*, Artech House, Norwood

3. Chrzanowski J., Gucma M., Jankowski S., Juszkiewicz W., Montewka J., Przywarty M. 2010. *Urządzenia Radarowe w Praktyce Nawigacyjnej*, Szczecin

4. Czaplewski K., Goward D. 2016, Global Navigation Satellite Systems – Perspectives on Development and Threats to System Operation, TransNav, nr 2/ 2016 vol. 10, pp. 183–192, Gdynia

5. Czaplewski K., Świerczyński S. 2015a *M-Estimation as a Tool Supporting a Vessel Traffic Controller in The VTS System*, Polish Maritime Research no. 3(87) 2015 Vol. 22; pp. 3–13, Gdańsk

6. Czaplewski K., Świerczyński S. 2015b, *Determining the Accuracy of Ship Position as a function of Radar Bearing*. 15th IAIN World Congress in Prague, IEEE Full Papers, 978-1-4673-7634-1/15/2015, pp. 42–47, Praha

7. Czaplewski K., Wąż M. 2017 *Improvement in Accuracy of Determining a Vessel's Position with the Use of Neural Networks and Robust M-Estimation*. Polish Maritime Research 1 (93) 2017 Vol. 24; pp. 22–31, Gdańsk

8. Dziewicki, M., Specht, C. 2009, Position Accuracy Evaluation of the Modernized Polish DGPS. Polish Maritime Research, Volume 16, Issue 4, pp. 57-61, Gdańsk

9. Guze S., Smolarek L., Weintrit A. 2016. *The area-dynamic approach to the assessment of the risks of ship collision in the restricted water*. Scientific Journals of the Maritime University of Szczecin, no. 45 (117), pp. 88–93, Szczecin

10. Świerczyński 2017.*Zastosowanie metod odpornej M-estymacji do wyznaczania położenia echa radarowego jednostki pływającej w systemach nadzoru ruchu statków*. Ph.D. thesis. Polish Naval Academy, Gdynia

11. Świerczyński S., Czaplewski K. 2012. *Determination of the precise observed ship's position using the traffic control systems and applying the geodesic estimation methods. Scientific Journals Maritime University of Szczecin*, no. 32 (104). pp–167–172, Szczecin

12. Świerczyński S., Czaplewski K. 2013. *The Application of Methods of Robust M-Estimation in Establishing Ship Position in Marine Traffic Surveillance Systems Based on Radar Observations. Annual of Navigation*, no. 20. pp–127–147, Gdynia

13. UMG, 2016a. SCANTER 2001[i] *Setting to Work, For VTS & CS Applications (262001-ZW)*, Gdynia

14. UMG, 2016b. *Terma Compliance Matrix*, Gdynia

15. UMG, 2016c. Koncepcja zastosowania radarów Terma w projekcie KSBM-I / Concept of Terma radars usage in KSBM-I Project, Gdynia

16. Urbański, J. Morgaś, W., Specht, C. 2008, Perfecting the Maritime Navigation Information Services of the European Union, In 1st International Conference on Information Technology, pp. 1–4

17. Wei Y., Meng H., Liu Y., Wang X., 2010. *Extended Target Recognition in Cognitive Radar Networks*, Sensor 10/2010, pp–10181–10197, China

18. Wiśniewski Z. 2016. *Rachunek wyrównawczy w geodezji (z przykładami)*. Wydawnictwo UWM, Olsztyn

19. Yates R. C. 1974. *Curves and their properties*, National Council of Teachers of Mathematics

CONTACT WITH THE AUTHOR

Krzysztof Czaplewski
e-mail: krzysztof@czaplewski.pl
Akademia Morska w Gdyni
Morska 81–87, 81–225 Gdynia
Poland

Sambor Guze
e-mail: s.guze@wn.am.gdynia.pl
Akademia Morska w Gdyni
Morska 81–87, 81–225 Gdynia
Poland

Sławomir Świerczyński
e-mail: s.swierczynski@amw.gdynia.pl
Akademia Marynarki Wojennej
ul. inż. J. Śmidowicza 69, 81–127 Gdynia
Poland