Safe Ship's Trajectory Determined by the Influence of the Drift

Sigurna putanja broda određena utjecajem zanošenja broda

Jelenko Švetak
University of Ljubljana
Faculty of Maritime Studies and Transportation
Slovenia
e-mail: jelenko.svetak@fpp.uni-lj.si

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Summary

The accuracy of ARPA (Automated radar plotting aid) calculations is a problem on which manufacturers and researchers have worked ever since the system was created. The elements of the situation of passing a target followed, as calculated by ARPA, are an important parameter for the safety of shipping. Nowadays the usage of ARPA as a part of the integrated bridge navigation system (IBNS) and its inclusion in the process of ship steering has raised new questions to the accuracy of the calculations. Analyses show that the factors taken into account, distance to the target and drift, play a crucial role. Their manifestation in the mode of steering the ship on a pre-set route, however, is in a manner which is different from those known so far. The present article analyses the influence of the drift and the distance to the target on the accuracy of ARPA calculations as an element of IBNS and the differences resulting from the manner of the stabilization of the ship's movement. Measurements with aids to navigation during passage in the region of the East China Sea are used.

KEY WORDS

ARPA
IBS
CPA
track mode

Sažetak

Preciznost ARPA (automatsko određivanje pozicije s pomoću radara) izračuna problem je na kojemu proizvođači i istraživači rade otkada je sustav napravljen. Elementi situacije prolaska određenog cilja, prema izračunu ARPA, bitan su parametar za sigurnost broda. Danas je upotreba ARPA dio integriranog sustava navođenja broda (IBNS) te je njegova uključenost u proces plovidbe broda skrenula pozornost na preciznost izračuna. Neke analize pokazuju da čimbenici koji se uzimaju u obzir, udaljenost do cilja i zanošenje, igraju ključnu ulogu. Njihov utjecaj na način navođenja broda na unaprijed određenoj ruti razlikuje se od dosad poznatih načina. U ovom radu analizira se utjecaj zanošenja broda i udaljenosti do cilja na preciznost ARPA izračuna kao elementa IBNS-a te razlike koje nastaju kao rezultat načina stabilizacije kretanja broda. Korištena su mjerenja i pomoć u navigaciji tijekom putovanja u Istočnom kineskom moru.

KLJUČNE RIJEČI

ARPA
IBS
CPA
track mode

1. INTRODUCTION / *Uvod*

Integrated Bridge and Navigation System (IBNS) in respect of steering the vessel is a system-combined navigation data from several aids to navigation – GPS receiver, Electronic Chart Display and information System (ECDIS), Radar ARPA, Gyrocompass and Autopilot. The IBNS finds growing application in modern navigation. Its wide scope navigational capabilities facilitate navigation, especially when sailing in regions with heavy traffic, close to dangers to navigation, in narrow waters, etc. As any other instrumental system, IBNS produces the data of measured and calculated navigational parameters with certain errors, which are subject to many analyses and publications (Jerlakov, A. V. et al, 1984), (Berking B. and Pfeiffer, J. 1994). But these publications do not analyse how the ship's drift calculated by IBNS affect the ARPA calculations for closest point of approach with moving targets. The present article deals with the dependence of the error in the calculated by the IBNS distance of own ship to a moving target on the measured navigational parameters in different ship control modes on a pre-set course. Analysis is made based on some experiments.

The operation and accuracy of the automated radar plotting aid (ARPA) have been studied thoroughly during the years since it was first employed as a means providing for the safety of shipping. The integrated bridge navigation system (IBNS), in which ARPA is the main control element, has found wider and wider application in navigation since the end of the 20-th century. The co-ordination of the radar information with the information from the electronic charts and display information system (ECDIS) provides an opportunity for implementation of new methods of control actions over the ship's steering gear. They result mainly from the principle of stabilization of the ship – relative to a route, pre-set by ECDIS (track mode or over ground), or, relative to a pre-set gyrocompass route (heading mode or through water). In the former case the ship is stabilized relative to the sea bottom, and in the latter – relative to the water. This causes a change in the ship's reaction to the external influences, which affects the ARPA operation when calculating the elements of a passing situation with a followed target (Bole, A. et al, 2005), (Švetak, J., 2009). Our main interest will lie with the calculation accuracy of the closest point of approach, since it is the basic criterion in classifying a target as dangerous or not.

The careful investigation of CPA values, when following a target from a certain distance in Track mode (TM) of steering, shows data instability when the distance to the target is great and a consecutive minimal deviation from a certain value when approaching the target at a distance of 5-6 miles. In Heading Mode (HM) of steering, the decrease of the distance between the target and the own ship would rather stabilize the changes of the CPA values and they increase or decrease evenly depending on the drift direction. The changes of the CPA values as function of the ship's drift and the distance to the followed target in TM of steering is the object of the present study. The aims are to trace the function dependences, to analyse the distribution of the CPA function and to establish the degree of trustworthiness of ARPA depending on the distance to the targets. The analyses were made on the basis of actual tests with real navigation aids and targets, the conditions of carrying out the tests being thoroughly described.

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2. COURSE CONTROL MODE IN IBNS / *Način kontrole kursa u IBNS-u*

The integrated bridge navigation system ensures fully automated control of the speed and the course of the ship (Švetak, J., 2009). The following two modes are used for course control:

- automated control in track mode – ship sailing following preliminary drawn track in the ECDIS or GPS, which input in the ARPA;
- automated control in heading mode ship sailing following given gyro compass course.

Fig. 1 shows the principle scheme of the IBNS configuration. When steering the ship the data from the radar, the electronic chart and the computerized track pilot system are of paramount importance. When approaching moving targets, different data sources for the own ship course are used in the two modes of ship control in IBNS.

In the track mode, the own ship's course of movement is entered by the GPS, i.e. the ship's course over ground. The speed is also calculated over ground, the speed data are calculated on the basis of the DOLOG measurements which are ground stabilized due to small depth. It is important to note that for the experiment purposes ship's speed data is used for calculation the own ship drift only. It is well known fact that own ship's speed affect ARPA calculation also. But this data is more precise and accurate and speed errors are relatively small compared with course errors (Berking B. and Pfeiffer, J. 1994).

Some experiments were carried out in the East Chinese Sea in order to analyse the correlation between the different errors from the own ship's course sensor and calculated drift in the IBNS and the calculated closest point of approach. Some of the results are shown in table 1 and table 2.

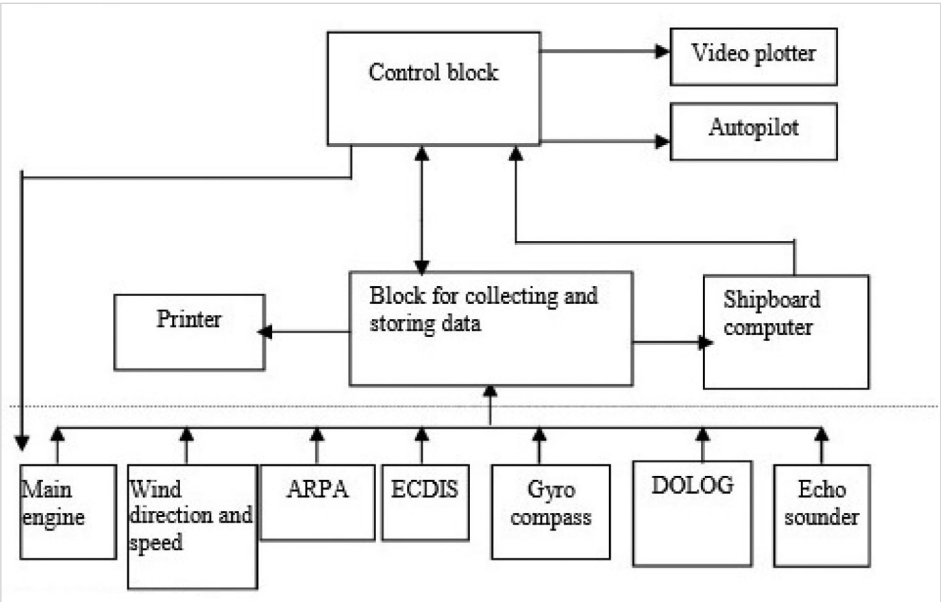

Figure 1 The IBNS structural scheme
Slika 1. IBNS strukturna shema

Source: own elaboration

Table 1
Tablica 1.

Gyro compass [deg]	Drift angle [deg]	Course relative to the ground [deg]	CPA [mile]	Distance to the target [mile]	Gyro compass [deg]	Drift angle [deg]	Course relative to the ground [deg]	CPA [mile]	Distance to the target [mile]
17.3	0.7	15.7	1.60	14.88	18.9	0.8	16.2	1.47	6.95
17.7	0.8	16.4	1.08	14.46	19.3	1.2	16.4	1.42	6.69
18.1	0.9	16.2	1.24	14.12	19.4	1.5	16.6	1.46	6.36
18.7	1.3	16.6	1.42	13.78	19.7	1.3	17.1	1.49	5.98
18.8	1.2	16.2	1.48	13.44	19.8	0.9	17.5	1.55	5.67
19.2	1.5	16.5	1.34	13.12	18.8	0.6	16.9	1.45	5.37
19.3	1.6	16.6	1.31	12.82	18.3	0.8	16.1	1.44	5.07
19.1	1.1	16.6	1.54	12.46	18.5	1.0	15.7	1.46	4.75
18.9	0.9	17.0	1.68	12.09	18.9	1.5	15.6	1.52	4.47
18.3	0.6	16.6	1.56	11.78	19.5	1.4	16.7	1.49	4.17
17.5	0.6	16.6	1.49	11.47	19.8	1.9	17.6	1.46	3.85
17.6	1.1	15.3	1.33	11.12	20.2	1.7	17.6	1.54	3.54
18.6	1.0	15.7	1.60	10.81	20.3	2.0	18.1	1.55	3.24
19.5	1.1	16.9	1.44	10.49	19.3	1.5	17.4	1.53	2.88
19.3	1.0	17.0	1.73	10.20	19.0	1.5	16.6	1.51	2.62
19.3	1.3	17.8	1.74	9.85	18.6	1.6	15.7	1.55	2.41
19.1	1.5	17.2	1.50	9.57	19.0	1.2	15.9	1.56	2.11
19.1	1.9	17.1	1.50	9.18	19.4	1.6	16.6	1.55	1.99
19.4	1.6	17.6	1.55	8.94	19.5	1.8	15.7	1.56	1.82
19.1	1.8	17.2	1.54	8.53	20.2	2.3	16.1	1.55	1.72
19.2	1.1	17.2	1.60	8.22	20.8	2.2	17.0	1.56	1.65
18.5	0.9	16.6	1.58	7.93	20.4	1.5	17.2	1.56	1.58
17.8	0.5	16.0	1.44	7.57	20.3	1.7	17.2	1.56	1.56
18.2	1.2	15.7	1.42	7.26					

Note: Ship's course in "track mode" – 016.6°

Table 2
Tablica 2

Gyro compass [deg]	Drift angle [deg]	Course relative to the ground [deg]	CPA [mile]	Distance to the target [mile]	Gyro compass [deg]	Drift angle [deg]	Course relative to the ground [deg]	CPA [mile]	Distance to the target [mile]
46.9	2.0	42.5	1.10	5.40	47.4	2.3	43.3	0.97	3.46
46.8	2.0	43.5	1.07	5.31	46.7	2.2	43.4	1.01	3.39
47.1	2.0	43.5	0.94	5.20	47.0	2.1	43.9	0.95	3.39
47.3	1.8	43.7	0.98	5.11	46.7	2.2	43.8	0.88	3.28
47.0	1.8	44.2	0.99	5.00	47.0	2.0	43.3	0.96	3.28
46.9	2.1	43.6	1.05	4.89	47.1	1.7	44.0	0.83	3.16
47.2	2.2	43.4	0.99	4.79	47.1	2.0	43.2	0.97	3.16
47.0	2.0	44.1	0.94	4.67	47.1	1.6	43.6	0.86	3.04
47.2	2.0	44.2	1.00	4.56	47.0	2.0	44.0	0.96	3.04
46.8	2.0	43.7	1.04	4.44	47.4	1.6	43.9	0.85	2.92
46.5	1.9	43.5	1.01	4.34	47.1	1.7	43.8	0.96	2.92
47.1	1.9	43.1	0.97	4.25	47.3	1.4	43.8	0.96	2.82
47.5	2.2	44.0	0.99	4.12	47.0	1.6	43.4	0.92	2.58
47.7	2.4	43.7	1.00	3.97	47.2	1.9	43.9	0.92	2.14
47.3	2.5	42.8	1.03	3.87	47.3	1.8	43.9	0.90	2.03
47.2	2.5	43.8	0.79	3.75	47.1	1.9	43.7	0.97	1.88
47.2	2.4	43.4	0.87	3.63	47.7	2.2	44.0	0.92	1.88

Note: Ship's course in "heading mode" – 047.0°

The configuration of the IBNS were used was of the type shown in figure 1. The data in table 1 were obtained in "track mode" of ship's course control, and those in table 2 - in "heading mode" of ship's course control. Measurements were taken every 30 seconds.

2.1. CPA dependence on the drift and the distance to the target followed in track mode of steering / *Ovisnost CPA na zanošenje broda i udaljenost do cilja u track mode plovidbi*

When analysing the CPA dependence on the drift and the distance to the target followed, it is assumed that the following conditions have been fulfilled:

- external factors affect own ship and the target in the same way;
- ships proceed in uniform rectilinear motion, without any changes in the course and speed.

The situation of own ship approaching the target is shown in the drawing (fig.2):

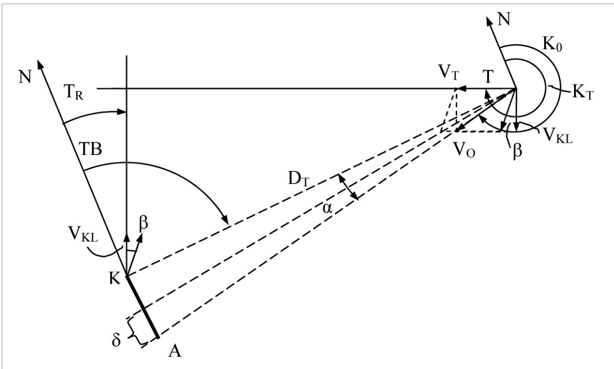

Figure 2 The situation of own ship approaching the target
Slika 2. Situacija približavanja broda cilju
Source: own elaboration

where V_{KL} is the own ship's speed according to DOLOG;
V_T – the target's speed;
β - the own ship's drift;

δ - variation of CPA due to the own ship's drift β;

K – the own ship;

T – the target.

The following dependence arises from triangle *KTA*:

$$CPA = D_T . \sin \alpha \, ; \; \alpha = (TB \pm 180°) - K_o \tag{1}$$

where D_T is the distance measured to the target, mile;

TB – the through bearing measured to the target;

K_o - the target's relative course.

t can be seen from fig. 2 that the value of the drift total *β* is contained in angle *α* through the target's relative course K_o. The relative course can be presented as a function in the following way:

$$K_o = f(C_G \; , ERR_G \; , \beta, C_T) \tag{2}$$

where C_{CG} is own ship gyrocompass course;

ERR_{GC} - own ship gyrocompass error;

C_T is own ship true course.

The root mean square error in the calculated CPA is determined by differentiating formula (1) by the variables D_T and *α*:

$$m_{CPA}^2 = (m_D . \sin \alpha)^2 + (D_T . m_\alpha . \cos \alpha)^2 \tag{3}$$

The first addend is influential only in the cases when the target and own ship pass at a great distance. Then the value of *α* is such that it makes the function *sin α* meaningful. We shall confine our analysis and stipulations to the occasion when CPA has small values. The *α* will also have small values. For the modern radars the maximum error in the distance measured m_D is $m_D = \pm 50$ meters. Therefore the first addend in the above case will be of a very small value and can be neglected. Formula (3) acquires the type:

$$m_{CPA} = \sqrt{D_T . m_\alpha . \cos \alpha} \tag{4}$$

where m_α is the root mean square error in the angle calculated *α*. Due to the variable character of the values, on which m_α is functionally dependent, it will be difficult to motivate its influence on m_{CPA}. From a geometrical point of view, however, it can be said that the value of m_α will have greater influence the greater the distances between own ship and target are and will have a negligible influence at short distances.

It is seen by formula (4) that the main influence in forming m_{CPA} lies with the distance to the target and the angle *α*. The latter is directly dependent on the drift *β*, contained in the relative course of the target. Therefore, the two main factors forming the error in the CPA as calculated by ARPA for each target are the distance to the target D_T and the own ship drift value *β*. The error m_{CPA} has a serious influence in the process of passing small targets at short distance. In the cases of heavy traffic it is of extreme importance to accurately determine the CPA due to the restricted space for manoeuvring.

Steering the ship using IBNS greatly facilitates the process of passing as well. Let us refer the above conclusions to the Track mode of steering in which the ship keeps to a pre-set route relative to the bottom. Any deviation from the route results in a control action for returning the ship. That influences the ship's gyrocompass course, and, as far as ARPA calculations are concerned, it also influences the CPA calculations.

To study the influence of the distance to the target and the drift on the CPA 318 measurements to small (vessel under 24 m) and large marine targets were carried out on each present course of own ship (track mode and heading mode). Measurements to the small targets were performed in heavy traffic with insufficient space for manoeuvring. We had to pass targets at distances much shorter than the recommended by COLREG-72. Therefore, 34 measurements were chosen, through which the analysis of the theoretical stipulation will be carried out.

The distances at which the various stages begin to apply will vary considerably. They will be much greater for high speed vessels involved in a fine crossing situation. For a crossing situation involving two power-driven vessels in the open sea it is suggested that the outer limit of the second stage might be of the order of 5 to 8 miles and that the outer limit for the third stage would be about 2 to 3 miles.

As a general guide it has been suggested that, using a 12 mile range scale in the open sea, radar observations should be assessed as an approaching target crosses the outer one third of the screen to see whether a close-quarters situation is developing. If so substantial action should be taken before the target reaches the inner one third of the screen (Cockcroft A.N., Lameijer J.N.F., 2004).

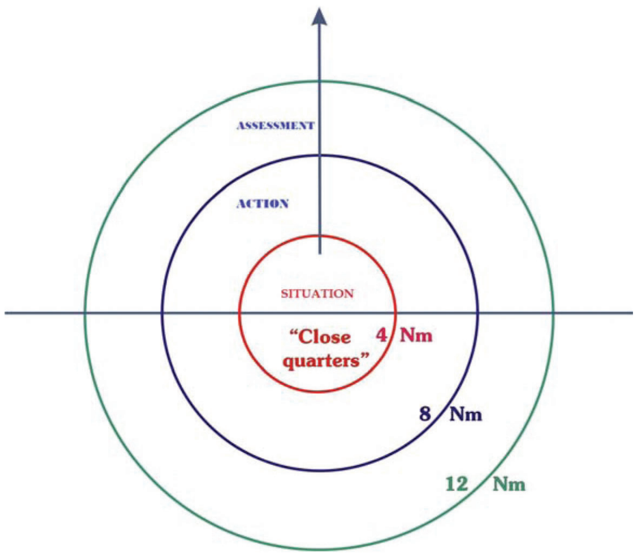

Figure 3 The general principles avoiding collisions on the high seas

Slika 3. Opća pravila za izbjegavanje sudara na otvorenom moru

Source: own elaboration

The conditions of the experiment were – drift total (by wind and current) from 0° to 1° in the direction of the target, own ship speed for the time of measurement 19,37 kn, own ship course in track mode of steering $K = 016{,}6°$ or $C_{CG} = 019{,}1°$ (Table 1), the initial distance of spotting the target 15,25 miles, final distance 0,60 miles. The target was proceeding on a constant course $K_T = 207{,}3°$ at a constant speed of $V_T = 8{,}18$ kn.

Minor targets such as small coastal vessels and trawlers should normally be detected at distances greater than 6 miles, provided the set is properly adjusted, but yachts, open boats and other small craft, especially boats of fibreglass construction, usually give poor echoes and may not be detected in time to take effective avoiding action.

It is seen from formula (2) and fig. 2 that the presence of a drift changes the CPA towards increase or decrease depending on the drift direction. At the same time the ship proceeds on a preset line with very small deviations in the order of several meters to 50 meters at a drift of up to ±2°. Therefore, the conclusion can be made that the calculated CPA will vary around a certain value. However the one, shown by ARPA as a momentary value, will contain an error proportionate to the ship's drift and the distance to the target. The uneven calculations of CPA in automatic mode of following a small marine target are seen by the measurements drawn on the diagram (fig.4):

The moments of occurrence of drift are marked by dots and the figures beside them show the value of the drift which during the whole time of measurement deviated the ship towards the target.

Let us draw, using the same measurements, the dependence of CPA on the distance to the target. The diagram produced is shown in fig.5.

It is seen from figure 4 that the frequent changes of the drift and the great distance to the target introduce a considerable error in CPA. It should be pointed out that these changes influence the target's course, as well. The fluctuation of the latter around a value within the limits of ±2,0° show that the target proceeds rectilinearly. This conclusion is also proved by the return of the target's course to the values from before the occurrence of a drift.

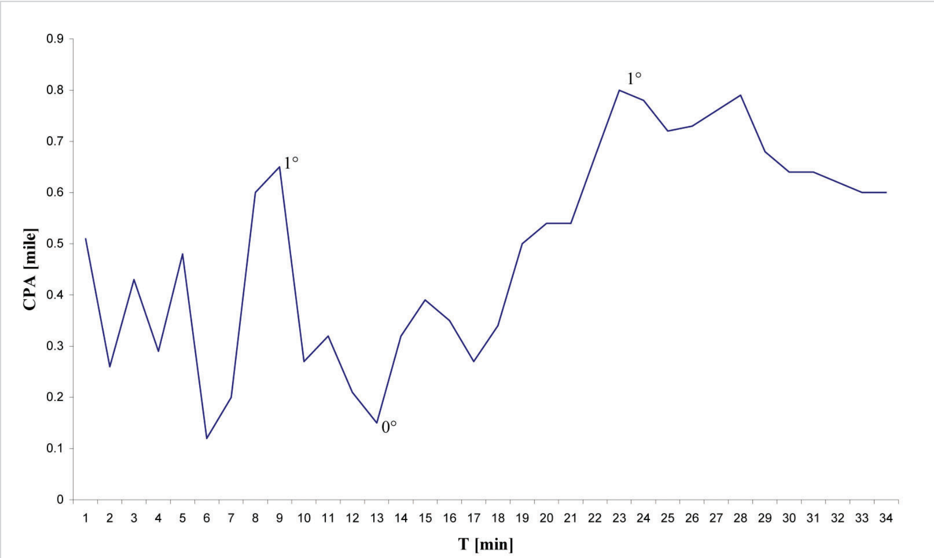

Figure 4 The calculations of CPA
Slika 4. Izračuni CPA

Source: own elaboration

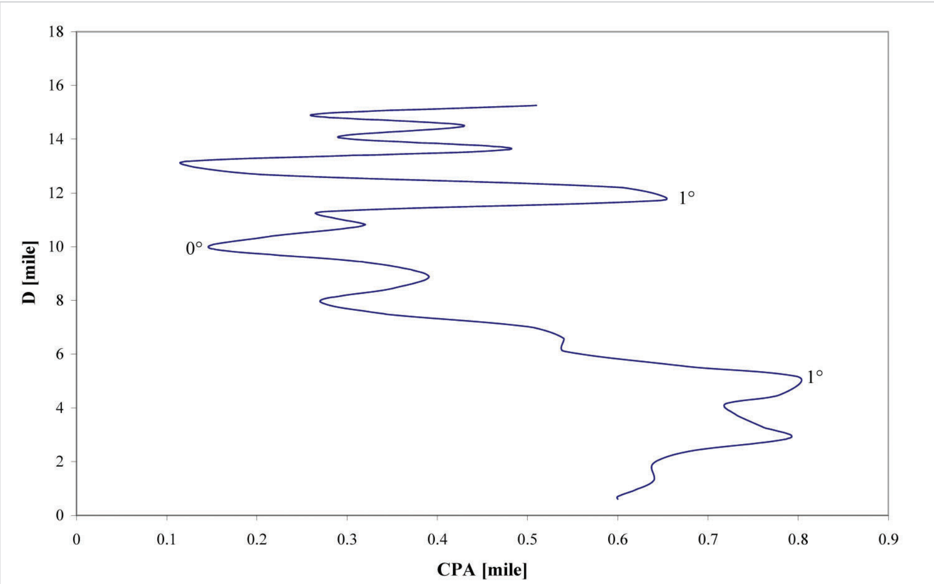

Figure 5 The dependence of CPA on the distance to the target
Slika 5. Ovisnost CPA o udaljenosti do cilja

Source: own elaboration

Table 3 The CPA distribution intervals

Tablica 3. CPA intervali distribucije

CPA [mile]	0.1–0.2	0.21-0.30	0.31-0.40	0.41-0.50	0.51-0.60	0.61-0.70	0.71-0.80
P %	0.08	0.12	0.15	0.17	0.21	0.16	0.11

2.2. CPA Distribution Law and a calculation accuracy criterion in track mode of steering / *CPA zakon distribucije i izračun kriterija preciznosti u track mode plovidbi*

According to most theoretical stipulations concerning the measurements in navigation, the distribution of the fortuitous values is performed as per the normal law (Kondrashichin V. T.(1969). In this case the conditions of measurement when steering the ship in Track Mode have not been included in the studies so far. To answer a number of questions related to the degrees of trustworthiness of ARPA, the distribution law of the fortuitous value CPA should first be determined. The CPA distribution intervals and their corresponding frequencies are presented in table 3.

Using the data in table 3 a histogram is drawn (fig.6):

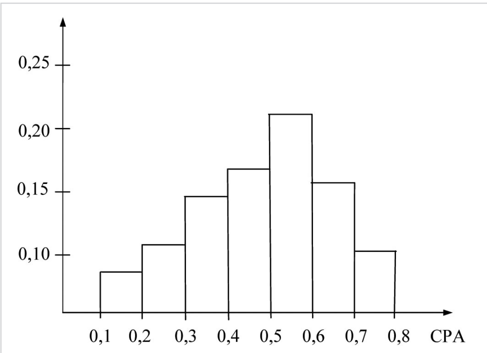

Figure 6 The CPA statistical distribution

Slika 6. CPA statistička distribucija

Source: own elaboration

The type of the histogram suggests that the CPA statistical distribution is most probably normal. To check this hypothesis, a criterion for the co-ordination of the statistical and theoretical distribution is employed – the criterion χ^2 (Pierson's criterion). Therefore the evaluations of the numerical characteristics of the fortuitous value CPA are determined using the formulas (Ventcel E. S. 1969):

- for the statistical average m^*_{CPA}

$$m^*_{CPA} = \sum_{i=1}^{34} \widetilde{x}.p^*_i \tag{5}$$

- for the statistical dispersion D^*_{CPA}

$$D^*_{CPA} = \sum_{i=1}^{34} \left(\widetilde{x} - m^*_{CPA}\right)^2 .p^*_i \tag{6}$$

where $\widetilde{x}$ is the average CPA value at each interval in table 1

p^*_i – the frequency corresponding to the i-th interval.

- for the statistical root mean square deviation

$$\sigma^*_{CPA} = \sqrt{D^*_{CPA}} \tag{7}$$

After the application of the formulas for the numerical characteristics, the following values are obtained:

$$m^*_{CPA} = 0{,}473;\ D^*_{CPA} = 0{,}284;\ \sigma^*_{CPA} = 0{,}533$$

The value χ^2 is adopted in order to check the distribution of the fortuitous value CPA as a measure for the difference between the theoretical and the statistical distribution.

After the calculations, a value χ^2 is obtained for χ^2 = 18,384. The normal law requires the relations S = 3. According to the number of degrees of freedom $r = k – S$ and χ^2 from table 3 the probability β = 0,0008 is obtained for the truthfulness of the hypothesis of the normal distribution. It is seen that β has a very small value, which shows that CPA is not distributed as per the normal law. Consequently, there exists another reason beside the external conditions, which has an influence on the CPA ARPA calculations in track mode of steering the ship.

A careful analysis of the diagram in fig. 5 reveals that at a great distance of spotting the target, the CPA data are unstable. From a certain distance on, these data begin changing within closer limits. In such a case the confidence interval, in which we find the mathematical expectation of CPA with a pre-set probability β at a different distance to the target, can show from what distances ARPA produces relatively accurate results in Track Mode. Therefore, the evaluations of the CPA numerical values are calculated using the formulas:

$$m^{**}_{CPA} = \frac{\sum_{1}^{n} CPA_i}{n} \quad \text{and} \quad \widetilde{D}_{CPA} = \frac{\sum_{1}^{n}\left(CPA_i - m^{**}_{CPA}\right)^2}{n-1} \tag{8}$$

The root mean square deviation $\sigma_{m^{**}_{CPA}}$ is obtained using the formula:

$$\sigma_{m^{**}_{CPA}} = \sqrt{\frac{\widetilde{D}_{CPA}}{n}} \tag{9}$$

Since the target is small and the conditions of sailing in heavy traffic require great probability of the findings, the value of the confidence interval for probability β = 0,95 is calculated. In order to make the necessary comparison, the CPA values are divided into three intervals according to the distance to the target D – namely D_1 = (15,25 ÷ 10,60), D_2 = (10,36 ÷ 0,60) and D_3 = (5,56 ÷ 0,60). The CPA confidence interval for each of these sets of measurements is determined. As a result of the calculations, the limits of the interval for the mathematical expectation m^{**}_{CPA} are obtained:

D_1 = (15,25 ÷ 10,60) for β = 0,95 ε = 0,07 miles

D_2 = (10,36 ÷ 0,60) for β = 0,95 ε = 0,07 miles

D_3 = (5,56 ÷ 0,60) for β = 0,95 ε = 0,039 miles

The diagrams in fig. 4 and 5 indicate that the drift is the preserved constant for the better part of the observations. The above result is confirmed for observations, carried out with variable values of the drift (from ±0° ÷ 1,1°) when following a large marine target from a distance of 10,27 miles to CPA= 1,52 miles. The results for the interval limits for m^{**}_{CPA} are:

D_1 = (10,27 ÷ 1,52) for β = 0,95 ε = 0,57 miles

$D_2 = (6{,}05 \div 1{,}52)$ for $\beta = 0{,}95$ $\varepsilon = 0{,}02$ miles

In this example the differences are even more substantial.

The above examples lead to the conclusion that at distances longer than 6 NM the ARPA error in the calculated CPA is substantial. Under the conditions of a variable drift, this error is dynamic, as well. That is also seen by formula (4) in which the drift value is included in the angle α. The direction of drift change also determines the direction of CPA change – when the drift is in the direction towards the target, ARPA will calculate CPA as being less than the actual and vice versa.

The above conclusions require still another parameter to be added to the degrees of trustworthiness in ARPA. In this case it is a new one in respect to the conditions of steering the ship through IBNS in Track Mode.

3. CONCLUSION / *Zaključak*

Integrated bridge navigation system is the state-of-the-art navigational equipment. Its data is widely used especially for safe passing ships. Closest point of approach is great important parameter when our ship sales around small targets, in heavy traffic and in condition of restricted visibility. Because of this the navigator shell knows the character of errors in the calculated closest point of approach by integrated bridge navigation system, the reasons that create these errors and the correlation between them. This article presents some experiments carried out in the East China Sea on board of container ship. The correlation between different errors from the ship's course and speed sensors in the integrated bridge navigation system and closest point of approach is analysed. The data is obtained in "track mode" and in "heading mode" of ship's course control.

The analysis made and the conclusions regarding the influence of the drift and the distance to the target, followed by ARPA, have a direct impact on providing the ship's safety. The criterion "Closest Point of Approach" with the targets is important for the ship navigators and they should be aware of the extent to which they could trust the equipment which provides these data. The Track Mode of steering, with its specific from mathematical point of view peculiarities, changes some of the accepted so far laws of the distribution of the fortuitous values characterizing the safety of shipping, in this case CPA.

The above stipulations and conclusions should mandatory be taken with the reservation that they are only valid for conditions of heavy traffic with restricted space for manoeuvring. In case sufficient space for avoiding a close-quarters situation is available, COLREG-72 rules should be followed.

To this end, it may in the future create a software solution for the quick route profile calculation and voyage optimization or it may be useful for *analysis of* critical *navigation* information *only*.

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