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Behaviour of Navigators in Critical Traffic Situations

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BEHAVIOUR OF NAVIGATORS IN CRITICAL TRAFFIC SITUATIONS

by

KONRAD LIMBACH

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BEHAVIOUR OF NAVIGATORS IN CRITICAL TRAFFIC SITUATIONS¹

by

KONRAD LIMBACH²

Abstract

For application in a mathematical model for calculating the probability of collisions investigations were performed to quantify the behaviour of navigators in critical marine traffic situations. Navigators with long experience were tested using a radar simulator and a questionnaire. Varying the speed of ships involved in the encounter, the relative bearing and the initial miss distance as parameters we recorded the range to the target ship when beginning to evade, kind and number of evasive manoeuvres, and maximum change of heading. The results show that navigators do not necessarily act in accordance with the official Rules of the Nautical Road. When a give-way vessel is approaching on an exact collision course the evasive behaviour of the test persons steering the stand-on vessel (as measured by the range at evasion) could be described by a bimodal distribution curve. The variation of the initial miss distance revealed certain response levels which trigger evasive action in different types of encounter.

1.0 Introduction

Naval architects often face the question what economic and safety benefit will be achieved by improving the manoeuvrability of ships, a question which at present can only be answered verbally and qualitatively. As this state is rather unsatisfactory, we have made some efforts to find out criteria by which

¹This work was done within the framework of the *Sonderforschungsbereich 98 "Schiffstechnik und Schiffbau"* at the *Institut für Schiffbau* with the financial support of the *Deutsche Forschungsgemeinschaft*.

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the influence of manoeuvrability on safety would become calculable and predictable.

A suitable criterion seems to be the rate of collision defined as the expected average number of collisions per unit time when passing a certain traffic area, see Krappinger (1972). The problem of collision avoidance is of course not only a question of better manoeuvring devices but to a great extent a problem of human behaviour too. In the system Man - Ship - Environment the element man is of crucial importance.

A navigator on board a ship receives a lot of data concerning number, course, speed and type of other ships in the area, weather and sea-state and possibly restrictions imposed by regulations (e.g. traffic lanes) or by natural circumstances. He has to collect and to process this information in order to come to a clear and realistic assessment of the scene. It depends on his judgement of the situation, his knowledge of the Rules and his estimation of the manoeuvrability of both ships, his own and the other ship, whether a given dangerous situation will lead to a collision. For this reason the question of the safety benefit of improved manoeuvring qualities cannot be answered without a knowledge of the behaviour of navigators in critical traffic situations.

In the situation shown in Fig. 1 capital letter O means own ship and capital letter A means the other ship, Greek letter α means the bearing from O to A , r_0 is the initial range and m is the miss distance if both ships do not take any evasive action. Here ship O has to stand on because the give-way ship A is crossing from port and a risk of collision is present ($m \approx 0$). According to the Rules ship A has to give way by an early and substantial action. However, ship O may take action to avoid collision by herself, when it becomes apparent to her that the other vessel is not taking appropriate action. If for whatever reason ship A does not take action, the occurrence of a collision depends only on the behaviour of ship O : If O is estimating the capability

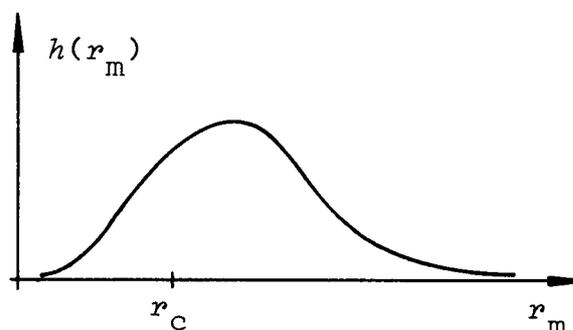
of A correctly and executes the proper last-minute evasive manoeuvre the collision will be avoided. This kind of situation was the primary object of our investigation because it is here that the manoeuvring capability plays a significant role in collision avoidance.

2.0 Basics

Following the concept used in the reliability theory of structural safety, where demand and capability of a structure are compared, we looked for a way of applying this concept to the problem of collision avoidance between ships.

In our context the demand is given by the environmental circumstances and the manoeuvrability of the ships involved, the capability is determined by the behaviour of navigators. It follows from physical considerations that ships approaching on a collision or almost collision course have to make an evasive manoeuvre at a certain critical range r_c . If they act at a range less than r_c , collision becomes unavoidable whatever they may do. For a given situation and known manoeuvrability of the ships the critical range r_c is calculable by means of the *Theory of optimal control* or the *Theory of differential games*, see Miloh and Sharma (1975).

Normally navigators do not know this critical range r_c , they are forced to estimate the manoeuvring qualities of the ships involved and to guess their mutual intentions. Thus, the range r_m at which navigators act in reality shows a random distribution with a probability density $h(r_m)$:



By comparison of the actual evasive behaviour r_m and the theoretically necessary range r_c we can define the probability of collision p_c under the condition that the give-way vessel does not evade:

$$p_c = \text{prob. } \{r_m < r_c\}$$

With known $h(r_m)$, p_c becomes

$$p_c = \int_0^{r_c} h(r_m) dr_m$$

This model is valid for collisions caused because the last-minute manoeuvre was not executed in time, or indirectly due to a lack of adequate manoeuvrability.

Our investigations on the behaviour of navigators were carried out according to this model, assuming open sea and a low traffic density.

Before proceeding further, I would like to emphasize that it was not the purpose of our investigation to detect causes for the wrong action of navigators in the sense of the Rules or to discuss the quality of the actual Rules. We were mainly interested in the question of how navigators do act in reality in so far as this is pertinent to the naval architectural aspects of the problem.

3.0 Details of the investigation

3.1. Methods of investigation

As measurements on board actual ships were excluded a priori because of their great expenditure in time, personnel and money, the following methods remained for investigating the behaviour of navigators in critical situations:

a) Evaluation of casualty reports of the Admiralty Courts.

It appeared that this method was not practicable because the evidence given before the courts by the navigators involved in a collision is sometimes extremely contradictory so that it cannot be used to study the behaviour of navigators in critical situations. Moreover, casualty reports contain no figures on the total frequency of critical encounters.

b) Measurements on a Ship-Handling-Simulator.

This method seemed to be a very suitable one, but upon evaluating the major European installations operating at Bremen, Wageningen and Gothenborg we realized, that these facilities could only simulate one moving ship at a time. As we intended to operate for our purposes with two freely movable objects, this method too had to be withdrawn from consideration.

As further methods remained

c) Experiments on a Radar simulator and

d) Questionnaires on selected traffic situations.

With these two methods the investigations were carried out.

3.2. Radar simulator

3.2.1. Radar simulator used

For our experiments we used the radar simulator of the *Hochschule für Nautik Bremen*. This simulator, which is controlled by a freely programmable computer (System Redifon), can display besides the own ship (ship 0) up to nine other ships (ships A), see Lübbers and Zajonc (1973). The test person controls his ship by means of rudder and engine manoeuvres. The trajectories of the ships are simulated by simplified equations of motion. An x-y-plotter records the trajectories during the experiments. In addition to this automatic recording for our investigations the test persons had to manually note down their observations, decisions and commands to enable a complete evaluation of the experiments.

3.2.2 Test persons

The test persons were experienced navigators visiting the *Hochschule für Nautik* for post-graduate courses. The experiments were carried out before the beginning of the course, so that the results of our investigations were not influenced by the subjects taught in the following course.

3.2.3 Test programme

Traffic conditions which remained constant for all test runs:

- a) Clear visibility
- b) Free, unconfined sea
- c) Initial range $r_0 = 5$ nm
- d) Ship 0: a container ship (length about 270 m, speed: 25 kts).
- e) Ship A, approaching from port despite being the give-way vessel kept speed and course constant so that a collision could only be avoided by ship 0.

Traffic conditions which were systematically varied from test run to test run:

- f) Ship A was either a container ship of the same type mentioned above or a tanker (length about 300 m, speed = 15 kts).
- g) Two-ship encounter
 - 1) Ships approaching at steady bearing ($m = 0, \dot{\alpha} = 0$)
 - 2) Ships approaching at almost steady bearing ($m \neq 0, \dot{\alpha} > 0$, maximum $|m| = 0.9$ nm).
- h) Traffic situations with more than two ships on the radar screen, but only one of them is approaching ship 0 at steady bearing.

These items were recorded:

- a) r_a : the range at which the situation was analysed by the navigator of ship 0
- b) r_m : the distance at which ship 0 started an evasive manoeuvre
- c) kind and number of evasive manoeuvres (rudder angle δ_{R_0} and change of engine setting)

- d) $\Delta\theta_o$: change of heading of ship 0
- e) t_M : duration of the evasive manoeuvre
- f) m_a : nearest distance to ship A when passing her (actual miss distance)

3.3 Questionnaire

3.3.1 General remarks

The questionnaire method has, so far as I know, not yet been used to investigate and to quantify the behaviour of navigators. Therefore the methodology used will be explained in more detail than for the method of radar simulation, which is known also from other publications, see especially Kemp (1973). There were some objections against questionnaires in the nautical field:

- the traffic situation is not displayable realistically
- the sense-stimulus of the environment is missing
- the persons questioned could have the feeling of being examined
- the persons questioned could intentionally bias the results
- the rate of return would probably be very low.

The reason why this method was used despite all the objections was the expectation of achieving the aim with a moderate expenditure.

Bearing in mind the objections, some suitable modifications were introduced.

- The navigators were interrogated personally by the author instead of the usual method of dispatching the questionnaire by mail. At first the possibility of interviewing ship officers during the loading/unloading operations in port was considered. But one can imagine that the willingness to give interviews would have been very small during the short stay in port, especially in view of the relatively high work load at such times.

The most suitable opportunity for our task turned out to be

the interrogation of navigators participating in post-graduate courses of four German nautical colleges.

- To avoid the feeling of examination, the navigators were assured at the beginning of the interview that all answers and remarks would be handled anonymously. In general the interviews were performed in a very relaxed atmosphere.

- The display of the situations on paper taxes the imagination of the persons tested. In an attempt to simulate the conditions in practice, the situations were given fully plotted on a radar-plotting-sheet in a manner rather familiar to the navigators. Furthermore, they were informed of the types of both ships. The situations were already analysed so that they only had to decide what action to take. These are conditions which by all means are often met in practice when sailing under radar. The sailor watching the radar screen passes on his observations to the officer on watch who for his part has to convince himself by looking at the marks plotted on the screen and then has to make his decisions. Fig. 2 gives an impression of the kind of display chosen. The interrogation was carried out individually and in groups. A comparison of the results of both methods did not show any significant difference in the statistical mean.

3.3.2 Test programme

The general traffic conditions were the same as in the experiments at the radar simulator. However, the number and kind of situations presented to the navigators were enlarged. Altogether there were presented 65 different situations.

- Ship A is approaching at port
 - Ship A is approaching at starboard
 - Ship A is overtaking
 - Ship A is in a head-on situation
- The initial range r_0 is about 7 - 8 nm, (r_0 is the range at

which the second bearing is taken and the plotting procedure completed).

- The miss distance m was taken as

$$m = \{0; \pm 0.5; \pm 2.0 \text{ nm}\} .$$

m positive means crossing astern of own ship O ,

m negative means crossing ahead of own ship O .

In head-on and overtaking situations m positive means passing on starboard, m negative means passing on port.

- The types of ship were the same as in the investigation at the radar simulator, with the difference that for the questionnaire both ships O and A were varied.

- These items were noted down:

a) r_m : the range at which the test person would evade

b) kind and number of evasive manoeuvres (rudder angle δ_{R_O} and change of engine setting)

c) $\Delta\theta_O$: change of heading of ship O

d) other nautical activities, e.g. giving signals.

3.3.3 Experiences with the interrogation

When performing the interrogation for the first time, the author was very anxious to know how this method would work. The results were very encouraging, so that the interrogation could be continued.

The fact, that the test persons were off duty during the interviews helped to generate sufficient interest and willingness to answer our questions.

My impression is that navigators will support all reasonable efforts aiming at the improvement of the safety at sea. I never had the feeling that the navigators tried to influence the investigations consciously or to just produce a good impression. This statement is valid for both methods applied.

A comparison of the results of both methods shows a good correspondence with regards to the range r_m and the kind of evasive manoeuvres taking into consideration the different initial conditions. In the questionnaire the situation presented was ready for decision, whereas in the radar experiments the situation at first had to be analysed.

4.0 Results

The results are based on 213 runs on the radar simulator and on the interrogation of 71 navigators. They may not be representative for all traffic conditions, but in the situations investigated they show how navigators will act. Therefore they deliver realistic figures for the computation of the probability of collision under conditions assumed at the tests.

4.1. Behaviour of ship 0 being the stand-on vessel

In this situation ship A is approaching at steady bearing from port, she has to give-way, while ship 0 has to keep course. As ship A does not manoeuvre according to our testing strategy, the collision can only be avoided by ship 0. The trajectories depicted in Fig. 3 give an impression of how the navigators tested evaded. The ranges r_m at which ship 0 has taken action are given as a histogram in Fig. 4.

The behaviour in such stand-on situation is not uniform. One can distinguish clearly two groups. One part of the persons tested is apt to evade immediately or very early while the other part awaits an evasive action of the give-way ship A and acts only after such action fails to appear. Those who evade immediately or soon after recognizing the threat posed by the other ship may be called preventive evaders. They do so disregarding the Rules. It seems that they tend toward more safety, but it has to be said that this is a misleading feeling. Both ships may come again in steady bearing if ship A does evade after all as required by the Rules while ship 0 manoeuvres simultaneously

disregarding the Rules. In such a case ship O could cancel the success of the manoeuvre of ship A with the effect that the situation becomes more complicated.

The histogram shows the results for a speed ratio $V_O/V_A = 1$ and for an encounter tanker/tanker. The results for other ratios and encounters investigated are similar. There are always two kinds of behaviour.

The behaviour of our test sample changes when the distance m is increased. The evasive behaviour in crossing-astern situations differs from that in crossing-ahead situations. Fig. 5 shows the results for $m = \pm 0.5$ nm, i.e. crossing astern or ahead respectively of own ship O . The opinions on the danger involved in the situations diverge considerably. While some of the navigators evaded early, others did not take any action. Summarizing the results for these situations, it seems that navigators consider crossing-ahead encounters ($m < 0$) as more dangerous than crossing-astern encounters ($m > 0$).

In the situations with a miss distance $m = \pm 2$ nm uniform behaviour was found. All persons tested kept speed and course constant. From this one can conclude that navigators feel quite safe if the miss distance is equal or greater than 2 nm.

Of some interest is the question whether the evasive behaviour depends on the relative approaching speed. The great difference in the speed of the types of ship was chosen with a view to clarifying this aspect. The investigations were carried out with the \hat{H} -Test by Kruskal and Wallis (1952), which is a suitable statistical test for this problem, see Kruskal and Wallis (1952). It could be shown that in crossing-ahead ($m < 0$) and direct collision ($m = 0$) situations the behaviour is independent of the relative velocity. Otherwise in crossing-astern situations ($m > 0$) a dependence of the evasive behaviour cannot be excluded. That means that navigators do not distinguish between more or less dangerous approaching speeds when the give-way ship is on a collision or a nearly collision course crossing-ahead of own ship. However, in crossing-astern situations they distinguish

between more or less dangerous relative velocities.

Such a complex matter as the behaviour of navigators in critical traffic situations can be described of course by more than one parameter. As further parameters suitable for our purposes we chose the number and kind of evasive manoeuvres.

Fig. 6 gives information about the rudder angles δ_{R_0} commanded to avoid collision. There are two favoured ranges: navigators take action either using rudder angles $10^\circ \leq \delta_{R_0} \leq 20^\circ$ or they put the helm over. This result is typical of all other situations referred to later on.

Fig. 7 depicts the changes of heading $\Delta\theta_0$ resulting from the evasive manoeuvres which were carried out nearly all to starboard.

Engine manoeuvres were hardly ever run. This fact was to be expected because of the small effectiveness of late engine manoeuvres as collision avoidance manoeuvres.

The question of correlation between r_m , δ_{R_0} and $\Delta\theta_0$ was investigated using the *Rank-correlation test* with ties according to Spearman, see Kendall (1962). A clear significance in the statistical sense was not detectable. However there exist the following trends:

- large ranges r_m coincide with small changes of heading $\Delta\theta_0$
- large changes of heading $\Delta\theta_0$ coincide with large rudder angles δ_{R_0} .

4.2. Behaviour of ship 0 being the give-way vessel

In this section I want to present the behaviour of navigators, when own ship is the give-way vessel.

Fig. 8 shows the results with regard to r_m when ship A is sailing at starboard and approaching at steady bearing, i.e. ship 0 is the give-way vessel. For the most part the persons tested

evaded immediately (indicated by the column at $r_m = 7$ nm) or very early. Only few navigators took action at a range r_m less than 4 nm.

Fig. 9 depicts the range r_m , when ship *A* is approaching on a head-on course. In this case both ships, ship *A* and ship *O*, have to give way. In these situations too, navigators take the evasive action required very early. (The column at $r_m = 7$ nm represents those who would evade immediately).

Summarising the results of these two give-way situations, it can be said, that the test persons act as give-way navigators in a quite different manner than as stand-on navigators. This statement is not surprising, the results have been expected at least qualitatively. That the behaviour expected could be verified by our methods allows the conclusion that the navigators tested handled the situations presented as they would have done it in practice.

4.3. Variation of the initial miss distance m

As a last point I want to present the evasive behaviour as a function of the miss distance m .

Defining

$$\kappa = \frac{\text{Number of navigators taking action}}{\text{Total number of navigators tested}}$$

and plotting κ for all types of encounter investigated as a function of m , Fig. 10 was obtained. In this drawing the full line in the columns denotes the part of the navigators evading and the dashed line denotes the part of the navigators not evading.

We now connect the ends of the ordinates κ by a curve. Assuming as a probable slope of the resulting curve $\kappa' = 0$ at points where $\kappa \rightarrow 0$ and $\kappa \rightarrow 1$ respectively, we can plot the dotted lines in Fig. 10.

A first view shows an evident unsymmetry in the case where the give-way ship *A* is crossing astern of own ship *O*. Presumably the reason for this is that the give-way vessel is always expected to carry out its evasive manoeuvre to starboard. Such a manoeuvre would indeed clear a situation very promptly even if carried out rather late.

The curves in Fig. 10 can be considered as an index for the feeling of security with regard to the miss distance m . The question where navigators feel secure and where navigators are motivated to take action can easily be answered by these curves. We get the critical miss distance m_c where κ becomes zero. For the different types of encounter we obtain the following values for m_c :

Ship <i>A</i> from port, astern	$m_c = 1.5$ nm
Ship <i>A</i> from port, ahead	$m_c = 2.0$ nm
Ship <i>A</i> from starboard, astern	$m_c = 1.9$ nm
Ship <i>A</i> from starboard, ahead	$m_c = 2.0$ nm
Ship <i>A</i> head-on, passing port	$m_c = 1.25$ nm
Ship <i>A</i> head-on, passing starboard	$m_c = 1.25$ nm
Ship <i>A</i> overtaking at port	$m_c = 1.0$ nm
Ship <i>A</i> overtaking at starboard	$m_c = 1.0$ nm

For the conditions given all encounters with an initial miss distance $m > m_c$ are considered as safe.

For encounters in which $m < m_c$ the value of κ indicates the probability that navigators will take action.

5.0 Final remarks and acknowledgements

These investigations are only a small contribution to the great field of the behaviour of man on board ships. In accordance with our specific aim they were restricted to a very small sector. Naturally not all questions could be answered, and in fact several new questions have arisen. Nevertheless, I hope that these

investigations will stimulate more extensive research in this field.

Coming to the end of my contribution I would like to thank all those persons who have enabled and supported these investigations. My special gratitude goes to Mr. Lübbers and Mr. Zajonc from the *Hochschule für Nautik Bremen* for their cooperation and advice during the tests at the radar simulator.

Furthermore I am grateful to the directors of the nautical colleges at Hamburg, Mürwik and Neustadt for their support of the interrogations and last but not least I am obliged to the tested and interrogated navigators for their willingness and patience during the investigations.

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List of symbols

A	The other ship
O	The own ship
m	Miss distance (to be expected if neither ship manoeuvres)
m_a	Miss distance actually obtained after evasive manoeuvre
m_c	Critical miss distance
p_c	Probability of collision
r_a	Range at which the situation was analysed
r_c	Critical range at which own ship must evade
r_m	Range at which ship O evades
r_o	Initial range
t_M	Duration of the evasive manoeuvre
V_A	Speed of ship A
V_O	Speed of ship O
V_{rel}	Relative speed (see Fig. 1)
α	Bearing angle of O relative to A
$\dot{\alpha}$	Time derivative of α
δ_{R_O}	Rudder angle applied in evasion by ship O
θ_A	Course angle of ship A
θ_O	Course angle of ship O
$\Delta\theta_O$	Change of heading of ship O effected in evasion
κ	Ratio of number of navigators evading to total number of navigators tested
κ'	Derivative of κ

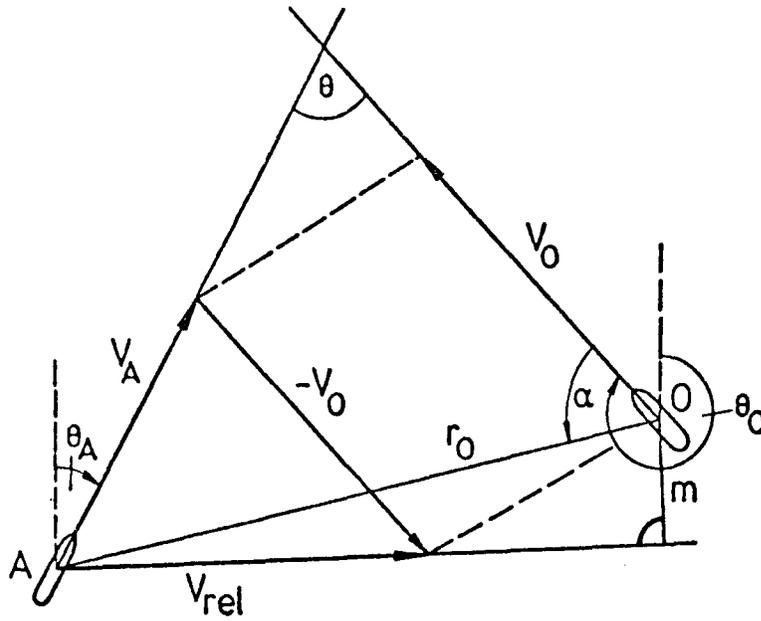


Fig.1 Geometry of two-ship encounter

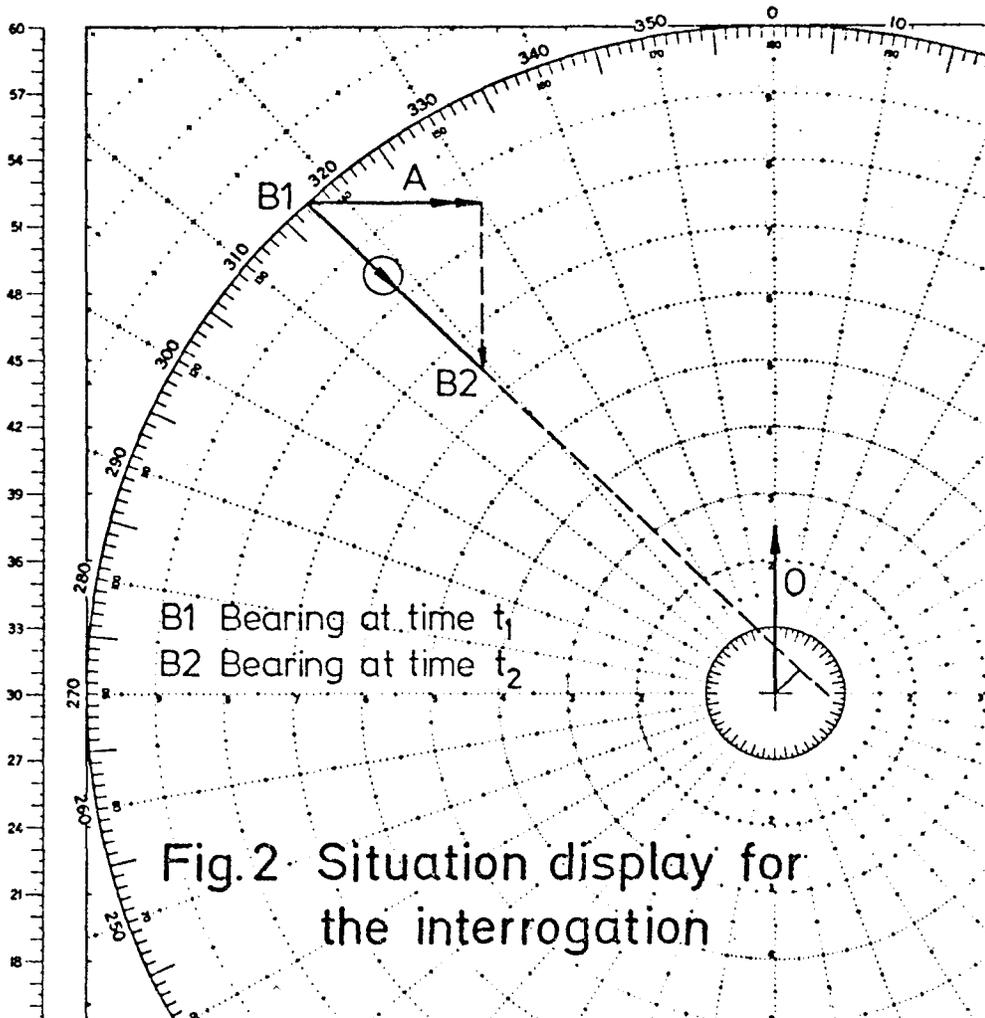
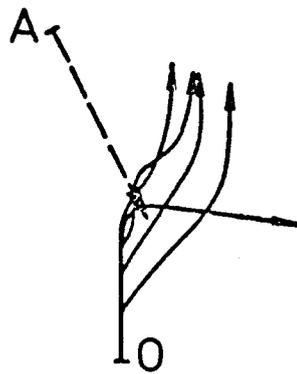
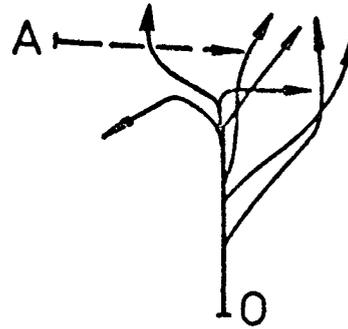


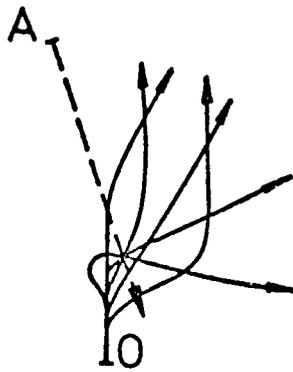
Fig.2 Situation display for the interrogation



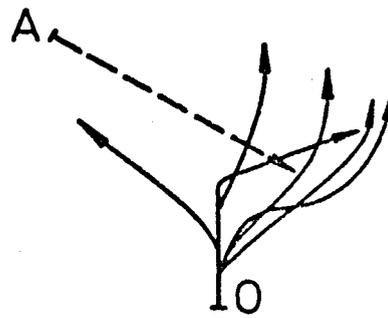
$V_A = 15$ kts
 $V_O = 25$ kts



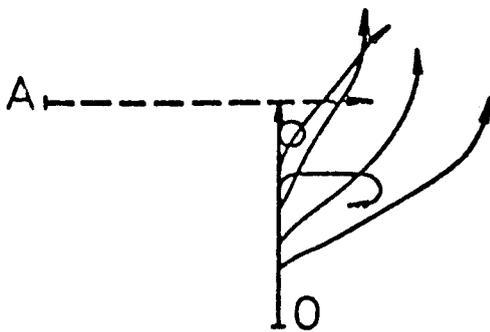
$V_A = 15$ kts
 $V_O = 25$ kts



$V_A = 25$ kts
 $V_O = 25$ kts



$V_A = 25$ kts
 $V_O = 25$ kts



$V_A = 25$ kts
 $V_O = 25$ kts

Fig. 3
 Evasive Behaviour
 of Ship 0
 (Trajectories)

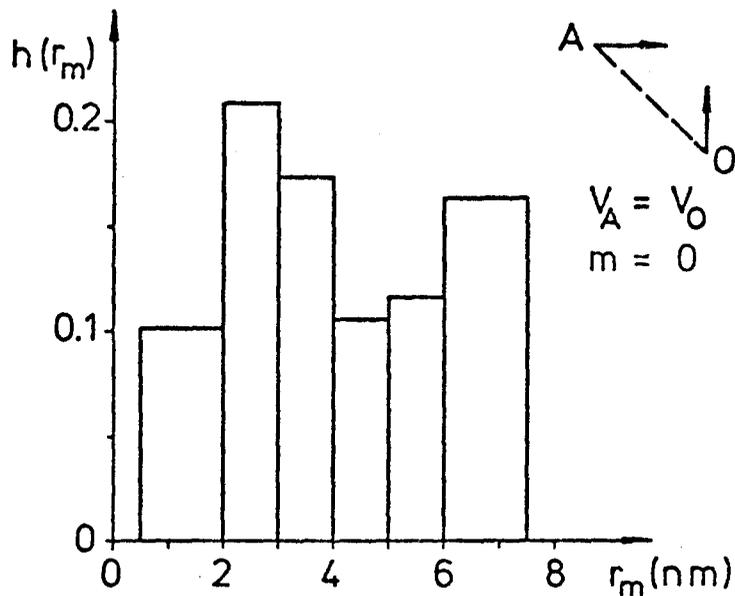


Fig. 4 Histogram of evading range r_m (Ship O is the stand-on vessel)

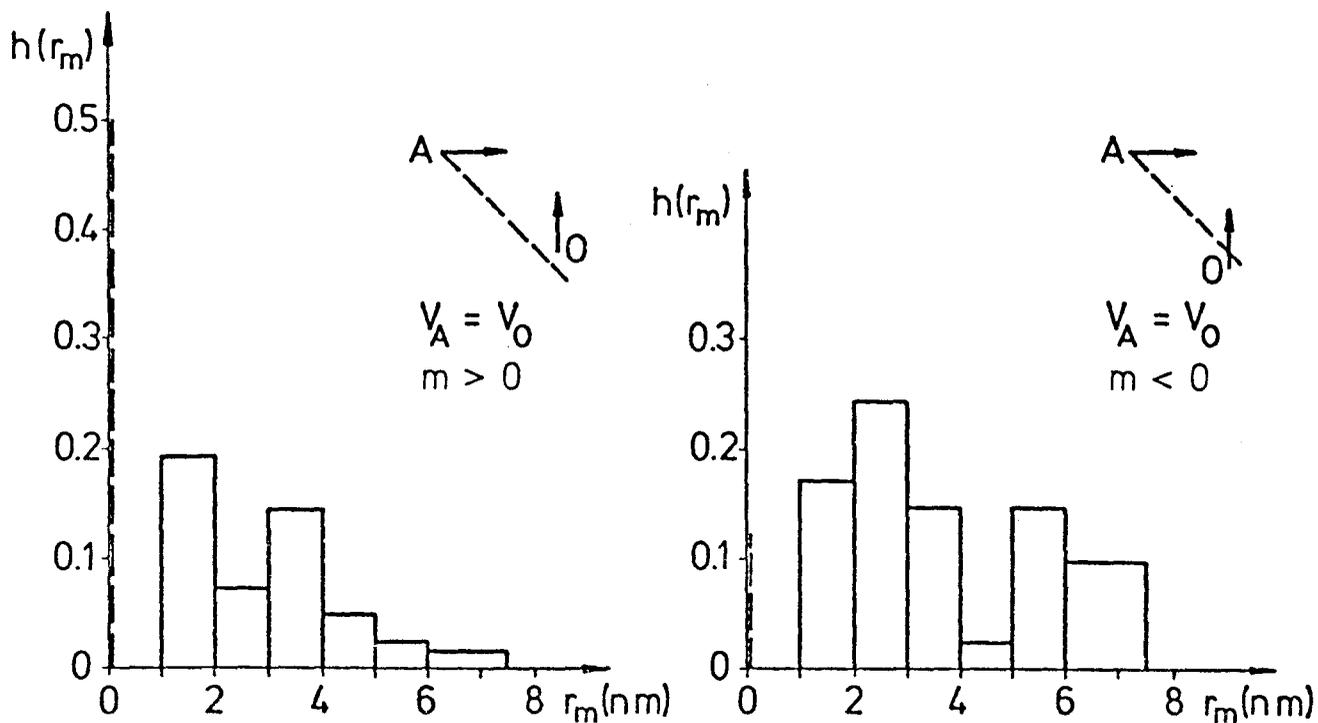


Fig. 5 Histograms of the evading range r_m

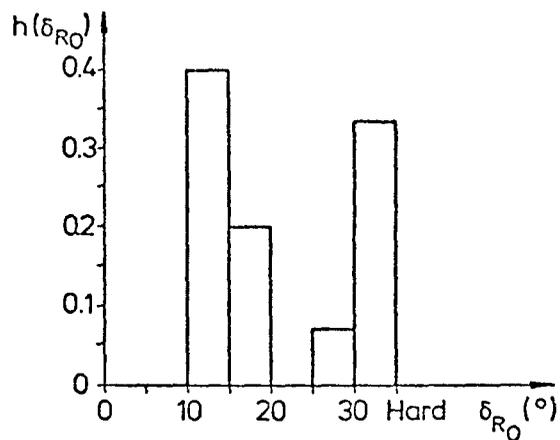


Fig. 6 Histogram of rudder angles δ_{R0} applied in evasion

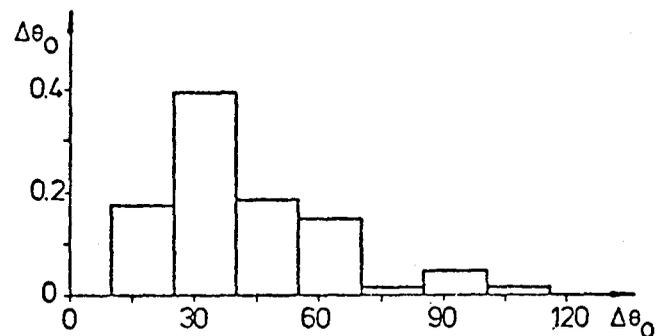


Fig. 7 Histogram of the changes of heading $\Delta\theta_0$ effected in evasion

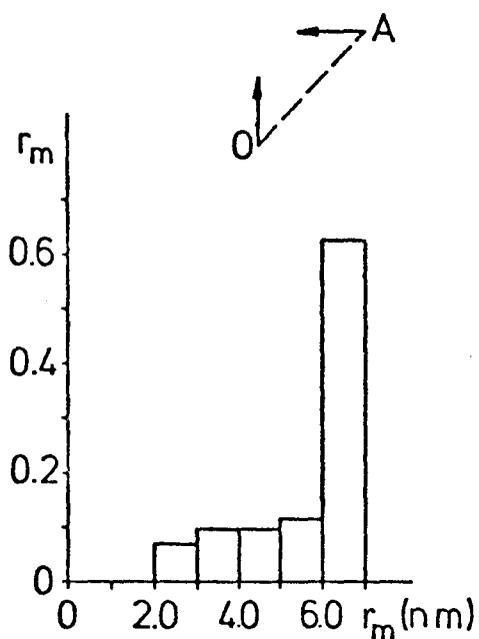


Fig. 8 Histogram of the evading range r_m . (Ship 0 has to give-way)

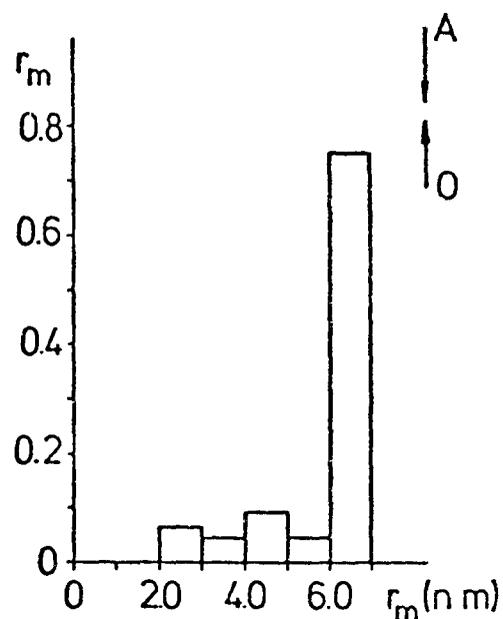


Fig. 9 Histogram of the evading range r_m . (Both ships have to give-way)

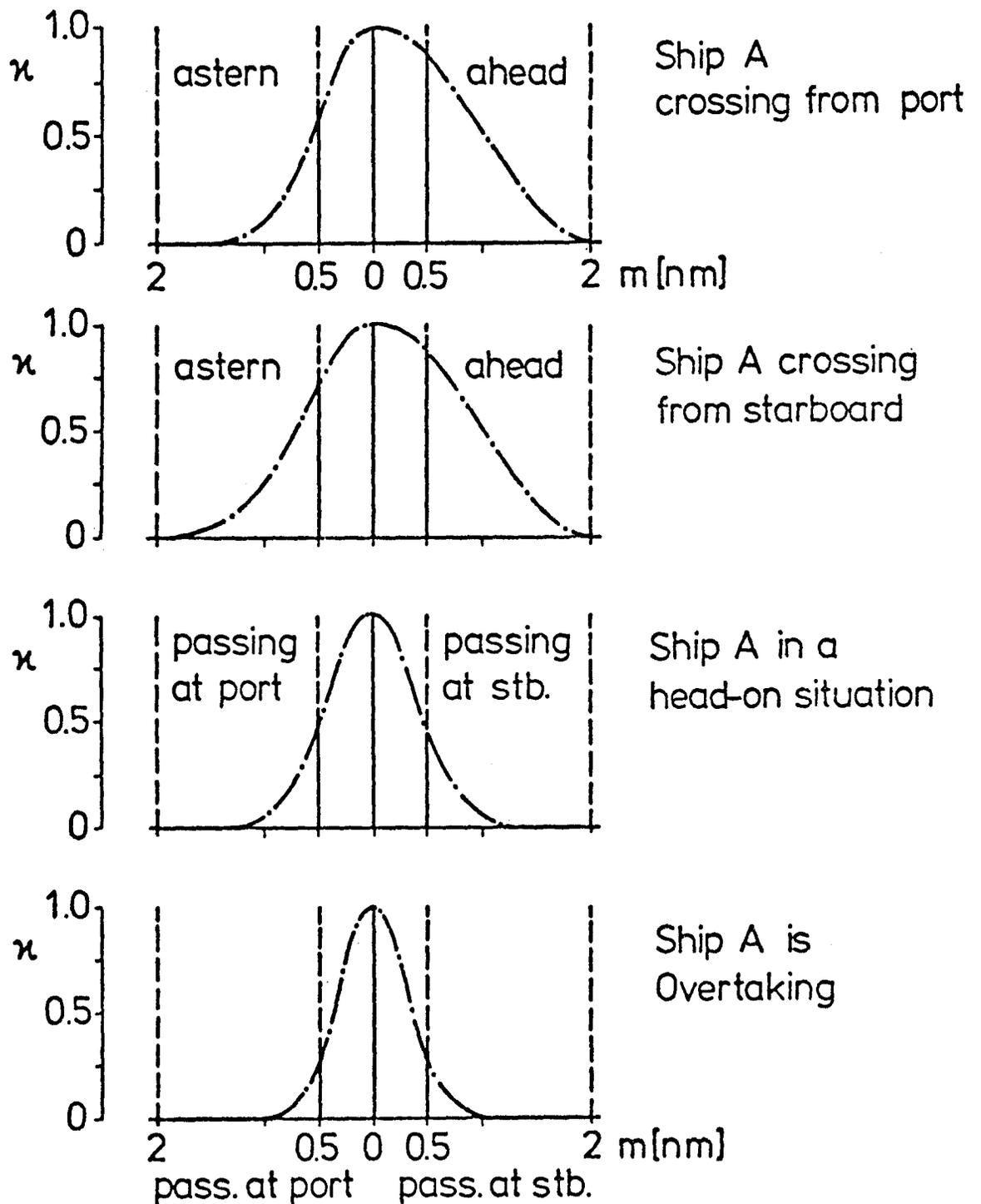


Fig.10 Evasive behaviour of Ship 0 as a function of the miss distance m