EVALUATION OF ACCURACY THE POSITION OF THE VESSEL DESIGNATED STEREOSCOPIC CAMERAS SYSTEM

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ABSTRACT

In this article a research to assess the applicability of CCD cameras in a stereoscopic system for determining the position of the vessel in the coastal zone has been presented. As a basic criteria for this assessment was adopted for determining the accuracy of the position coordinates of the vessel dimensioned of the root mean square error value.

Construction of stereoscopic system measuring the distance from the vessel, method of determining distances to navigation aids identified in the images recorded two cameras and brief analysis of measurement errors in vision system have been presented in the first part of the article.

A scientific experiment that involving the computation of the accuracy diagram (root mean square error distribution) position of the vessel assigned to the stereoscopic system of the Gulf of Gdansk have been presented in the second part of the article. In the description that characterized method of determining the accuracy diagrams of the items referred to two or more measurements of the distance from the ship to the selected navigation aids. The results of the experiment was carried out in the accuracy diagrams for the position determined stereoscopic system against the Gulf of Gdansk navigation aids system.

In the final section an analysis of the results obtained in the experiment, taking into account the International Maritime Organization positioning accuracy requirements of the vessel in coastal shipping and generalized conclusions have been presented.

1. INTRODUCTION

During the process of maritime navigation conduction, navigator identifies navigation marks being within his sight visually. He measures bearings and distances in respect to the marks. Based on the measurement results, with analytical or graphical methods applied, he determines coordinates of the vessel position. In general, one may say that he acts at the time as measuring equipment and devices processing visual signals together with information about the navigation marks coming from nautical publications, turning them into coordinates of the position.

Trials to automate activities of navigators have not been undertaken so far, however there are high-resolution visual cameras supporting the identification and measurements existent already, there also electronic navigation maps in digital form containing information about the navigation marks or high processor capacity computers capable of processing visual pictures in real time.

But, this new situation implicates interesting questions in respect to scientific point of view.

Is it possible to elaborate digital methods of navigation marks' automatic identification based on a sequence of coast pictures and electronic navigation map?

What accuracy of the vessel position coordinates determination can be obtained based on measurements of distances and bearings to the navigation marks made with high-resolution CCD cameras?

Answers to these questions may justify purposefulness of conduction of farther research related to optical systems' application in the process of automation of maritime coastal navigation performance.

An attempt to answer the second question has been undertaken in this elaboration.

Accuracy of the position determination based on distance measurements made with two Rolleiflex and Sony cameras have been evaluated. It has been assumed that the cameras are situated in normal (canonical) layout. One of the cameras is mounted on a bow, and the other – on a stern, and the distance between them is 100 and 200 metres (Fig. 1).

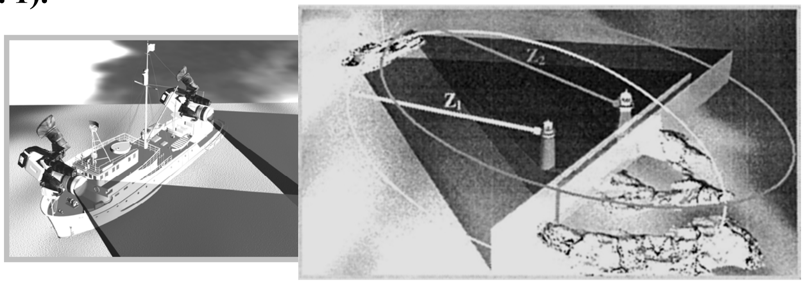


Fig. 1. Determining the position of the vessel assigned to the stereoscopic system.

2. EXPERIMENTAL PROCEDURES

2.1. Accuracy off the distance measurement with a use of stereoscopic System

Accuracy of the distance measurement with two cameras applied may be characterized with two parameters: resolution and measurement mean error. Their values mainly depend on: locations of the cameras against each other, possibility to focus optical systems and *r* pixel sizes on their CCD matrices. Length of *b* base , determining a distance between centres of the CCD matrices' coordinate systems, is a basic parameter characterizing locations of the cameras and having impact on accuracy of the measurement. Focusing specifies "concentration of force" of light rays. The shorter is the focal length, the stronger are the rays refracted by the lens, that is – the rays are more focused resulting in bigger distance of the picture and lower accuracy of the measurement. Sizes of single pixels in contemporary CCD matrices are of 3-14 micrometers. Smaller size of the pixel ensures better imaging of the picture details and therefore they result in higher accuracy of the measurement accuracy.

Fig. 2 presents the concept of surveying distances with a use of cameras in canonical system.

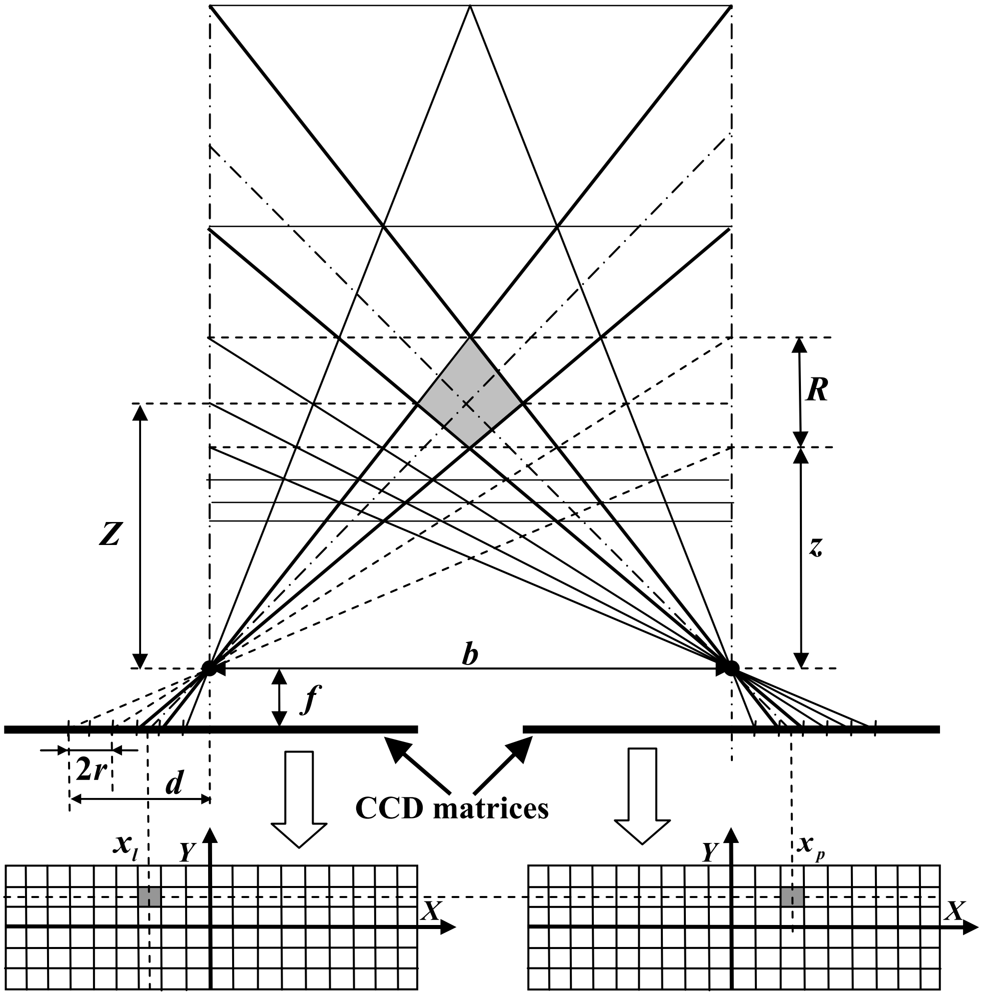


Fig. 2. Idea of the measurement with distances of the cameras in canonical layout.

Formula for resolution of R distance measurement can be easily derived by applying similarity of right-angled triangles which hypotenuses determine projection of rays. Dependences describing this conversion have the following form:

$$\begin{cases} \dfrac{z+R}{b} = \dfrac{f}{d-2\cdot r} \\ \dfrac{z}{b} = \dfrac{f}{d} \end{cases} \Rightarrow \quad R = \frac{2\cdot r\cdot z^2}{b\cdot f - 2\cdot r\cdot z}. \tag{1}$$

Mean error of the distance measurement can be determined with a use of C. F. Gauss law regarding transfer of mean errors.

Having mean errors of b, f, p independent variables function of a single measurement result known:

$$Z = \frac{b\cdot f}{p}, \tag{2}$$

where: $p = x_l - x_p$, it is easy to formulate an equation of the mean error:

$$m_z = \left[\left(\frac{\partial Z}{\partial b}\cdot m_b\right)^2 + \left(\frac{\partial Z}{\partial f}\cdot m_f\right)^2 + \left(\frac{\partial Z}{\partial p}\cdot m_p\right)^2\right]^{1/2}, \tag{3}$$

which – after determining partial derivatives – shall get a form of:

$$m_z = \left[\left(\frac{f}{p}\cdot m_b\right)^2 + \left(\frac{b}{p}\cdot m_f\right)^2 + \left(-\frac{b\cdot f}{p^2}\cdot m_p\right)^2\right]^{1/2}. \tag{4}$$

Assuming that $p = \frac{bf}{Z}$, we shall obtain:

$$m_z = \left[\left(\frac{Z}{b}\cdot m_b\right)^2 + \left(\frac{Z}{f}\cdot m_f\right)^2 + \left(-\frac{Z^2}{b\cdot f}\cdot m_p\right)^2\right]^{1/2}. \tag{5}$$

where:

m_b **- mean error of the base length measurement,**

m_f **- mean error of the focal length measurement,**

m_p **- mean error of the** p **disparity measurement.**

2.2. Accuracy of determining vessel position coordinates based on distance measurement

Mean error of position from two distances Z1 and Z2 can be expressed with the following formula 00:

$$m_{poz} = \frac{\left(m_{Z_1}^2 + m_{Z_2}^2\right)^{1/2}}{\sin\theta}. \tag{6}$$

Determination of the position from three or more distances requires application of a measurement adjustment method in order to determine optimal position of the vessel. A classic adjustment problem can be formulated in the following way 0:

$$\left.\begin{array}{l} \mathrm{V} = \mathrm{A}\hat{\mathrm{d}}_{\mathrm{x}} + \mathrm{L} - \text{functional model} \\ \mathrm{C}_{\mathrm{x}} = \delta_0^2\mathrm{P}^{-1} - \text{statistical model} \\ \mathrm{V}^{\mathrm{T}}\mathrm{PV} = \min - \text{adjustment criterion} \end{array}\right\}, \tag{7}$$

where:

A **– matrix of coefficients for unknown parameters of the observation equations,**

$\hat{\mathrm{d}}_{\mathrm{x}}$ **– true vector of parameters to be estimated,**

L **– matrix of the free term,**

δ_0^2 **– variance coefficient,**

P **– weights matrix.**

The following dependence is applied to calculate mean error of the adjusted vessel position:

$$m_{poz} = \left(m_{\hat{X}_S}^2 + m_{\hat{Y}_S}^2\right)^{1/2}, \tag{8}$$

where: $m_{\hat{X}_S}$, $m_{\hat{Y}_S}$ stand for mean errors of adjusted coordinates $(\hat{X}_s, \hat{Y}_s)$ of the vessel position. The values $m_{\hat{X}_S}$, $m_{\hat{Y}_S}$ are to be obtained by determining estimator of covariance matrix:

$$\hat{\mathrm{C}}_{\hat{\mathrm{X}}} = \hat{\delta}_0^2\left(\mathrm{A}^{\mathrm{T}}\mathrm{PA}\right)^{-1} = \begin{bmatrix} m_{\hat{X}_S} & \hat{\mathrm{cov}}(\hat{X}_s, \hat{Y}_s) \\ \hat{\mathrm{cov}}(\hat{Y}_s, \hat{X}_s) & m_{\hat{Y}_S} \end{bmatrix}, \tag{9}$$

where:

$$\mathrm{A}=\begin{bmatrix}-\cos NR_1 & -\sin NR_1\\ -\cos NR_2 & -\sin NR_2\\ \vdots & \vdots\\ -\cos NR_n & -\sin NR_n\end{bmatrix},\ \mathrm{P}=\begin{bmatrix}\frac{1}{m_{Z_1}^2} & 0 & \cdots & 0\\ 0 & \frac{1}{m_{Z_2}^2} & \cdots & 0\\ \cdots & \cdots & \cdots & \cdots\\ 0 & 0 & \cdots & \frac{1}{m_{Z_n}^2}\end{bmatrix},\ \hat{\delta}_0^2=\frac{V^{\mathrm{T}}\mathrm{P}V}{n-k}\ ,$$

$\hat{\delta}_0^2$ – variance coefficient estimator ($\hat{\delta}_0^2=1$ has been taken for the calculations, assuming that values of the distance measurements' mean errors have been selected correctly, thus weights matrix P elements - determined based on them),
n – number of observation equations,
k – amount of the unknowns being calculated,
NR – approximate bearing from the vessel position (before adjustment) onto navigation mark of known coordinates (to which the distance has been set).

2.3. Method of determining accuracy areas

Navigator planning the vessel itinerary usually faces a problem of determining position accuracy not in selected points but on the entire route of the planned navigation. Therefore, it is important to determine an area on which accuracy of the position shall be higher than the set one. Depending on a method of the position determination, the accuracy areas are determined with various methods, however – based on the same assumptions, i.e. determination of geometric places of the points representing the same position accuracy. For stereoscopic system, positions determined from two or more distances make a basis for determination of the accuracy areas (in geodesy, this method is called linear resection).

Fig. 3 presents the authors' algorithm applied for construction of image of accuracy areas in a form of the matrix, with values of the mean errors in the position coordinates, fixed applying the stereoscopic system. A value of the mean error for a singular point in the matrix is computed basing on theoretical results of surveying distances between that point and the stable (fixed) navigational marks located within the sea area under research.

The additional input parameters for calculations are the following:

geographical coordinates (φ_0, $_0$) of the left bottom corner and ($\varphi_{\max}$, $_{\max}$) the right top corner of the matrix covering the water area under research;

meridional size and parallel size φ of the matrix mesh;

limiting distance (radius) r_p of searching the navigational marks;

mode of computation, for l_z= false position determined from two distances, for l_z= true position fixed from two and more distances;

length of base b and the focal f;

values of the mean errors m_b in measurement of base length, m_f measurement of the focal length, m_p determination of disparity;

information about navigational marks, e.g.: a type of marks, coordination of the position read from electronic navigational chart covering the sea area under research.

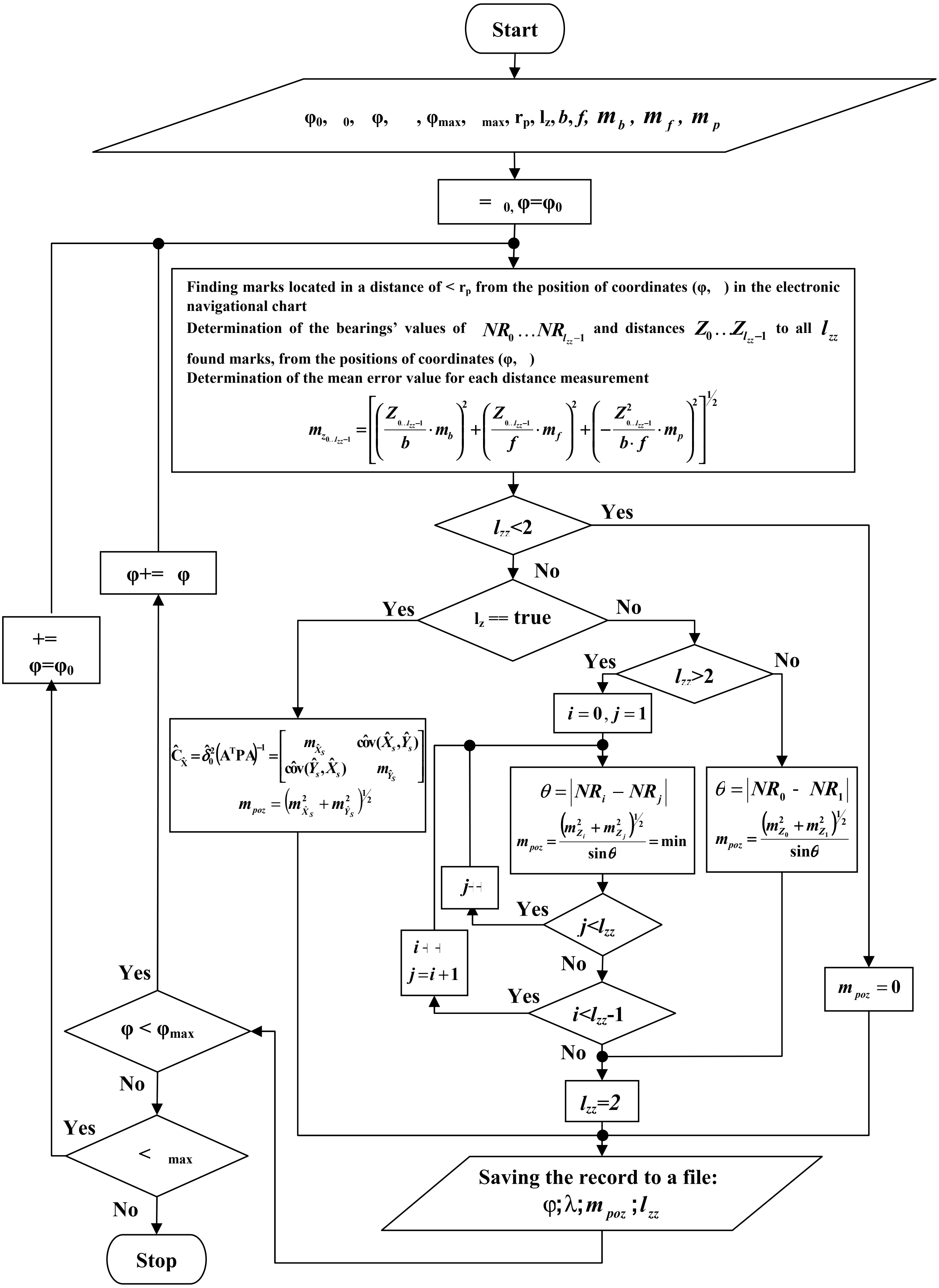

Start
φ0, 0, φ, , φmax, max, rp, lz, b, f, m_b, m_f, m_p
= 0, φ=φ0
Finding marks located in a distance of < rp from the position of coordinates (φ,) in the electronic navigational chart
Determination of the bearings' values of $NR_0 \ldots NR_{l_{zz}-1}$ and distances $Z_0 \ldots Z_{l_{zz}-1}$ to all l_{zz} found marks, from the positions of coordinates (φ,)
Determination of the mean error value for each distance measurement
$m_{Z_{0..l_{zz}-1}} = \left[\left(\frac{Z_{0..l_{zz}-1}}{b}\cdot m_b\right)^2 + \left(\frac{Z_{0..l_{zz}-1}}{f}\cdot m_f\right)^2 + \left(-\frac{Z^2_{0..l_{zz}-1}}{b\cdot f}\cdot m_p\right)^2\right]^{1/2}$
l_{zz}<2
Yes
No
lz == true
Yes
No
l_{zz}>2
Yes
No
$i=0, j=1$
$\hat{C}_{\hat{X}} = \hat{\delta}_0^2\left(A^T P A\right)^{-1} = \begin{bmatrix} m_{\hat{X}_S} & \hat{cov}(\hat{X}_S,\hat{Y}_S) \\ \hat{cov}(\hat{Y}_S,\hat{X}_S) & m_{\hat{Y}_S}\end{bmatrix}$
$m_{poz} = \left(m^2_{\hat{X}_S} + m^2_{\hat{Y}_S}\right)^{1/2}$
$\theta = \left|NR_i - NR_j\right|$
$m_{poz} = \frac{\left(m^2_{Z_i} + m^2_{Z_j}\right)^{1/2}}{\sin\theta} = \min$
$\theta = \left|NR_0 - NR_1\right|$
$m_{poz} = \frac{\left(m^2_{Z_0} + m^2_{Z_1}\right)^{1/2}}{\sin\theta}$
j++
Yes
j<l_{zz}
No
i++
$j=i+1$
Yes
i<l_{zz}-1
No
$m_{poz} = 0$
l_{zz}=2
φ+= φ
+=
φ=φ0
Yes
φ < φmax
No
Yes
< max
No
Stop
Saving the record to a file:
φ;λ;m_{poz};l_{zz}

Fig. 3 Algorithm of constructing the matrix with the mean errors in positions fixed applying the stereoscopic system.

At the algorithm output, the file with records containing the following areas is obtainable:

point's geographical coordinates (φ,) of the matrix;

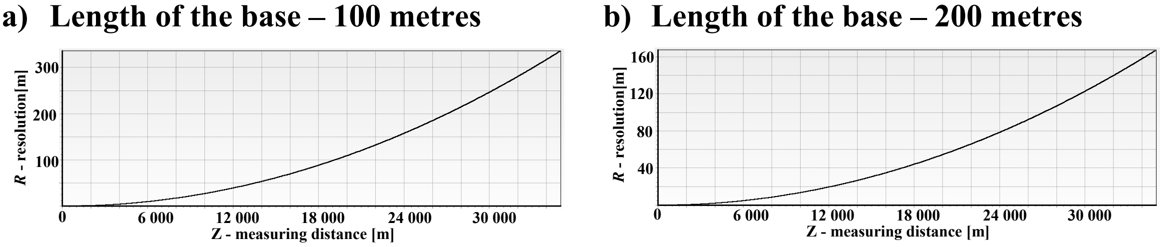
value of the mean error in coordinates of the position m_{poz} determined at the point;

number of marks l_{zz} taken for computations

3. RESULTS

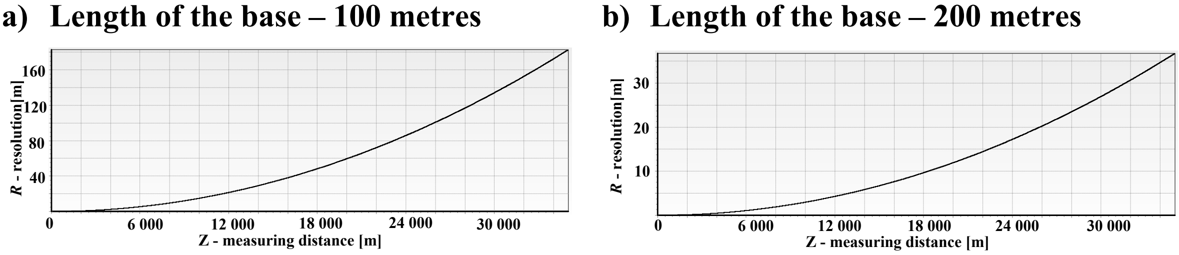
Basing on the derived relationships (1), (5) and the worked out algorithm (Fig. 3) there have been compiled in turn: diagrams of resolution and the mean error in distance measurement, also the charts with accuracy areas for the stereoscopic system built of two cameras of Rolleiflex and Sony made. For computation of the mean error in distance measurement and accuracy areas it has been assumed, that the mean error in length measurement of the base $m_b = 0{,}005$ m, the focal $m_f = 0{,}0008$ m, disparity m_p for Rolleiflex camera is equal to $6{,}8\,\mu m$ and $5{,}94\,\mu m$ for Sony camera (assuming that m_p corresponds to a size of pixel in CCD matrix).

3.1. Graphs of the measurement resolution


a) Length of the base – 100 metres

b) Length of the base – 200 metres

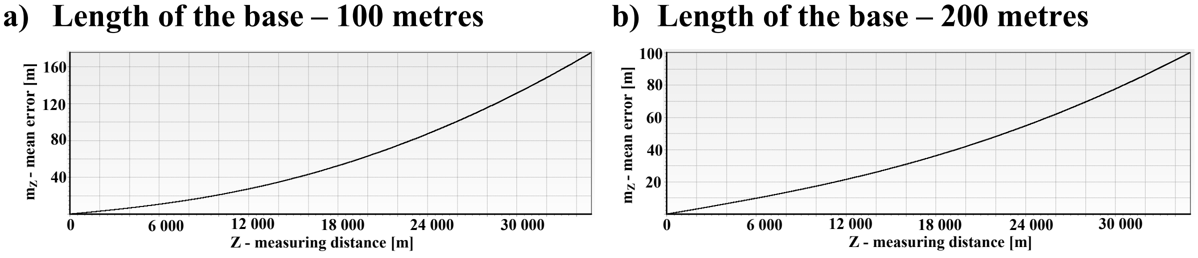
Fig. 4. Graphs of the measurement resolution in a function of the distance under measurement for stereoscopic system built out of Rolleiflex 6008 cameras with P45 matrices (pixel size on the matrix is 6.8 μm, focal length – set on 500 mm).


a) Length of the base – 100 metres

b) Length of the base – 200 metres

Fig. 5. Graphs of the measurement resolution in a function of the distance under measurement for stereoscopic system built out of Sony α 900/ F4-5.6 G SSM cameras (pixel size on the matrix is 5.94 μm, focal length – set on 400 mm).

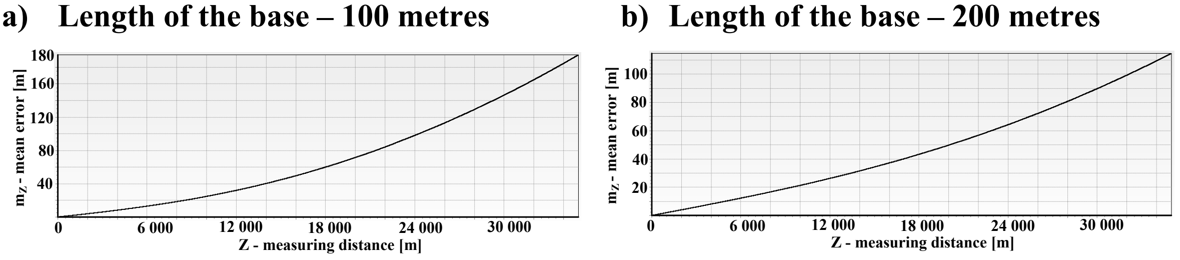
3.2. Graphs of the measurement mean error



a) Length of the base – 100 metres

b) Length of the base – 200 metres

Fig. 6. Graphs of the measurement mean error in a function of the distance under measurement for stereoscopic system built out of Rolleiflex 6008 cameras with P45 matrices (pixel size on the matrix is 6.8 µm, focal length – set on 500 mm).

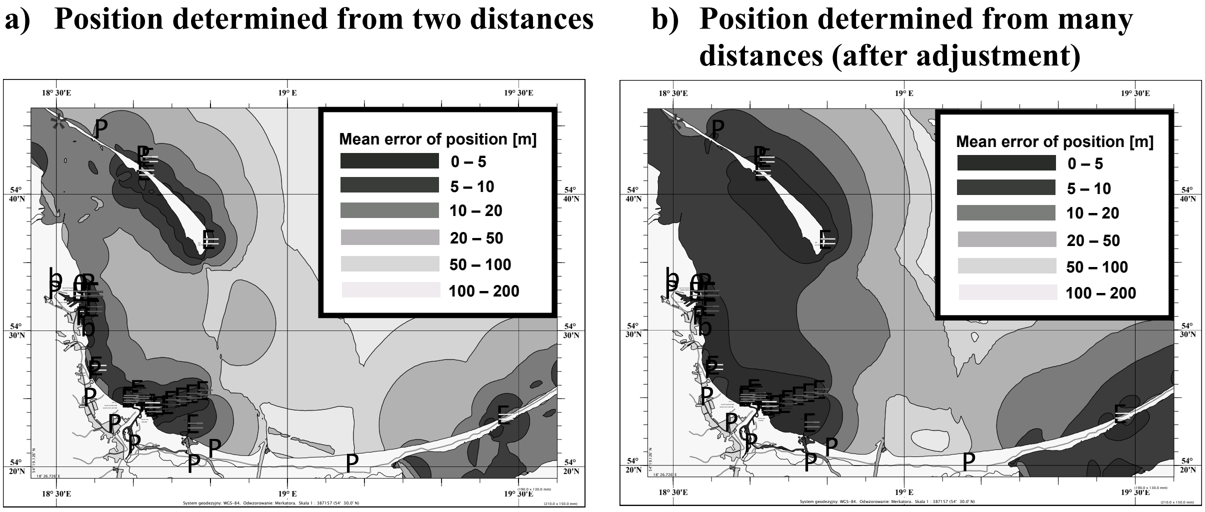


a) Length of the base – 100 metres

b) Length of the base – 200 metres

Fig. 7. Graphs of the measurement mean error in a function of the distance under measurement for stereoscopic system built out of Sony α 900/ F4-5.6 G SSM cameras (pixel size on the matrix is 5.94 µm, focal length – set on 400 mm)

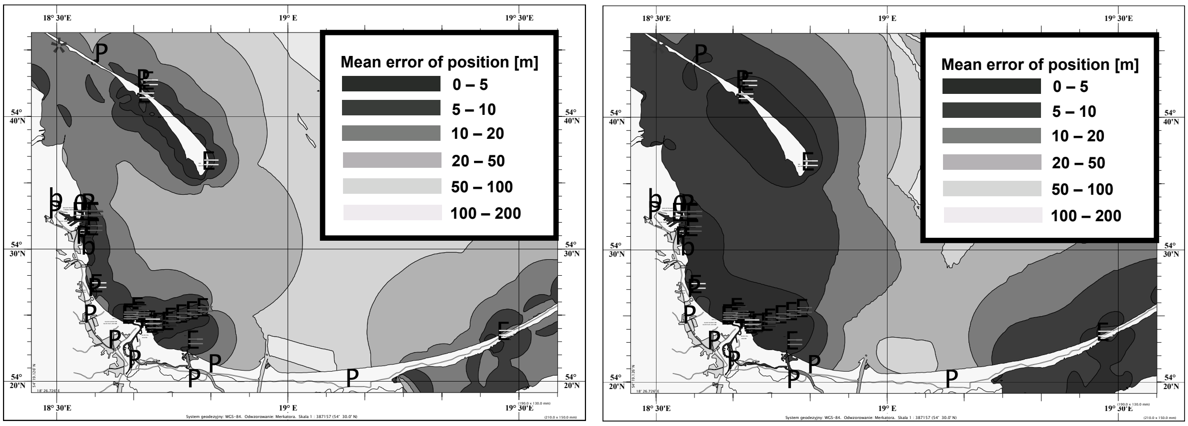
3.3. Maps of the bay of Gdansk with accuracy areas



a) Position determined from two distances

b) Position determined from many distances (after adjustment)

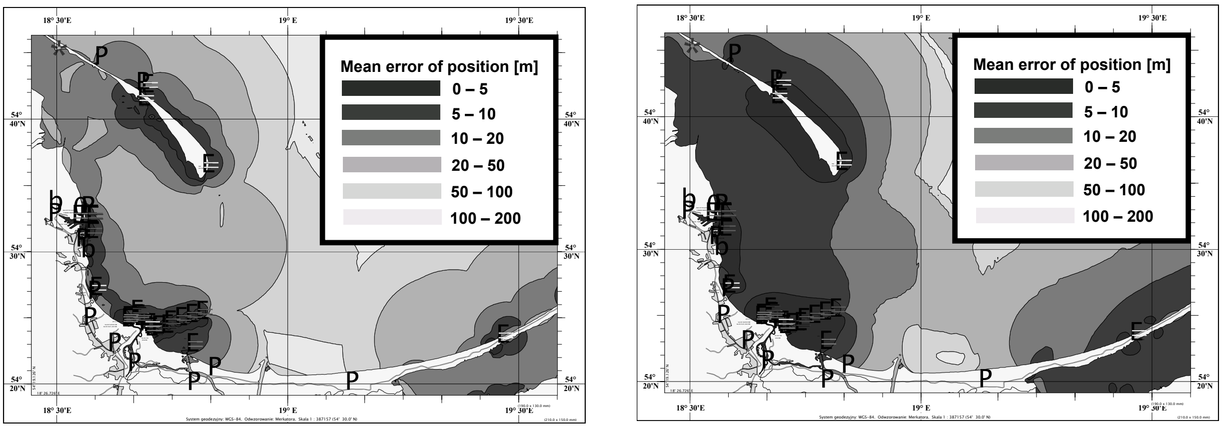
Fig. 8. Maps with accuracy areas for Rolleiflex cameras layout (length of the base – 100 metres.)



a) Position determined from two distances

b) Position determined from many distances (after adjustment)

Fig. 9. Maps with accuracy areas for Rolleiflex cameras layout (length of the base – 200 metres).



a) Position determined from two distances

b) Position determined from many distances (after adjustment)

Fig. 10. Maps with accuracy areas for Sony cameras layout (length of the base – 200 metres).

CONCLUSIONS

1. **Stereoscopic system of 100 metre base, built base on high-resolution cameras available on the market and installed on board of a vessel, may guarantee high accuracy of measurement of a distance to navigation marks and lights within limits of visibility optical range (the optical range may reach even 30 nautical miles at very good visibility).**
2. **Accuracy of the distance measurement may be corrected without changing external and internal parameters of the cameras' layout by more accurate measurements of the base and focal lengths.**
3. **Results of the distance measurements done by means of stereoscopic system from a vessel board to navigation marks allow obtaining coordinates of the vessel position if connected with information from electronic navigation map.**
4. **Accuracy of obtained position is higher than the required one in phases of coastal, sea port approaching and harbour navigations. In respect to requirements of the**

GMDSS NAV 47/7/1 ANNEX2 p.5 IMO (International Maritime Organization), one may state that accuracy of the position under determination during coastal navigation phase should be higher than 100 metres (P=95%). However, in respect to the Res. 815(19) IMO, it may be stated that the required accuracy depends on local conditions if regarding the port approaching and harbour navigation phases. Most often, it is accepted and the level of 10 metres (P=95%) and more 00.

5. **Although the research under conduction is promising, attention should be paid to the fact that factors having impact on accuracy of optical measurements, i.e. lenses distortion and astronomical refraction, have not been taken into consideration herein. Therefore, next research over the stereoscopic systems in the coastal zone should be conducted on board of a vessel manoeuvring in the coastal zone and under conditions of various visibilities at both day and night. Respective results would give a possibility of drawing conclusions not only as to theoretical considerations but also in respect to real measurements.**

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