

## Determination of the precise observed ship's position using the traffic control systems and applying the geodesic estimation methods

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### Abstract

In the sea areas with heavy traffic, there is a great danger of collision or grounding. In order to improve maritime safety at the gulf of Gdańsk in the middle of 90s, a vessel traffic services was installed. The VTS system operators can provide navigational assistance, if the parameters of the ships movement endanger the safety of navigation. For proper functioning of the system there is a network of coastal radars stations whose signal is used to create a radar picture of the navigational situation. In the vts determination of the ship position based on radar observations may lead to large errors. The IMO organization recommends to reject and repeat measurements containing large errors. For a moving ship perform a re-measurement in the same position is not possible. This paper presents possibility of compensation the coordinates of the vessel position based on radar observations using the of M-estimation methods.

### Introduction

Basing on the definition of navigation [1], describing it as a process of driving a vehicle safely in a certain physic geographical environment, one of the most principal tasks in navigation at sea is safe travelling of a vessel between the points of its departure and destination. Still developing techniques offer various potentialities in raising a level of safety at sea, especially essential for water areas of very intensive traffic. In such water areas, vessels' traffic safety is guarded with the Vessel Traffic Services systems. The research was carried out using a structure of the VTS Gulf of Gdańsk system, activated in the mid-90s of the twentieth century. In the last 10 years its significance has been growing, owing to the fact of putting into service the second container terminal at the Gulf of Gdańsk, the one in the Nowy Port of Gdańsk.

The coastal radar stations provide one of the main sources of information referring to ships movement and in VTS system. Basing on signals reflected off objects, a radar image is created, displaying a situation of an area within the radar antenna operation range. Thereby, it is possible to

trace traffic of vessels and to detect obstructions to navigation, having also the coast line displayed – even in severe meteorological conditions and at poor visibility.

Determination of vessel positions basing on radar observations carried out with a use of the vessels traffic control systems may be encumbered with gross errors. Upon navigation, due to movement of vessels, there is no chance to repeat taking measurements of the same positions of theirs. Therefore, to improve accuracy in fixing positions, one may apply the classic methods of estimation, also the contemporary M-estimation methods [2], which are used in geodesy. This paper is the first one in a series of articles presenting a potentiality of using the survey methods in determining vessel positions in VTS system. The classic method of the observation results' estimation in VTS systems is described below.

### Gulf of Gdańsk radar sub-system characteristics

Within its operation range area, the VTS system provides control over navigation and furnishes the

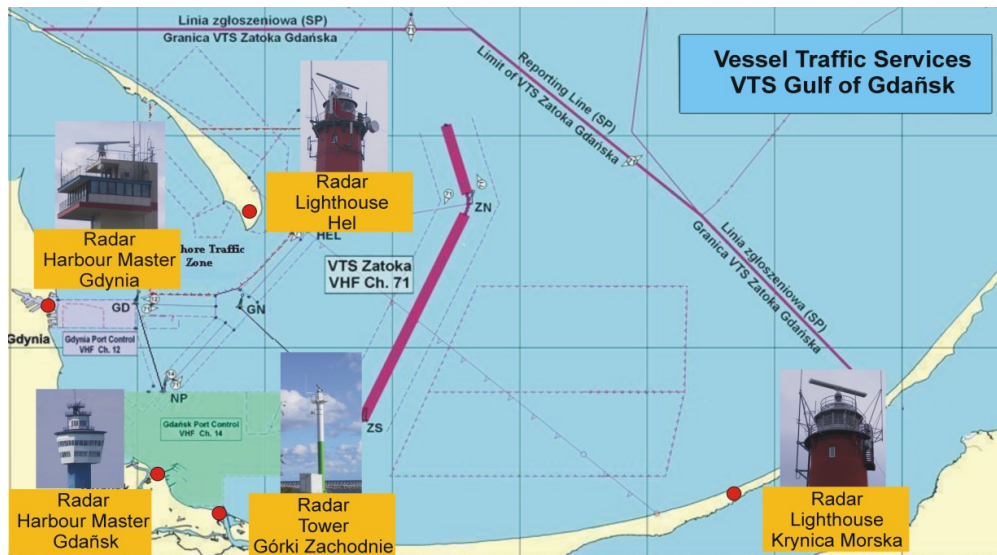


Fig. 1. Location of the coastal stations supporting the VTS Gulf of Gdańsk system [compiled by the authors]

system’s users with such service as information, navigational assistance and traffic organization instructions. To ensure its functionality, the VTS system has to be equipped with applicable facilities. The facilities providing information about vessels are coastal radar stations. They are elements of the radar sub-system, which is a basic unit in a system, monitoring ships’ traffic at the Gulf of Gdańsk, i.e. the VTS Gulf of Gdańsk system. The main task of the sub-system is supplying, in true time, information on ships’ traffic, received from the coastal radars. The location of 5 coastal stations supporting the VTS system is presented in figure 1.

Parameters of locations of the coastal radar stations are presented in the table 1.

Table 1. Coastal radar stations in VTS Gulf of Gdańsk system

Item	Radar Station	Coordinates	Height above sea level	Range
1	Hel Lighthouse	$\varphi = 54^{\circ} 35.9' N$ $\lambda = 18^{\circ} 48.7' E$	41 m	20 km
2	Gdynia Harbour Master	$\varphi = 54^{\circ} 32.0' N$ $\lambda = 18^{\circ} 32.8' E$	31.4 m	30 km
3	Gdańsk North Port Harbour Master	$\varphi = 54^{\circ} 23.9' N$ $\lambda = 18^{\circ} 41.8' E$	67.7 m	30 km
4	Górk Zachodnie Radar Tower	$\varphi = 54^{\circ} 22.2' N$ $\lambda = 18^{\circ} 46.7' E$	17.5 m	30 km
5	Krynica Morska Lighthouse	$\varphi = 54^{\circ} 23.1' N$ $\lambda = 19^{\circ} 27.1' E$	28.4 m	30 km

The radars’ ranges cover the whole VTS Gulf of Gdańsk system’s operation range area; moreover, some areas are covered by two, even three radars’ operation ranges. It is of peculiar importance, especially in case echoes sent back off the vessels is weak or a failure of any of the devices occurs. The data received from the coastal radar stations, after

initial processing, are transferred to the Centre of Safety of Navigation, where after final processing they are displayed at the VTS System Centre operators’ work stands and at the stations at Gdynia Harbour Master, Gdańsk – North Port Master and Krynica Morska Port Master offices.

Apart from the standard equipment, all the radars in the VTS Gulf of Gdańska System are fitted with additional computers, defined as the RDP – Radar Data Processors. They are applied to convert the transmitter’s analog signal to its digital form with a use of the Video Processor Card, also to transfer such information to VTS Centre by a microwave links or submarine fibre-optic cable. The above is presented in figure 2.

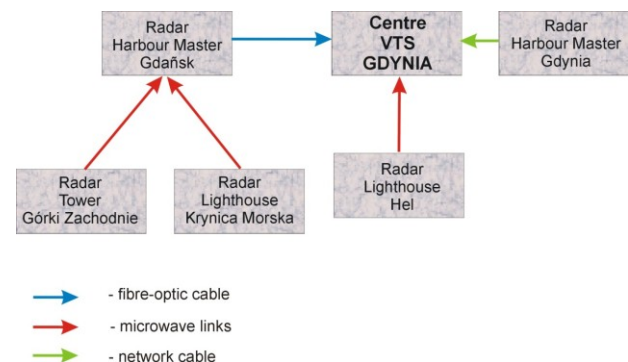


Fig. 2. The method of transferring information about objects from the radar stations to the VTS Centre [worked out by the authors]

### Classic method of the observation results estimation

Radar is a piece of equipment for detecting any objects which appear within the VTS operation range area – not only the large vessels but also the small ones as fish cutters and sport boats. In case

their effective echo reflection area is small, then such watercrafts are equipped with radar reflectors. The IALA requirements specify in what conditions and state of sea the sailing vessels are detectable for the radar systems. For proper determination of ships' positions using the VTS systems, a high accuracy of radar is a requisite. In case the angular differentiability is applied, the radar is to be capable to detect and to differentiate 2 steel ships 20 m long, positioned azimuthally one to another, at a distance of 75 m, at rainfall not exceeding 25 mm/h [3]. Moreover, it has to determine a distance from the object with  $\pm 30$  m of accuracy. The radar images' displays are error biased, but it may not disqualify radar navigation as a source of information about vessel positions.

One of the methods of determining vessel positions at sea is measuring distances from the coastal stations. Such measuring structure is presented in figure 3. Survey of distances to the vessels can be taken at five coastal stations, located within the VTS System range.

The distances, measured at the coastal stations of the known geographic coordinates, may be helpful in determination of the estimated (corrected) position of the ship. The applied method is to enable correction of the vessel's position coordinates determined by a watchman on the radar observation basis.

The estimation problem described in this paper consists in determining a position of the vessel observed at sea (at the water area covered by the VTS system range) basing on radar observations and positions fixed by the watchman on the ship. The distances measured at the radar coastal stations enable to determine the linear corrections' equation system:

$$\begin{cases} d_1^p = \sqrt{(X_{S1} - X_Z)^2 + (Y_{S1} - Y_Z)^2} \\ d_2^p = \sqrt{(X_{S2} - X_Z)^2 + (Y_{S2} - Y_Z)^2} \\ d_3^p = \sqrt{(X_{S3} - X_Z)^2 + (Y_{S3} - Y_Z)^2} \\ d_4^p = \sqrt{(X_{S4} - X_Z)^2 + (Y_{S4} - Y_Z)^2} \\ d_5^p = \sqrt{(X_{S5} - X_Z)^2 + (Y_{S5} - Y_Z)^2} \end{cases} \quad (1)$$

Coordinates of the ship's position fixed by the watchman are assumed to be the expected vessel coordinates:

$$\mathbf{Z}^0 = \begin{bmatrix} X_Z^0 \\ Y_Z^0 \end{bmatrix} \quad (2)$$

The linear corrections system takes the following form:

$$\begin{cases} v_1 = \frac{\partial d_1}{\partial X_Z} \hat{d}_{X_Z} + \frac{\partial d_1}{\partial Y_Z} \hat{d}_{Y_Z} + d_1^0 - d_1^{Obs} \\ v_2 = \frac{\partial d_2}{\partial X_Z} \hat{d}_{X_Z} + \frac{\partial d_2}{\partial Y_Z} \hat{d}_{Y_Z} + d_2^0 - d_2^{Obs} \\ v_3 = \frac{\partial d_3}{\partial X_Z} \hat{d}_{X_Z} + \frac{\partial d_3}{\partial Y_Z} \hat{d}_{Y_Z} + d_3^0 - d_3^{Obs} \\ v_4 = \frac{\partial d_4}{\partial X_Z} \hat{d}_{X_Z} + \frac{\partial d_4}{\partial Y_Z} \hat{d}_{Y_Z} + d_4^0 - d_4^{Obs} \\ v_5 = \frac{\partial d_5}{\partial X_Z} \hat{d}_{X_Z} + \frac{\partial d_5}{\partial Y_Z} \hat{d}_{Y_Z} + d_5^0 - d_5^{Obs} \end{cases} \quad (3)$$

where:

$$d_i^0 = \sqrt{(X_{Si}^0 - X_Z^0)^2 + (Y_{Si}^0 - Y_Z^0)^2} \quad \text{for } i = 1, \dots, 5$$

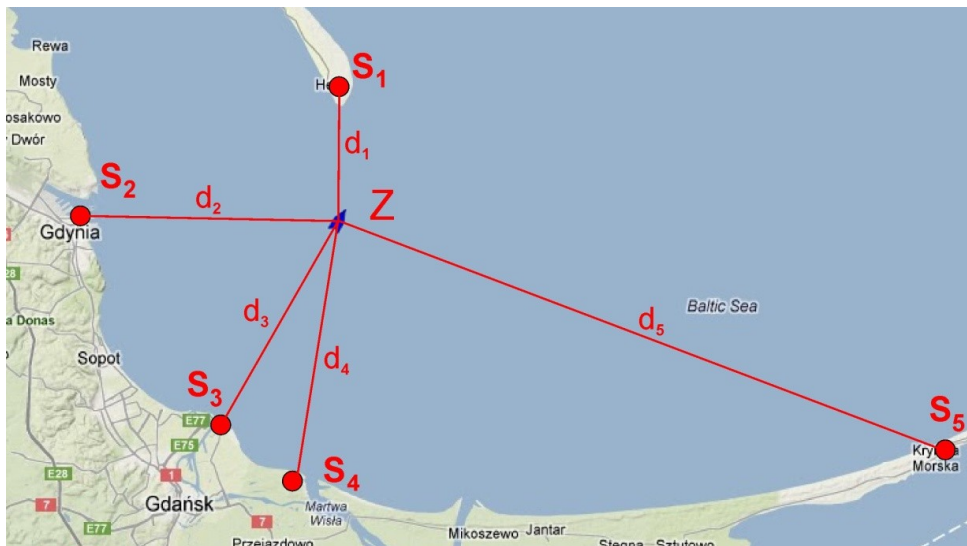


Fig. 3. Measurement structure [worked out by the authors]

Assuming that:

$$\mathbf{V} = \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \\ v_5 \end{bmatrix} - \text{corrections vector;}$$

$$\mathbf{A} = \begin{bmatrix} \frac{\partial d_1}{\partial X_Z} & \frac{\partial d_1}{\partial Y_Z} \\ \frac{\partial d_2}{\partial X_Z} & \frac{\partial d_2}{\partial Y_Z} \\ \frac{\partial d_3}{\partial X_Z} & \frac{\partial d_3}{\partial Y_Z} \\ \frac{\partial d_4}{\partial X_Z} & \frac{\partial d_4}{\partial Y_Z} \\ \frac{\partial d_5}{\partial X_Z} & \frac{\partial d_5}{\partial Y_Z} \end{bmatrix} - \text{matrix of coefficients with the unknowns;}$$

$$\hat{\mathbf{d}}_X = \begin{bmatrix} \hat{d}_{X_Z} \\ \hat{d}_{Y_Z} \end{bmatrix} - \text{the searched vector of increments to the expected coordinates;}$$

$$\mathbf{L} = \begin{bmatrix} d_1^0 - d_1^{Obs} \\ d_2^0 - d_2^{Obs} \\ d_3^0 - d_3^{Obs} \\ d_4^0 - d_4^{Obs} \\ d_5^0 - d_5^{Obs} \end{bmatrix} - \text{absolute terms matrix;}$$

Then the matrix system of corrections' equations assumes the form as follows:

$$\mathbf{V} = \mathbf{A} \cdot \hat{\mathbf{d}}_X + \mathbf{L} \quad (4)$$

where:

$$\hat{\mathbf{d}}_X = -(\mathbf{A}^T \mathbf{P} \mathbf{A})^{-1} \mathbf{A}^T \mathbf{P} \mathbf{L} \quad (5)$$

and

$$\mathbf{P} = \begin{bmatrix} \frac{1}{m_1^2} & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{m_2^2} & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{m_3^2} & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{m_4^2} & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{m_5^2} \end{bmatrix} - \text{is the weights matrix of the observations performed;}$$

$m_i$  – mean error of the  $i$ -th observation for  $i = 1, \dots, 5$ .

Thus, it may obtain the estimators of the estimated coordinates of the vessel at sea, applying the following equation:

$$\hat{\mathbf{Z}}_i = \mathbf{Z}^0 + \hat{\mathbf{d}}_{XY} = \begin{bmatrix} X_Z^0 \\ Y_Z^0 \end{bmatrix} + \begin{bmatrix} \hat{d}_{X_Z} \\ \hat{d}_{Y_Z} \end{bmatrix} = \begin{bmatrix} \hat{X}_Z \\ \hat{Y}_Z \end{bmatrix} \quad (6)$$

where:

$$\begin{bmatrix} \hat{X}_Z \\ \hat{Y}_Z \end{bmatrix} - \text{the estimated coordinates of the vessel at sea in the } X, Y \text{ system.}$$

The statistic model of the estimation problem takes the form:

$$\hat{\mathbf{C}}_{\hat{X}} = m_o^2 (\mathbf{A}^T \mathbf{P} \mathbf{A})^{-1} = \begin{bmatrix} m_{\hat{X}_Z}^2 & \hat{\text{cov}}(\hat{X}_Z, \hat{Y}_Z) \\ \hat{\text{cov}}(\hat{Y}_Z, \hat{X}_Z) & m_{\hat{Y}_Z}^2 \end{bmatrix} \quad (7)$$

where:

$$m_o^2 = \frac{V^T P V}{n - r} - \text{estimator of variance coefficient;}$$

$n$  – number of the observations;

$r$  – number of the unknowns.

The mean error of fixing the observed position is determined using the dependence:

$$M_{po} = \sqrt{m_{\hat{X}_Z}^2 + m_{\hat{Y}_Z}^2} \quad (8)$$

Assuming that the objective function is consistent with the objective function in the least squares method, it can finally note the estimation problem for the discussed research subject:

$$\begin{cases} \mathbf{V} = \mathbf{A} \cdot \hat{\mathbf{d}}_X + \mathbf{L} \\ \hat{\mathbf{C}}_{\hat{X}} = m_o^2 (\mathbf{A}^T \mathbf{P} \mathbf{A})^{-1} \\ \psi(\mathbf{V}^T \mathbf{P} \mathbf{V}) = \min \end{cases} \quad (9)$$

### Proving test

Following up the theoretic assumptions described in this paper, 5 observations were performed from the coastal radar stations to the warship of "Mewa" class. The performed observations are the distances; the values of these distances are presented in table 2.

Table 2. Values of the observations measured from the coastal radar stations

Item	Coastal station	Observation performed [m]
1	Hel Lighthouse	$d_1^{Obs} = 7842.00$
2	Gdynia Harbour Master	$d_2^{Obs} = 16\ 980.00$
3	Gdańsk North Port Harbour Master	$d_3^{Obs} = 16\ 501.00$
4	Górki Zachodnie Radar Tower	$d_4^{Obs} = 18\ 113.00$
5	Krynica Morska Lighthouse	$d_5^{Obs} = 44\ 718.00$

According to the information received from the watchman on the vessel, in a time of performing the observation, the vessel's position was following:

$$\varphi = 054^{\circ} 31.9' \text{ N}$$

$$\lambda = 018^{\circ} 48.6' \text{ E}$$

It was decided to simplify the calculation process, the further calculations have to be carried out applying the rectangular coordinate system instead of the geographic coordinate one. Therefore, after converting to the  $X, Y$  system, the coordinates of the vessel assume the following values:

$$X = 6044974.43$$

$$Y = 358258.43$$

The coordinates of the coastal stations are presented in table 3.

Table 3. Coordinates of the coastal radar stations

Item	Coastal station	Rectangular coordinates ( $X, Y$ )
1	Hel Lighthouse	$X = 6052469.34$ $Y = 358694.38$
2	Gdynia Harbour Master	$X = 6045676.69$ $Y = 341307.40$
3	Gdańsk North Port Harbour Master	$X = 6030435.11$ $Y = 350472.86$
4	Górki Zachodnie Radar Tower	$X = 6027021.91$ $Y = 355714.18$
5	Krynica Morska Lighthouse	$X = 6027542.89$ $Y = 399407.33$

Let's assume that the coordinates of vessel positions at sea, fixed by the watchman, are the expected vessel's coordinates at sea. For such an observational system it can assume the system of corrections' equations (3), for which:

$$d_1^0 = \sqrt{(X_{S1}^0 - X_Z^0)^2 + (Y_{S1}^0 - Y_Z^0)^2} = 7507.58 [\text{m}]$$

$$d_2^0 = \sqrt{(X_{S2}^0 - X_Z^0)^2 + (Y_{S2}^0 - Y_Z^0)^2} = 16965.57 [\text{m}]$$

$$d_3^0 = \sqrt{(X_{S3}^0 - X_Z^0)^2 + (Y_{S3}^0 - Y_Z^0)^2} = 1649263 [\text{m}]$$

$$d_4^0 = \sqrt{(X_{S4}^0 - X_Z^0)^2 + (Y_{S4}^0 - Y_Z^0)^2} = 18131.91 [\text{m}]$$

$$d_5^0 = \sqrt{(X_{S5}^0 - X_Z^0)^2 + (Y_{S5}^0 - Y_Z^0)^2} = 4468882 [\text{m}]$$

With the above data substituted, the following elements of the matrix corrections' equations system are received (4):

$$\mathbf{A} = \begin{bmatrix} -1.00 & -0.06 \\ -0.04 & 1.00 \\ 0.88 & 0.47 \\ 0.99 & 0.14 \\ 0.39 & -0.92 \end{bmatrix}$$

$$\mathbf{L} = \begin{bmatrix} 7507.58 - 7482 \\ 16965.57 - 16980 \\ 1649263 - 16501 \\ 18131.91 - 18113 \\ 4468882 - 44718 \end{bmatrix} = \begin{bmatrix} 25.58 \\ -14.43 \\ -8.37 \\ 19.81 \\ -29.18 \end{bmatrix} [\text{m}]$$

Assuming that the mean error of the observation is  $m_i = 100$  [m], for  $i = 1, \dots, 5$  and also assuming that the performed observations are independent, the observations' weights matrix takes the form:

$$\mathbf{P} = \begin{bmatrix} 0.0001 & 0 & 0 & 0 & 0 \\ 0 & 0.0001 & 0 & 0 & 0 \\ 0 & 0 & 0.0001 & 0 & 0 \\ 0 & 0 & 0 & 0.0001 & 0 \\ 0 & 0 & 0 & 0 & 0.0001 \end{bmatrix} [\text{m}]$$

Vector of increments to the expected coordinates is:

$$\hat{\mathbf{d}}_X = -(\mathbf{A}^T \mathbf{P} \mathbf{A})^{-1} \mathbf{A}^T \mathbf{P} \mathbf{L} = \begin{bmatrix} \hat{d}_{X_Z} \\ \hat{d}_{Y_Z} \end{bmatrix} = \begin{bmatrix} 8.99 \\ -5.44 \end{bmatrix}$$

Whereas the corrections vector's value is:

$$\mathbf{V} = \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \\ v_5 \end{bmatrix} = \begin{bmatrix} 16.92 \\ -20.33 \\ -3.05 \\ 27.04 \\ -20.58 \end{bmatrix}$$

Thus, the estimator of the observed vessel's position at sea, applying the observations from the coastal stations is:

$$\hat{\mathbf{Z}} = \begin{bmatrix} \hat{X}_Z \\ \hat{Y}_Z \end{bmatrix} = \begin{bmatrix} X_Z^0 \\ Y_Z^0 \end{bmatrix} + \begin{bmatrix} \hat{d}_{X_Z} \\ \hat{d}_{Y_Z} \end{bmatrix} = \begin{bmatrix} 6044974.43 \\ 358258.43 \end{bmatrix} + \begin{bmatrix} 8.99 \\ -5.54 \end{bmatrix} = \begin{bmatrix} 6044983.42 \\ 358252.89 \end{bmatrix}$$

And the performed observations estimators are respectively:

$$\begin{bmatrix} \hat{d}_1 \\ \hat{d}_2 \\ \hat{d}_3 \\ \hat{d}_4 \\ \hat{d}_5 \end{bmatrix} = \begin{bmatrix} 7498.92 \\ 16959.67 \\ 16497.95 \\ 18140.04 \\ 44697.42 \end{bmatrix}$$

The variance coefficient's estimator is:

$$m_o^2 = \frac{V^T P V}{n-r} = 0.249$$

Evaluating accuracy of the carried out determinations it can calculate the covariance matrix estimator for the performed observations:

$$\hat{C}_{\hat{X}} = \begin{bmatrix} m_{\hat{X}_Z}^2 & \hat{\text{cov}}(\hat{X}_Z, \hat{Y}_Z) \\ \hat{\text{cov}}(\hat{Y}_Z, \hat{X}_Z) & m_{\hat{Y}_Z}^2 \end{bmatrix} = \begin{bmatrix} 215.205 & -21.863 \\ -21.863 & 299.138 \end{bmatrix}$$

Basing on matrix  $\hat{C}_{\hat{X}}$  the mean error of the determined ship's coordinates is respectively as follows:

$$m_{\hat{X}_Z} = \sqrt{215.205} = 14.67 \text{ [m]}$$

$$m_{\hat{Y}_Z} = \sqrt{299.138} = 17.30 \text{ [m]}$$

Whereas the mean error of determining the position is:

$$M_Z = \sqrt{m_{\hat{X}_Z}^2 + m_{\hat{Y}_Z}^2} = 22.68 \text{ [m]}$$

## Conclusions

Radar is one of the basic facilities applied in on-shore and off-shore navigation; upon its operation, visualization of the surrounding space is possible. The signal sent from radar comes back to the equipment after being reflected off an object. After processing it creates radar image display of the specific space. The image accuracy is affected by many distortions, characteristic for specificity of carrying out radar observations and causing, that the image differs from the real picture. The contemporary technology enabled to reduce errors which encumber radar observations, what allowed finding new concepts as regards application of radar for navigation, especially for fixing vessel positions.

The authors have not found any solutions that use information received from all the VTS coastal stations simultaneously to determine vessel's positions at sea and to apply the methods of estimation, used in geodesy. The obtained-till-now results of the research prove that such line in automation of positions determinations in coastal navigation can significantly support VTS systems operators in the process of verification of the observed position of ships, transferred by watchmen.

The mean error determined in this paper may not be a basis for evaluation of quality of the effected position determinations. The mean error of the position may only be applied as a comparative parameter of two irrespectively fixed positions. To denominate a quality of the determinations described in the paper, it would be necessary to define the level of determinations' confidence and the confidence ellipse elements (called ellipse of error). It is not presented in this paper as it was not a subject of deliberations included in this paper.

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