ZESZYTY NAUKOWE AKADEMII MARYNARKI WOJENNEJ
SCIENTIFIC JOURNAL OF POLISH NAVAL ACADEMY

2015 (LVI) 2 (201)

DOI: 10.5604/0860889X.1172071

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CRITERIA FOR ESTIMATING NAVIGATIONAL SAFETY AT SEA

ABSTRACT

This article presents a structure of marine safety relating to navigation. It includes examples of documents which are currently in effect.

Key words:
navigation, navigation safety, marine hydrography.

INTRODUCTION

The transportation of various goods, including those connected with the fishing industry and marine warfare have been the main kind of human activity for ages. Until the beginning of the 20th century the main objective of human activity at sea was almost the same as the objective of marine navigation, understood as a kind of human activity at sea. This aim was to provide for the safe and effective navigation of ships.

THE SYSTEM OF NAVIGATIONAL SAFETY

Analyzing provisions in the main maritime conventions relating to maritime safety, a conclusion can be made that the main components (conditions) of this safety are:
- ships seaworthiness;

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- presence and appropriateness of individual and team emergency and life saving equipment;
- quality of support provided for a ship from outside (infrastructure, information, communications, search and rescue, etc.);
- necessity and capability to take into account conduct of other users of the sea;
- necessity and capability to take into consideration continuous changes in an environment;
- capability to observe safety rules and acting appropriately in dangerous situations;
- proper professional skills and psycho physiological conditions, required especially of teams operating onboard a vessel.

The above requirements allow for reducing all the conditions necessary to be met to only three in order to provide for navigational security. They are as follows:
- ships seaworthiness to appropriate standards;
- external suport systems of appropriate quality for human activity at sea;
- able, efficient and safe performance of crew members combined with ability to take into account the conduct of other users of the sea.

Taking the above into consideration, it can be stated that assessment of safety in relation to a single ship boils down to assessment of three components, i.e.
- exploitation safety;
- navigational safety;
- personel safety.

However, it must be mentioned that of the components constituting maritime safety the most variable is navigational safety. For this reason maritime safety assessment of an individual ship usually comes down to assessing her navigational safety.

The place of navigational safety in shipping safety is presented in figure 1 and its hierarchical structure in figure 2.

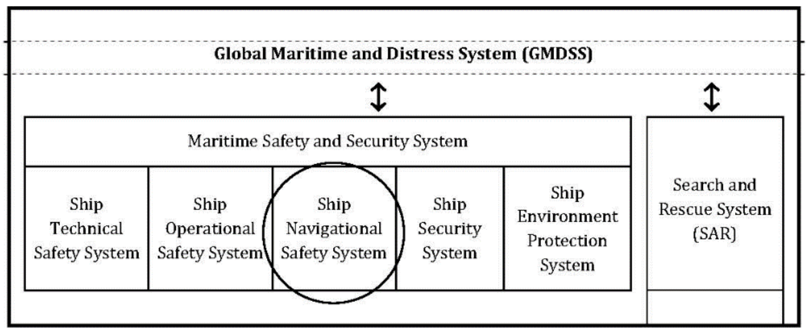

Fig. 1. The place of a ships navigational safety in the shipping safety system

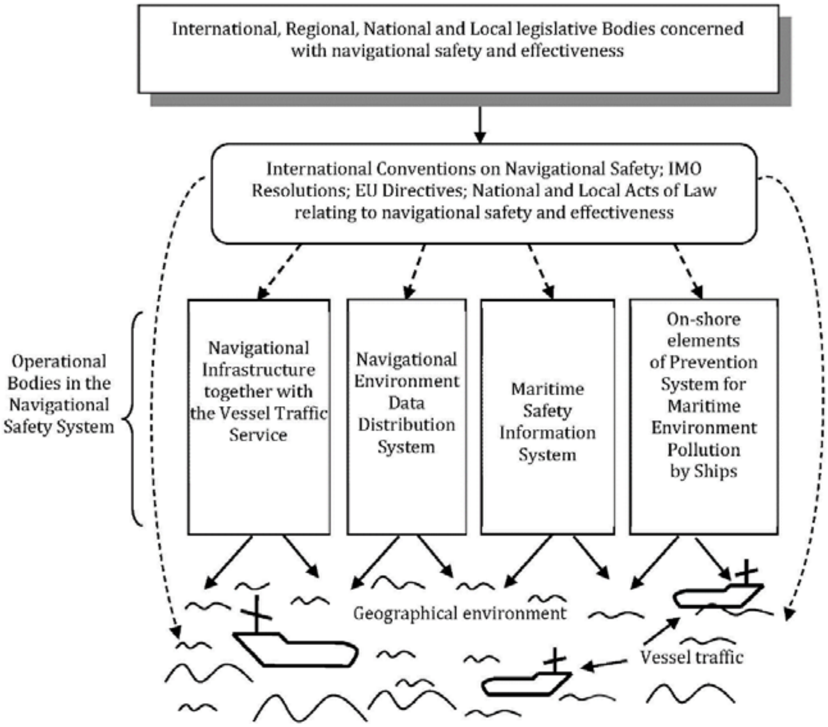

Fig. 2. Hierarchical structure of maritime navigational safety

THE ASSESSMENT OF SHIP NAVIGATIONAL SAFETY

Navigation infrastructure, as figure 2 indicates, constitutes the main component part of a ships navigational safety system. The infrastructure generates fast changing data together with changes in ship's position. Data on marine navigational environment and data from the maritime safety system changes at a slower rate as it refers to larger maritime regions. Data from the system for prevention of sea pollution will not be considered as it is mainly concerned with marine environment and not a ship as such. The general characteristics of data on marine navigation environment are presented in table 1.

Table 1. An example of data division on navigational environment in navigational processes into standard and special ones

Geographical data	
Standard	Special
• content of navigational charts • content of nautical publications	• content of special charts and publications • data for corrections in special publications

• correction data for Publisher • climatic data	• detailed bathymetric data for delineated regions and fairways • detailed geo-morphological and geo-physical data • data on specialized navigational infrastructure designed to support special activities at sea
Operational data	
Standard	Special
• ways and procedures for use of existing navigational infrastructure and SAR system • rules on use of harbors and landing stages • data on traffic of other vessels in a water region from vessel traffic systems • data on changes in an operational situation	• data on traffic and missions of naval vessels • data on exercise ranges, fairways and other special regions • additional detailed data on maritime traffic • data on pollution
Law-related data	
Standard	Special
• international and national rules and standards(e.g. IMO, SOLAS, STCW, COLREG) and national rules and standards relating to safety at sea (e.g. law on maritime regions, port rules, directives by maritime authorities) • internal rules of organizations (e.g. navy regulations, directives and regulations issued by ship owners)	• international rules (e.g. NATO STANAGs) • standards and normative documents of a ministry (e.g. defense standards) • orders made by supervisors • internal regulations and standards (e.g. rules of engagement, standards relating to hydro-technical, dredging work, etc.)

Talking about assessment of safety it is necessary to adapt a criterion and measures relevant to the type of hazard. 'Criterion' in this article means a measure of size or value, standard, etc., i.e. every adopted judgment measure relating to navigational infrastructure. 'Assessment' is understood as an opinion, evaluation or evaluative judgment, i.e. judgment about the value, size or usefulness of a seamark, object, procedure, navigational process, etc.

The job of navigators is to analyze assessment measures, i.e. criteria used to assess particular kinds and elements of navigational infrastructure. Characteristics of elements of the same kind of infrastructure are marked by the same sets of tactical and operational parameters. They can only differ in magnitudes of these parameters.

Technical parameters and their magnitudes are very important, especially for designers of a specific kind of infrastructure elements, constructors (builders) and technical operators of each kind of infrastructure. Users of the, i.e. users of the infrastructure are mainly interested in operational parameters, especially magnitudes of these parameters. For example, for position fixing systems the main operational parameters are: position accuracy, credibility, size of the operational zone, etc.

In order to be able to compare particular kinds of navigational infrastructure with each other and determine their share in maritime safety management only one common criterion should be used, i.e. the same kind of size for all kinds of navigational infrastructure and its elements. This assessment measure and its criterion exist and it is commonly used for assessing navigational safety in shipping regions — this measure is a risk coefficient, whereas for an individual ship its position error and its reliability.

Further in the article a few remarks will be presented concerned with position accuracy assessment.

ACCURACY IN NAVIGATION IN THE STANDARD NAVIGATION PROCESS

Assuming that accuracy related requirements in navigation should be met during the navigational process realized by a ship possibilities of carrying out this process so that established error border lines are not exceeded should be taken into consideration. This way the accuracy requirements derive not only from navigational infrastructure but also from the possibility of keeping to the preset line above the sea bottom.

As mentioned earlier, the main elements providing for accuracy in a navigational process are:

- navigational situation in a water region (mainly infrastructure);
- maneuver elements of a ship;
- navigation model.

Accuracy in true position, directions and water regions borders are dependent on navigational infrastructure in the water region. Depending on the ship routes in relation to navigational hazards safe distances from hazards are required.

Maneuver elements of a ship affect only the width of the ship traffic lane. The essential effect on this width have:

- ship dimensions;
- ship maneuver elements;
- navigation conditions;
- hydrological-meteorological conditions.

Accuracy in a navigation process also depends on the adopted model for carrying out navigation. At present, in marine navigation, two navigational models are employed:

- classical (in the standard process); in literature the term 'traditional' is often found;
- integrated (in the special process).

The classical model is most often employed by ships for sea passage, whereas the integrated model is employed in carrying out difficult operations. In the classical model a current ship position bears a higher error than in the case of position by observation ($M_b > M_o$).

An error in current position in the classical model is calculated following the formula:

$$M_b = \sqrt{M_o^2 + M_{gr}^2 + M_z^2}\ , \tag{1}$$

where:
M_o — error in position by observation;
M_{gr} — error in plotting the position on a chart;
M_z — error in dead-reckoning position.

In the classical method, also referred to as standard or traditional, used for navigational calculations a few simplifications have been adopted:

- a ship is regarded as a point;
- area in which reckoning is carried out is regarded as a plane;
- it is assumed that a ship travels along her route with constant speed;
- it is assumed that ship movement takes place in degrees of freedom (φ and λ);
- location of the plane on which navigation is carried out is assumed as unchanging.

During a sea passage it is necessary to know the current sip position in relation to the navigational chart as well as to the planned route. However, some of the tasks, e.g. keeping the ship at a pre-set position with the course laid down does not require plotting the position on a chart. Reporting the ships position in relation to the pre-set position errors in graphical work and reckoning can be neglected. In such a situation the formula assumes the form $M_b = M_o$. Carrying out such a task it is necessary to make sure navigational appliances co-operate with the computer as calculating coordinates for position by observation is difficult and in practice it is not used.

In the integrated model, a computer is used in order to fix the current position and at least two different systems delivering continuous position. In this model $M_b \leq M_{o1}; M_{o2}$, and the observed M_b is an integrated position.

Due to high possibilities of making calculations in the integrated model (instead of drawing on a chart, as in the classical model) so many simplifications in the navigational model are not used. To make calculations in the integrated model the following are often assumed:

- ship's dimensions;
- position fix representing a ship in relation to the diametral axis and bow and positions of antennas in radar systems;
- ellipsoid area on which dead reckoning is carried out;
- the fact that a ship travels at various speeds is taken into account (often longitudinal, transverse and vertical acceleration is taken into account as it occurs);
- in navigation geoid area is regarded as identical to the ellipsoid area;
- in calculating ship movement seven degrees of freedom are taken into account, i.e. rolling and pitching, heating, yawning, changes in longitudinal and transverse and change in position of the geoid (sea level).

In considering navigational requirements it must be born in mind that a large number of the present-day ships uses the classical navigational model.

THE DEFINITIONS OF NAVIGATIONAL CHARACTERISTICS RELATING TO SHIPS POSITION

Accuracy

In these considerations accuracy is a statistical magnitude. It is defined as a degree of conformity between an estimated or measured position and the true position, at a certain level of confidence, at a certain moment in any point in an operational zone. This accuracy is expressed with an error of 95% confidence unless stated specifically otherwise. It must be remembered that accuracy is also employed to measure other parameters such as e.g. speed, time, course, etc.

In marine navigation a few kinds of position accuracy are used. The use of each of them is dependent on the technology applied to carry out tasks at sea.

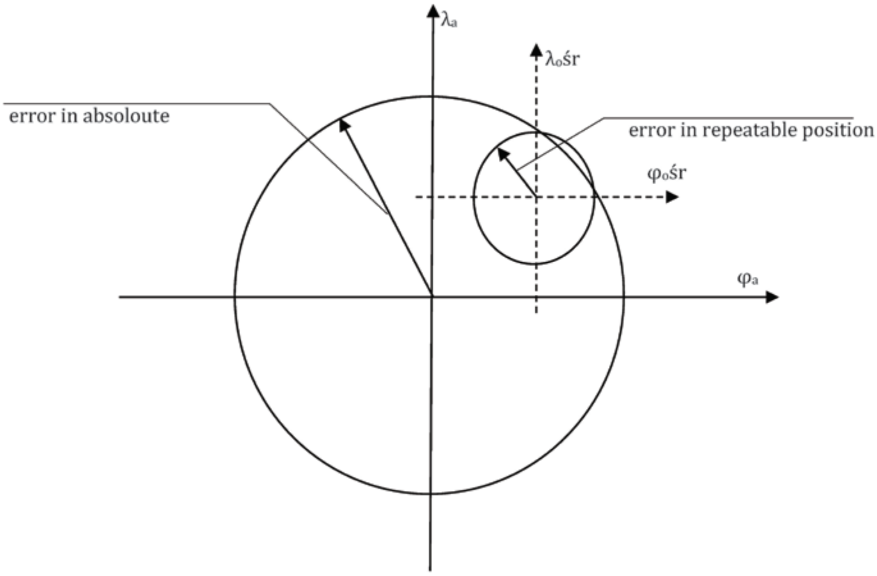

Fig. 3. Ralations between error in absolute position and repeatable position

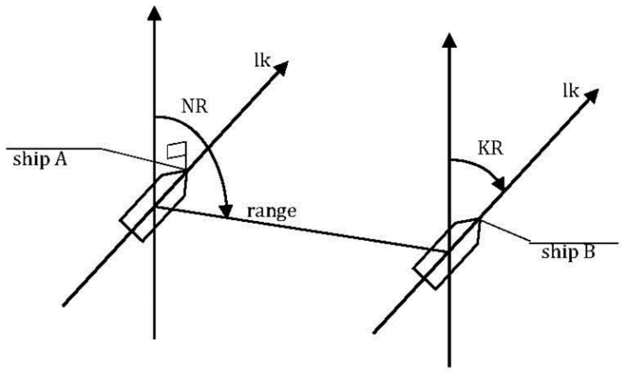

Fig. 4. The relative position of ship A in relation to B in NR function

Quantitative accuracy assessment (navigational parameter, position)

The 95% probability that the measured magnitude is in the error figure should be used to describe observed errors. (IMO Res. A.1046). The 95% level (of errors, position accuracy) should be applied to used in all navigational and hydrographic documents. If, for justifiable reasons, a different probability level is applied, this should be clearly stated.

Types of position accuracy

The absolute or geodetic accuracy is an accuracy in fixing a position in relation to geographical coordinates in the adopted reference system:

- the beginning of the error vector is in geographical coordinates;
- $\Delta t \neq 0$ (difference in time between fixed positions).

The repeatable accuracy is an accuracy with which the user can return to the previously fixed position in coordinates relevant for the system:

- the beginning of the error vector is in coordinates for a previously fixed position;
- $\Delta t \neq 0$.

The relative accuracy is an accuracy with which a user can fix his/her position in relation to another user working in the same navigational system and at the same time:

- the beginning of the error vector is in coordinates of another user;
- $\Delta t = 0$.

The predictable accuracy is an accuracy with which a position can be defined, when there occur errors adopted to calculate it as assumed for calculations. This accuracy depends on the state of knowledge relating to error sources:

- the beginning of the error vector is in coordinates — relative to the kind of position accuracy.

The kinds of position accuracy presented above can be used in carrying out a navigational process whereas to plan this process the predictable ship position accuracy should be employed. Conformity of the predicted position accuracy with the achieved accuracy depends mainly on the state of knowledge concerning error sources. The predicted ship accuracy can be referred to the absolute, repeatable and relative accuracy.

POSITION RELIABILITY

In marine navigation there are several ways of securing reliability. The most often used way is delivering information to a user when an error in position exceeds the pre-arranged acceptable magnitude. This method requires monitoring a position by an land-based station, usually on-shore station. This type of monitoring is usually defined as: *capability to deliver warnings to a user under pre-arranged time limits, when a system should not be used for navigation*.

ACCURACY IN A SHIPBOARD NAVIGATION SYSTEM

There, undoubtedly, exists a relation between operations executed at sea and technology used for their execution a navigational process. In order to be able to set navigational requirements for a water region it will be advisable to present a structure of a shipboard navigational system and its sub-systems (fig. 5).

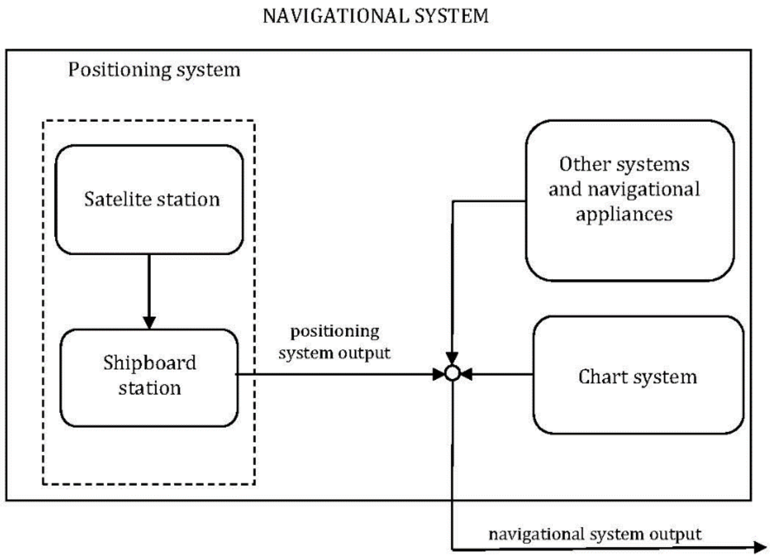

Fig. 5. The structure of a shipboard navigational system

A ship position will be represented by a current position received at an output from a shipboard navigational system. Formula 1 shows distribution of particular error in position components. It is often equated with a position by observation, especially when the GPS is used, and position accuracy announced by IMO in Res. 1.1046 is adopted as the criterion providing for safety in navigation. The fact that errors in navigational system are often generated by different other sources, e.g. a chart system, other systems and navigational appliances, local hydrological-meteorological conditions and others. In some operations it is justified but in the great majority of cases it is not.

Interpretation of errors in a positioning and chart systems are most often beyond any discussion, however, sometimes some component elements are omitted in calculating errors in dead reckoning. Still not all the sources of these errors will be a source of errors in the course made good. Therefore more important component for ship safety is the transverse component than the longitudinal component. The latter is usually omitted (this is not right while e.g. making changes in course on water lanes relating to dead reckoning position, approaching an obstacle, etc.), and hence

$$M_z = \sqrt{M_{cp}^2 + M_m^2 + M_t^2}\,, \tag{2}$$

where:

M_z — error in ship estimated position;

M_{cp} — error in ship estimated position caused by not knowing the accurate magnitude of total correction by compass;

M_m — error in estimated position caused by inaccurate steering (ship yawning);

M_t — error in estimated position caused by inaccurate knowledge of total drift.

CONCLUDING REMARKS

1. To define safety in precise and unequivocal terms for all water regions and operations is difficult. Taking into account regions for which safety is defined, a variety of operations and ships executing them in marine regions of the world, it is almost impossible. However, there is a question whether the borders delineating navigational safety which are adopted for today are sufficient enough to develop criteria to define it.
2. Ship safety in a water region is represented mostly by navigational safety. To asses it an analysis required is of:
   - navigational situation in the water region (mainly limitations relating to the region),
   - maneuver elements of a ship,
   - use of navigational models.
3. In this article only the standard classical model of navigation has been adopted for considerations. Maneuver elements have significance in confined water regions (imposing navigational limitations) and in other water regions they can be neglected (except for collision avoidance maneuvers). In such a situation the highest impact of navigational infrastructure on the precision of carrying the navigational process must be taken into account.
4. It is commonly accepted that criteria used to fix a ship position are those included in IMO Resolution A.1046(27) as of 30 November, 2011. The title of the resolution

is Worldwide Radionavigation System and it is concerned with accuracy in position fixing using this system. Such positions are referred to as positions by observation. Can such a position be equated with a ship's position? If the answer is yes, does this apply to all conditions?

5. The first, and at the same time the last resolution concerned with accuracy standards in navigation was IMO Res. A.529(13) as of 17 November 1983 Accuracy Standards for Navigation. Successive resolution which have suprseded it i.e. Res. A.666(16); Res. A. 815(19); A. 953(23) and the one being in effect A. 1046(27) have had the title Worldwide Radionavigation System. In fact in Res. A.666(16) it was stated that the system the resolution is concerned with should offer position accuracy not lower than the one specified in A.529(13), but can this position by observation be, in every situation, regarded as the ship position (current ship position)?
6. Taking into account the taxonomy relating to safety at sea presented in figure 1 and the required accuracy in position fixing of 100 m in open water regions (in accordance with IMO Res. 1046) it can be concluded that it is too stringent as for ship navigational safety. However, if the fact that SAR is included in the shipping safety is taken into account(fig. 1) this requirement is justified with regard to SAR. In other cases it would be necessary to consider why marine astronomy should be taught if positions fixed with accuracy lower than 100 m were to be rejected as useless.
7. When considering position accuracy in relation to a water region and adopting the classical navigation model, position accuracy can be assumed as a measure of safety for a passage between port roadsteads, whereas for a route from a roadstead along a water lane to a harbor basin, instead of positions, most often it is a 90 degree angle drift from the axis of a water lane. Often positions of a ship on a water lane are defined as conformity of places of vertical planes running the lane's axis and ship's diametric plane. Such requirements bring about a necessity to take into account maneuver elements of ship.
8. Taking into account the classical navigation model it can be assumed that accuracy requirements presented in IMO Res. A.1046 are too high and in practice their criteria are often exceeded.
9. If ships are equipped with integrated systems (INS, IBS) and navigational appliances (compass, log, inertial system) to obtain the position accuracy criterion presented in IMO Res. 1046 is possible. Then, to obtain position accuracy along the pre-arranged route line becomes a problem because of ship maneuvering capabilities such as, e.g. yawning. Although the integrated navigation models in

use has such a capability but navigating a ship in a rough sea with winds from bow course angles remains dubious. There can be an impression that The Worldwide Radionavigation System requirements were formulated with regard to capabilities of modern satellite systems, and not to navigation safety purposes.

REFERENCES

[1] Hansel H., *Podstawy rachunku błędów*, WNT, Warszawa 1968 [*Fundamentals of calculus of error* — available in the Polish language].

[2] IMO Res. A529(13); A666(16); A.815(19); A.953(23); A.1046(27).

[3] Kopacz Z., Morgaś W., *Dokładność pozycji okrętu w procesie prowadzenia nawigacji*, Konferencja 'Satelitarne metody wyznaczania pozycji we współczesnej geodezji i nawigacji', 2010 [*Accuracy in ship position in navigation*, Conference on 'Satellite position determination method in modern surveying and navigation' — available in the Polish language].

[4] Kopacz Z., Morgaś W., *Nawigacyjno-hydrograficzne zabezpieczenie działalności ludzkiej na morzu* (maszynopis) [*Navigation-Hydrographic support for human activity at sea* (typescript) — available in the Polish language].

[5] Odincov V. A., *Radionawigacija Letatelnych Aparatow*, Izdatelstwo Maszinostroenie, Moskva 1968 [*Radionavigation in Flying Machines* — available in the Russian language].

KRYTERIA OCENY BEZPIECZEŃSTWA NAWIGACYJNEGO NA MORZU

STRESZCZENIE

W artykule przedstawiono strukturę bezpieczeństwa morskiego związanego z procesem nawigacyjnym. Podano przykłady dokumentów z zaliczeniem ich do obszarów obowiązywania.

Słowa kluczowe:
nawigacja, bezpieczeństwo nawigacji, hydrografia morska.