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COMPUTER MODELLING OF MARINE TRAFFIC BEHAVIOUR

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COMPUTER MODELLING OF MARINE

TRAFFIC BEHAVIOUR

Paul Vernon Davis, B.Sc (Hons)

This thesis is submitted to the Council for National Academic Awards in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

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DECLARATION

No part of this thesis has been submitted for any award or degree at any other institute.

While registered as a candidate for the degree of Doctor of Philosophy the author has not been a registered candidate for another award of the C.N.A.A. or of a University.

Copies of material published in connection with this research in The Journal of Navigation are bound at the end of the thesis.

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ABSTRACT

The increase in marine traffic has resulted in the need for traffic routing schemes in areas of high vessel density. In order to assess the viability of a scheme before it is brought into use a simulation study can be used.

This thesis describes the construction of a computer model to simulate the behaviour of mariners using the concepts of domains and arenas to control their actions. The arena is an area around a ship where one navigator takes account of another ship's presence. The domain is the area around his ship which a navigator wishes to keep clear of other vessels and stationary objects.

The model is validated against data gathered in the Dover Strait from the coastguard radar station at St. Margaret's Bay and from experiments conducted in a radar training simulator. The model is shown to produce realistic results for vessels overtaking one another and for vessels meeting with a collision risk 96 per cent of situations can be realistically simulated.
GLOSSARY

Calcomp  Graph plotter linked to the computer with its own routines.
C.P.A.    Closest Point of Approach.
C.P.A.D.  Closest Point of Approach to Domain centre.
D.H.A.    Desired heading with alteration.
F.C.R.I.  Fog Collision Risk Index.
N.M.I.    National Maritime Institute.
T.C.P.A.  Time of Closest Point of Approach.
T.R.S.    Traffic Routing Scheme.
Ushant    Isle d'Ouessant. Island off North-West France.
CHAPTER 1

INTRODUCTION

SECTION 1.1

Traffic Routing Schemes

The increase in the size and number of ships in the 1960's and 1970's together with the increase in casualties (IMCO (1980)) has resulted in greater control of marine traffic in congested waters by the use of Traffic Routing Schemes (T.R.S.). These schemes have sometimes been hastily constructed and forced upon regulatory bodies due to the weight of public concern shown after marine accidents.

On 1st June, 1967, a Traffic Separation Scheme for the Dover Strait was introduced (Fig. 1.1). This scheme was recommended by the Inter-Governmental Maritime Consultative Organisation (IMCO), a branch of the United Nations, but was entirely voluntary. It consisted of a re-stating of the rule that vessels in narrow channels should keep to the starboard side, together with laid down separation zones. In 1971 the Texaco Caribbean sank after a collision on January 11th. The next day the Bradenburg struck the wreck and sank, while on 27th February the Niki did the same. Following this series of disasters the United Kingdom government decided that voluntary enforcement was insufficient, and in September 1972 it became compulsory for all U.K. registered ships to use the traffic scheme.

The incidents of the Torrey Canyon and Amoco Cadiz, while resulting
FIG. 1.1  THE CURRENT TRAFFIC ROUTING SCHEMES
through totally different causes, produced the same catastrophic effects of oil pollution for sealife and seashore. Scenes of this devastation were shown on television, newspapers and magazines activating politicians, the public and ecology groups to bring pressure on the regulatory bodies concerned with marine safety. In reaction to this pressure the French government, in notices to mariners, banned all tankers from its territorial waters. A new T.R.S. was constructed for the region of Isle d'Ouessant which kept tankers a long way offshore (Fig. 1.1), consisting of three traffic lanes. The lane nearest to land is for North-East bound vessels, except laden tankers, the next lane is for South-West bound traffic with tankers keeping to the outer half of the lane. Lastly the lane furthest from the coast is for North-East bound laden tankers. This scheme produced the desired effect of keeping laden tankers a long way from the coast, but as it is not homogeneous with the T.R.S. further up Channel it has resulted in a dangerous situation off the Casquets which has been surveyed by Chalk and Coupard (1980).

Traffic passing through territorial waters is regulated by the coastal state, and must conform to the rules laid down by that state. The extent of territorial waters is not uniform. As Ringdal (1981) points out the French have a 12 mile territorial area, while the British zone only extends for 3 miles. The French can fine violators of the T.R.S. within their territorial zone on the spot, or if need be arrest the vessels and take them to Brest.
On the high seas, which comprises all the water not claimed by states as territorial waters, traffic regulation is operated by IMCO. IMCO currently regulates about 75 separation schemes in the world, together with a number of advisory deep-draught routes. The major influencing factor on these schemes is Rule 10 of the Collision Regulations (1972) (see Appendix 4), which has made it mandatory to abide by the IMCO rules. A vessel violating an IMCO scheme on the high seas is reported to its flag state for punishment. Some states are rather lax over enforcing the regulations, but since July 1977 when the Collision Regulations (1972) took effect about 250 fines have been levied for violation of Rule 10 (Ringdal (1981)). A vessel violating a T.R.S. is in a weak defensive position. A mariner violating an IMCO scheme, if something should go wrong, is also likely to be very unpopular with his insurers.

Before IMCO introduces new schemes, or modifies existing ones, individual governments take advice from mariners as to the actual form the scheme should take. Very little work has so far been carried out to simulate the effect of the different schemes when they are considered at the consultative stage (an exception being Degré and Lefevre (1981)), and sometimes political pressure can over-rule objections from mariners.

Parker (1978), in an open discussion of various schemes proposed for the English Channel, argues that traffic separation schemes are needed in areas of high ship density as uncertainty exists when
more than two ships meet. When traffic density is low the Collision Regulations apply to all two ship encounters but as the density increases these rules become less certain. Cockcroft (1981) has shown that by introducing routeing schemes the navigators are given guidelines so that the most risky encounters are reduced. Some mariners directly concerned with the problem of the Dover Strait would appear to take the opposite view. Irving (1981) puts forward the concept that part of the Dover Strait Traffic Separation Scheme should be down-graded to a Precautionary Area in order to allow for the number of crossing vessels to be encountered off Dover.
SECTION 1.2
Collision Risk

Silverleaf (1973) states, "the aim of the traffic engineer is to permit the maximum degree of freedom for individual vehicles and people consistent with safety for all directly or indirectly affected by their movement. Indeed it is a basic principle that traffic flow and safety cannot be considered separately". He goes on to state that the benefits should outweigh the costs in any traffic scheme, but it is difficult to assess to whom the benefits accrue and on whom the costs fall. It is possible that overall benefits may result from imposing disbenefits upon individual operators, as may be the case in the Dover Strait.

In order to assess the benefits accruing from a certain T.R.S. we need to have a series of rules from which to work. Fujii (1977) and Lewison (1978), amongst others, have used various shapes around ships to describe collision risk within certain waters. Fujii has used the term 'collision diameter' to describe an ellipse about a ship which, if infringed by another vessel, shows a collision risk occurs. Fujii's collision diameter is dependant upon the ship's length, while Lewison chose a circle of arbitrary radius 0.5 n. miles in order to produce similar results.

Goodwin (1975) proposes that there is an "area about his ship which a navigator wishes to keep clear of other vessels and stationary objects". This area is called the domain, and can be calculated by
looking at the density of shipping about each ship in turn. If there were no interaction the density of shipping will be constant at any distance from the central ship. The graph of density against distance (Fig. 1.2) shows the relationship not to be constant, but rather some ships close to the central ship have been displaced outwards.

Glansdorp and Goldsteer (1981) incorporated the concept of the domain into their calculations when calculating the traffic flow through a channel or river. The movement of ships carrying ecologically sensitive cargoes (crude oil and liquified natural gas) was examined in order to determine where, during their passage, they are at greatest risk. This calculation needed to allow for the depth of available water, the width of the channel, the state of the tide and movement of other traffic within the same waterway. Glansdorp and Goldstein allow for a domain and prevent vessels from passing where the narrowness of the channel means the domain would be infringed.
FIG. 1:2  GRAPH OF DENSITY AGAINST DISTANCE
SECTION 1.3

The Role of Simulation

The major cause of ship casualties is human error. The Panel on Human Error in Merchant Marine Safety (1976) showed that 85\% of all collisions were due to human error. The tolerance for human error has decreased greatly over the years with the introduction of large, fast, highly sophisticated ships meaning the consequences of any accident will be greater. In order to study the situations which could develop, given human error, into disasters it is necessary to build a model of the traffic. Batkin (1976) produced a model using parallel lanes to guide ships through a routeing scheme. Degré and Lefèvre (1978) have simulated the total flow of traffic through the Dover Strait in a 24 hour period, not taking into account ships' avoiding manoeuvres. In order to give an idea of the risks associated with each routeing scheme Degré and Lefèvre (1981) have produced an area called the 'manoeuvring room' of a vessel. This is based upon the total combinations of manoeuvres that a ship could take to avoid collision. By comparing the area which is available for manoeuvre with no collision risk with the total area available for manoeuvre Degré and Lefèvre have shown the Anglo-French Safety of Navigation Group's routeing schemes for the English Channel (Fig. 1.3) to be safer than the current IMCO scheme (Fig. 1.1). The model used, however, still does not incorporate vessel manoeuvres.
FIG. 1.3 THE AFSONG PROPOSAL
The Present Work

The aim of the current project is to investigate the actions of mariners in order to be able to simulate movement of vessels through a traffic separation scheme. A model has been produced which accurately reflects the reactions of the mariner to various situations, incorporating the concept of the domain as proposed by Goodwin.

The adaptation of the concept of the domain to make it suitable for a simulation model is described in Chapter 2, together with the introduction of the arena. The arena is one of the controlling factors of collision avoidance and determines when a navigator starts to take account of another vessel. A questionnaire was used to obtain values for the domain and arena which is explained in Chapter 3.

A model was produced showing the reaction of mariners in a two-ship encounter. The development of this model is described in Chapter 4 together with an explanation of the model concepts. In Chapter 5 the model is extended to include multi-ship encounters and the incorporation of land.

The model thus produced was validated in three ways as described in Chapter 6. Firstly mariners verified the tracks of the ships were logical, then the model was used to simulate certain known scenarios for vessels in the Dover Strait. Finally a series of
passing encounters were simulated in the model which compared favourably with similar data gained from radar records of the Dover Strait and radar training simulator experiments.

The results from the validation are discussed in Chapter 7. These show that the model correctly simulates the actions of mariners a large proportion of the time. When rogue vessels are encountered it is not possible to simulate their behaviour as these vessels are not obeying the International Rules. The model is therefore a useful tool for examining the behaviour of mariners when they conform to the rules, and a contribution to safer navigation.
CHAPTER 2

SECTION 2.1
The Concept of Domains

Goodwin (1975) proposes that a navigator manoeuvres his ship so that other vessels do not pass within a certain area surrounding his ship. This area is termed a ship 'domain', and is defined as being 'the area around a ship which a navigator would like to keep free with respect to other ships and stationary objects'. This has parallel concepts within other transport modes.

The Ministry of Transport (1968) recommends in the Highway Code the distance that should be left between one's own car and the preceding car. This distance depends upon the speed of the vehicle and the prevailing conditions. However, observation of vehicles on a motorway or in a queue of moving traffic will show that there is a variation in the distance left by drivers, depending upon their temperament and experience.

In air transport aircraft are kept separated by air traffic control. There are certain fixed standards, dependant upon the type of aircraft, which are set so as to minimise risk of collision. These standards allow for flying errors which could result in the aircraft being at a very different position from their intended position at any time.

Within sea transport various names and shapes have been given to an area around a ship which the navigator wishes to keep clear.
Lewison (1978), when looking at collision risk, defined an arbitrary area around a ship of half a mile which he called the encounter area. If a ship's projected track passes through this area then risk of collision exists. From the risk of collision leading to an actual collision it is thus possible to predict the probability of collision. In later papers Lewison (1980) and Chalk et al (1981) take into account in their calculations the varying probability factors associated with differing visibilities. By determining the occurrence of the different conditions it is possible to produce a fog collision risk indicator (F.C.R.I.). This is specific to a chosen area, as visibility is a localised phenomenon, but gives an indication of the number of collisions expected.

Fujii (1969, 1977) alone, and when working with Tanaka (1971), uses an area around a ship called a 'collision diameter' which is elliptical in shape and dependant on the length of the ship. Using this area Fujii has predicted flow in the Japanese inland sea and the dangers of collision.

Goodwin (1975, 1978), and together with Kemp (1977, 1980), has taken the concept of a three sector domain as defined earlier to examine mariners' behaviour and to study marine encounter rates. A three sector domain was chosen as this reflects the priorities and obligations imposed upon a ship by the Collision Regulations (1972). A vessel carries sidelights and a sternlight which shine over the same arcs as the domain sectors. Sector 1 corresponds to the arc over which the starboard green light shines, from ahead to two points abaft the beam (112.5 degrees). Sector 2
corresponds to the arc of the red port sidelight from ahead for 112.5 degrees, and Sector 3 covers the astern segment of 135 degrees showing equally from right aft on each side of the vessel. (Fig. 2.1). These sectors correspond respectively to the give-way, stand-on and overtaking arcs of a vessel. Thus sector 1, the give-way area, has the largest value as when a navigator has another ship on her own starboard side he must keep out of the way of the other. The domain is defined as the distance to the edge of the domain from the ship.

Goodwin (1975) suggests three ways in which the three sector domain could be adapted to provide a workable analytical model for encounter rates. The first method is to consider the encounter area as a circle with radius equal to the greatest value of the three sectors. This has the disadvantage of losing the weighting between the different areas. To overcome this the second method suggests an ellipse with major axis in the direction of the ship's head. This allows for the weighting between ahead and astern, but ignores the weighting associated with each side. The last suggestion is an ellipse with major axis inclined to the direction of the ship's head. This allows for differences in domain between sector 1 and sector 2. All these calculations are based upon the value derived for the domain, and not the area enclosed in the domain. The latter two methods involve complicated mathematical equations to describe the ellipse.

For simulation a discontinuous domain, with sudden jumps at the
FIG. 2.1 GOODWIN'S SHIP DOMAIN FOR SUNK AREA, NORTH SEA
boundary, is not suitable. A ship in the open ocean situation approaching from 112 degrees on the starboard side enters the domain at 2.35 n. miles, while at 113 degrees on the same side the domain boundary is only 0.85 n. miles. (Goodwin 1975). It is therefore necessary to produce a smoothed domain containing all of the inherent properties of the three sector domain if the domain concept is to be applied in the simulation.

The definition of a domain refers to the area around his ship that a navigator wishes to keep clear. An initial attempt was made to smooth the domain boundary by taking the areas enclosed in the three sectors, summing them and using a circle with an equivalent area as the equivalent domain. This, however, lost the original benefit of the weighting of the different sectors when the ship was placed at the centre. By moving the ship from the centre of the circle, in such a way that the areas in the original sectors are equal to the areas produced by equivalent arcs at the ship, the concept of weighting is retained (Fig. 2.2). This new domain is therefore the desired, smoothed version of the original.

A circle is an easy figure to construct as all points on the circumference are an equal distance from the centre. It was found easiest to produce the domain as a circle around a 'phantom ship' which was at the centre of the circle, the real ship being fixed by a distance and an angle (relative to ship's head) from the phantom ship. The distance and angle were originally produced using an empirical method of counting squares on graph paper, and later by devising a
FIG. 2.2  THE SMOOTHED DOMAIN FOR OPEN OCEAN CASE
computer program to find the solution iteratively (Appendix 1). Distances can be directly compared from the phantom ship between the domain size and the distance to the target ship. As the domain is a circle about this fictitious point, if the target is closer than the domain then the domain is infringed.

The size of the three sector domain, and therefore the smoothed domain, has been shown to vary (Goodwin 1975). This variation comes about because of a number of factors influencing each ship (e.g. size, experience of navigator, type of propulsion) together with the overall local situation (proximity of land, density of shipping, traffic routing schemes, etc.). Taking the case of traffic density it could be argued that the greater the density of shipping, the greater the domain size should be as the navigator is experiencing greater pressure and therefore requires more thinking time.

However, as traffic density increases, so the mariner is forced to accept the erosion of the boundaries of his domain in order to navigate in congested waters. The navigator, however, has a limit to which he will allow his domain to be eroded, called the 'hard core domain', as suggested by Fujii et al (1977).

Kemp (1974) produced evidence to suggest there is an inverse relationship between the size of domain and the experience of the mariner. He found that given a certain type of encounter subjects with more experience tended to resolve the situation more quickly than subjects with less experience, but in so doing entailed a
greater measure of risk. More experienced mariners are willing to accept a closer passing distance without feeling threatened, and therefore have a smaller domain size than less experienced mariners.
SECTION 2.2

Concept of an arena

A preliminary attempt was made to produce a computer model of a two-ship encounter situation using the domain to decide the ship's alteration of course. This is effected by constructing the domain centre and then testing for the distance to the target from the phantom ship. If phantom-to-target distance is less than the danger the domain is infringed and the ship will alter to starboard. When the danger is over and the two ships are clear of one another they both resume their original courses. (Fig. 2.3).

When this model was tried with ships approaching each other on collision courses it was found that the ships were manoeuvring too late to avoid a close-quarters situation. Generally the stand-on vessel would also take avoiding action, although the alteration of course was not so severe as for the give-way vessel. This situation, with small closest point of approach, was not considered realistic so the theory of domains was re-examined.

The domain, as defined by Goodwin (1975), is the area the navigator wishes to keep vacant. Action would need to be taken well before the domain is infringed, as shown by Limbach (1977) and Holmes (1979), in order to keep it clear of other ships. Therefore the idea of a larger domain was considered, based upon the distance from another ship at which a mariner would start to take action in order to avoid a close quarters situation. This super-domain is called the 'arena' (Oxford Dictionary definition: 'sphere

23.
FIG. 2.3 MODEL RESULTS USING ONLY A DOMAIN
of action'), and when it is infringed the mariner will make his decisions as to appropriate action. Only when there is a predicted position where the domain is infringed will the ship alter course, and the alteration will be such as to bring the closest point of approach of the other ship just outside his own domain. By virtue of the off-centring of the domains the domain of the stand-on vessel is not infringed, and so the vessel need not alter course.

It is reasonably easy to collect data from mariners using the three-sector approach to any situation as the priorities are easily calculated. From this three-sector data it is then possible to construct the arena as a circle about a phantom ship using the technique described in section 2.1 for the domain. Thus a ship is enclosed in two areas (Fig. 2.4) with the centres of these two areas not being concurrent but dependant upon the data collected.

The arena finally decided upon is a compromise area for all the possible encounter situations. The circular form offset, however, has the benefit of simplicity and efficiency of computing.
FIG. 2.4. MODEL DOMAIN AND ARENA
CHAPTER 3

THE QUESTIONNAIRE

SECTION 3.1

Collection of Data

It is necessary to know the reactions of mariners to potentially hazardous situations in order to conduct any marine traffic research. These reactions can be described in a number of different ways, but the parameters chosen for the model are domain and arena, from which data other factors such as course alteration can be deduced.

There are four major methods of measuring mariners' reactions, namely:-

1. Observing the mariner on the bridge;
2. Observing ships by radar;
3. Use of a navigation training simulator;
4. Use of a questionnaire.

All these methods have disadvantages which result in incomplete or false data.

To observe each individual mariner onboard his own bridge entails a great deal of work as only one person is being measured by the observer. The mariner will behave conscious of the fact that he is being watched, and the likelihood of a dangerous situation arising is small compared to the total time expended, e.g. time spent deep-sea is very routine with a small number of ships sighted each day. The immediate reactions of the mariners are known, but the
opportunity is not afforded of producing a dangerous situation in order to test reaction times and each individual encounter has its own peculiar circumstances.

The use of a distant radar to observe traffic flow has the benefit of producing data that is collected from real life with no outside interference. Mariners may be aware that they are in an area of sea that is being scanned by radar (for instance they report to the Channel Navigation Information Service) but there is no direct interference unless action for a potential hazard has clearly been omitted. There are limitations on the accuracy of the radar scan, dependant both upon the method used to photograph or record the screen and the particular radar set's characteristics, e.g. pulse length, beam width and scale selected. The National Maritime Institute have used time-lapse photography with 16 mm cine film which has been analysed by Barratt (1976, 1980), Batchelor and Johnson (1977), Cash & Borribond (1973); Fujii and Tanaka (1971) describe a method called Programmed Radar Photography where a 35 mm camera takes 6 pictures of a radar screen every minute, while Goodwin and Kemp (1977) have exposed one 35 mm frame every 3 minutes in various traffic surveys off the Sunk Lightvessel using the M.V. Sir John Cass as a floating radar base. All these methods result in incomplete details of the ships recorded with regard to size, experience of the mariner on watch, type of cargo, etc.

When a radar training simulator is used to collect data the mariners observed are usually participating in a course and are aware that
their actions will be analysed at the end of each particular exercise. While mariners may cause their actions to be better controlled in a simulator than at sea due to this, the converse could be true as ships which apparently collide on a simulator cannot sink. Mariners can therefore be presented with very difficult situations with no risk of pollution, etc. Exactly the same situations can be simulated for a large range of subjects and close note taken of their reactions. Training simulators assume thick fog, which is not the most common occurrence at sea (1% of the time at the Varne Light Vessel), in order fully to extend the participants' experience of radar. Running sufficient courses on the training simulator to provide a large sample of reactions to a particular situation is expensive in terms of manpower, simulator time and therefore costs.

Use of a questionnaire has the benefit of being a relatively cheap method of gaining data, quickly acquiring a sizeable amount. The settings of the questions have to be worded so that they are feasible problems that the respondees might meet at sea, and the goodwill of the mariners is needed in filling in the questionnaire. Difficulty is often expressed by mariners in judging distance, especially in a classroom situation with just a sheet of paper in front of them for information. Mariners are aware that the situation is an artificial one and may give 'textbook' answers rather than their instinctive reactions. In view of the difficulties encountered in collecting data from the other methods the questionnaire method was considered to be sufficiently reliable to
produce data for the model. This has the added advantage of providing a reasonably large sample at small cost.
SECTION 3.2

The Questionnaire

A questionnaire was devised to study the actions of mariners in various situations. All respondees were given the same pages 1, 2 and 3 while there were five alternative sets of questions on page 4 of which the mariner received one at random. (Appendix 2) The questions were posed in multiple choice ('tick one box') manner asking for details of the mariner's experience, last vessel and reactions to various situations. The multiple choice system of questioning lends itself readily to computation of results as the various answers can be allocated integer equivalents for storage in a data base. (Appendix 2).

Page 2 of the questionnaire presented two separate definite collision situations to the mariner. The respondee was told he was Officer of the Watch onboard his last vessel, deep-sea with no restrictions on navigation, and meeting a vessel on a constant bearing, i.e. on a collision course. The mariners were given two cases:-

(a) with a vessel on their starboard side, and
(b) with a vessel to port.

They were asked to give the distance off at which they would alter and the minimum closest point of approach they would venture to the other vessel.

A spread of results was obtained from the questionnaire for all the different variables, due to the human perception of the problems
posed and their reactions to them. This was expected, rather than there being one 'correct' answer, as the human will draw upon his relevant experience and training which is personal. By summing the response to the port, starboard, and overtaking questions, a domain and arena can be constructed for each individual respondee using the techniques outlined in Chapter 2. This gives a spread of results, (Fig. 3.1) with the average domain size 1.94 n. miles radius with an off-centring of 0.7 n. miles at an angle of 221 degrees relative to the ships head. (Fig. 3.2). The average arena size is 2.7 n. miles radius, off-centred by 1.7 n. miles at an angle of 199° relative to the ship's head. (Fig. 3.2). These distance compare favourably with the values obtained by Goodwin (1975), in her open ocean tests (starboard side domain of 2.35 n. miles) and Limbach (1977), (decision distance of 5.6 n. miles). These discrepancies could be accounted for by the fact that the comparison data quoted were taken from radar simulators where the mariner assumes he is in dense fog. Thus the results obtained are of the correct order of magnitude.

Curtis (1977, 1980) has carried out calculations to determine the minimum safe overtaking distance (MSOD) of a 16 knot vessel overtaking a 12 knot vessel and has carried out experiments on a radar simulator to determine mariners' acceptable passing distances. Question 36 on page 4E of the questionnaire was designed to convey a similar situation to respondee, viz 'You are overtaking a vessel steaming 4 knots slower than your own on a parallel course. What is the minimum track separation at which you would pass without
FIG. 3.1 SPREAD OF DOMAIN RADII FROM QUESTIONNAIRE RETURNS
FIG. 3.2  AVERAGE DOMAIN FROM QUESTIONNAIRE
altering course, in visibility of 1 cable?

By extracting the results of those respondees who were serving on board 16 knot vessels the probability acceptance graph is drawn (Fig. 3.3).

The MSOD given by Curtis for this situation is 8.5 cables while nearly all (96%) questionnaire respondees said they would leave greater track separation than this. 57% of the simulator navigators required greater than the MSOD to pass (Davis (1981)).

The differences point towards how mariners react under pressure (simulator data) and how they think they react or would ideally act (questionnaire response). The perception of distance at sea is very difficult, and without the assistance of radar, mariners when asked later would seem to over-estimate. Due to the low occurrence of fog mariners have little experience of this situation and, as there are no constraints in the questionnaire, they tend to be cautious.
FIG. 3.3  QUESTIONNAIRE PROBABILITY OF PASSING A 12 KNOT SHIP WITHOUT MANEUVRING
CHAPTER 4

MODELLING A TWO-SHIP ENCOUNTER

SECTION 4.1

Initialising The Model

In order to allow a thorough investigation of encounters it is necessary to build a model which can operate for an adequate length of time. The majority of two-ship encounter situations are resolved after approximately an hour. During the course of a simulation it is possible to stop the model when the desired situations have fully evolved, but it is not possible to extend a model beyond the initial constraints. When looking at two-ship encounters three hours was decided to be sufficient time.

The area for the simulation is defined by the X and Y axes of a graph. The area under consideration is only a small part of the earth's surface, usually less than twenty miles square. The axes are therefore marked linearly in nautical miles, assuming the area under consideration to being approximately flat. All positions during the simulation are related to the origins of the axes and therefore the X and Y graph co-ordinates replace the traditional latitude and longitude for shipping. When a ship leaves the area defined by the axes it is assumed to be of no further concern and is ignored at subsequent iterations.
In order to produce a readily apparent result of each model run, a graph is plotted of the tracks of the ships, the position of the ship at the final iteration being labelled with the ship number. Each ship's track is also annotated, with the standard symbol available on the computer's Calcomp graph plotter for the number associated with each ship, at three minute intervals. Three minutes was chosen (one twentieth of an hour) as this aids any necessary hand-plotting of relative tracks.

An interval counter is marked to the right of, and slightly above, the standard symbol. In this way it is possible to see at a glance whether tracks that appear to be close together were formed by ships when they were close together, or separated by a long time interval.

In order to simulate a cross-section of shipping, details of five ship types are stored in a data file. These details concern speed, length, and rate of turn of vessels, and represent typical ships between 10,000 and 210,000 dwt extracted from manoeuvring characteristics for Shell International Marine Ltd. tankers (1968) as in Table 4.1.
<table>
<thead>
<tr>
<th>SHIP SIZE (D.W.T.)</th>
<th>LENGTH (FEET)</th>
<th>SPEED (KNOTS)</th>
<th>ALTERATION/ MINUTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>10,000</td>
<td>300</td>
<td>10</td>
<td>55</td>
</tr>
<tr>
<td>19,000</td>
<td>530</td>
<td>13.5</td>
<td>46</td>
</tr>
<tr>
<td>50,000</td>
<td>715</td>
<td>15.0</td>
<td>41</td>
</tr>
<tr>
<td>110,000</td>
<td>830</td>
<td>15.0</td>
<td>37</td>
</tr>
<tr>
<td>210,000</td>
<td>1,017</td>
<td>15.5</td>
<td>28</td>
</tr>
</tbody>
</table>

Table 4.1

The value for Alteration/Minute is the rate of angular change of course when a ship has reached a constant rate of turn during a manoeuvre.

The graph of heading against time during a turn is approximated to a delay of between one-third and one minute, followed by a constant rate of turn. (Figure 4.1) In the model a constant delay of two-thirds of a minute, followed by the constant alteration is used for each ship type.

To develop the model, ships were chosen at random from the five given ship types using the random number generator provided by the computer's N.A.G. library routines to produce a number between one and five corresponding to a ship type. The procedure was then repeated to give a second ship. The two random numbers generated next were between nought and three hundred and sixty to correspond to the course of each ship in degrees. In order that the model was able to function properly it was not feasible
FIG. 4.1  SHELL MANOEUVRING GRAPH

CHANGE OF HEADING  
18,000 dwt Steamship

TIME (MINUTES)

CHANGE OF HEADING (DEGREES)
to present a collision risk requiring immediate action, as it takes time in real life to assess a situation and plan the appropriate action. In order to ensure the model had generated sufficient information before avoiding action started, the ships were given initial positions so that they would collide in the middle of the plot area after forty minutes if no avoiding action were taken. Action to avoid collision was not allowed until a minimum of six iterations, representing two minutes, had elapsed. This corresponds to the shortest time that a radar plot could be made in real life, although Radar plotting practice (e.g., Moss 1973) recommends a longer period for accurate plots. Most ships did not take avoiding action until well after the advised plotting time as the ships started well outside one another's arenas, the one exception being the fine-overtaking case with small speed differential (Fig. 4.2).
FIG. 4.2  OVERTAKING WITH 4 KNOT DIFFERENCE
SECTION 4.2

Updating the Model

When the model is initialised the speed of the standard ship is given in knots (nautical miles per hour) and the course is generated in degrees. The model is, however, updated every one-third of a minute and calculations within the computer are carried out in radians. The speed and course are therefore easier to store as the distance moved in one iteration (speed in knots divided by 180) and a course in radians.

At each iteration the coordinate positions of each ship are updated by the distance moved during the last interval. Thus the $X$ value increases by:

\[ \text{Distance travelled in one interval } \times \sin \text{ of the course} \]

Using the same logic the $Y$ value increases by:

\[ \text{Distance travelled in one interval } \times \cos \text{ of the course} \]

Thus the direction of travel indicates whether the increment is positive or negative due to the cyclical nature of sines and cosines.

When the position of the ship has been updated it is necessary to update the positions of the arena and domain centres. This is carried out by offcentring from the new ship position the desired distance and direction relative to the ship's head. A test is carried out to check whether the ship is still in the area of the graph plot. If a ship moves outside this area the speed is set to zero and the ship is ignored at subsequent iterations.
SECTION 4.3

Development of the Two-Ship Encounter

The first time in the model that a ship takes notice of another vessel is when the other enters her arena. Thus if the other vessel is further away than the arena boundary she is not considered to be a threat. When the other ship lies inside the arena calculations are made to discover whether the domain is threatened. The point of most interest is when the threatening ship is closest to the domain centre, and in particular whether or not this distance is greater than the domain. In order to discover this closest point of approach to the domain centre, (CPAD) a derivative of the traditional radar plot is used, as shown in Figure 4.3.

For ship A:

\[ X_{t-1}, Y_{t-1} \] is the position at time \( t-1 \)
\[ X_t, Y_t \] is the position at time \( t \)
\[ R, S \] is the centre of the domain at time \( t \)

The track of ship A from time \( t-1 \) to time \( t \) \((X_{t-1}, Y_{t-1}, \text{to} X_t, Y_t)\) is transferred to the position of ship B at time \( t-1 \). This gives the position ZZ, WW. The line from ZZ, WW to \( Z_t, W_t \) is the vector difference between the track of ship A and ship B in one iteration and is thus the track of ship B relative to ship A. The line from the centre of ship A's domain which cuts this relative track at right-angles gives the CPAD.

When the CPAD is greater than the domain ship A is not threatened.
\[ \phi = \tan^{-1} (W_t - S) + (Z_t - R) \]
\[ \alpha = \tan^{-1} (WW - W_t) + (ZZ - Z_t) \]
\[ \Theta = \phi - \alpha \]

CPAD = DISTANCE × SIN \( \Theta \)

**FIGURE 4.2: CALCULATION OF CPAD**
and so does not alter course. If the CPAD is less than the domain radius ship A feels threatened and calculations are undertaken to see what is the best action to take with due regard to the collision regulations. When the CPAD has passed the ships consider altering back onto course.

The distances between each ship's domain centre and the other ship are compared to discover which is the stand-on and which is the give-way vessel. The ship which has the other the further from her own domain centre is the stand-on vessel. This vessel waits for the give-way vessel to take action, but if no change of course occurs she takes action in compliance with Rule 17a of the International Regulations for Preventing Collision at Sea (1972). This action consists of altering course to run parallel to the other ship and, if after 5 minutes the give-way vessel has still not altered course, taking a 'round turn' before resuming course.

Rule 13 states that a vessel overtaking another vessel shall be the give-way vessel. The definition of an overtaking vessel is one that is:

(a) going faster than the other vessel
and
(b) is approaching the other vessel in such a way that at night she would see the other's sternlight.

This sternlight shines over an arc of twelve points (135 degrees), equally divided either side of the fore and aft line. Thus any vessel approaching another with a course $\pm 67\frac{1}{2}$ degrees either side...
of the other's course is tested to see whether it should be considered an overtaking vessel.

This vessel tests whether the best action to avoid collision is to alter to port or to starboard. Rule 8a stresses due regard for good seamanship and therefore in this situation discourages manoeuvres where the give-way vessel crosses ahead of the stand-on vessel. Thus a ship overtaking another vessel initially on her port bow would alter to port to pass around the stern, and vice versa. The courses tested are the initial courses, as under Rule 13b no subsequent alteration of course relieves the overtaking vessel of her obligations.

When the encounter is a crossing situation the give-way vessel has the other on her own starboard side, and so the normally approved action to avoid collision is an alteration of course to starboard. This action takes place when the CPAD is less than the domain radius, and continues at successive iterations of the model until the predicted track of the stand-on vessel's passes clear of the give-way vessel's domain.

In Fig. 4.4 the positions $R^*$, $S^*$ and $Z_2^*$, $W^*$ correspond to $R$, $S$ and $Z_2$, $W$ respectively after the alteration of course giving rise to the new relative track and the movement of the domain centre. The time of CPAD has passed when two ships are moving apart by definition of the closest point of approach. Thus if the distance apart at two successive time intervals has increased the CPAD has already occurred and the give-way vessel alters back onto its original course. During the resumption of course the distance
FIGURE 4.4: FINAL ALTERATION TO STARBOARD
between the ships from one interval to the next may decrease because of the change of course. In order that this does not delay the resumption of course, a test is carried out for the current distance apart and the predicted distance in ten intervals time if no alteration takes place. When this test shows the ships to be moving apart if no alteration of course occurs then it is clear CPAD has passed and an alteration towards the desired course is permissible.

In order to reduce the distance travelled away from the desired course, calculations are made for altering back towards course whenever a ship is not on the desired heading. An alteration of course towards or onto that desired is perfectly legal providing the domain does not become infringed on the new track. In this way the time off-course is reduced, but the domain is always unviolated.
CHAPTER 5

SECTION 5.1

Extension to the Multi-ship Encounter

The Collision Regulations specify the action to be taken when two vessels meet one another with a risk of collision. When more than two ships are involved there is no specific guidance to the correct action for mariners, but it is assumed that each pair of ships obeys the collision regulations for two-ship encounters. As a general rule there is a give-way vessel and a stand-on vessel from any pair of ships (unless meeting head-on). Thus in a three-ship encounter one vessel may be a stand-on vessel for one ship, and a give-way vessel for the other. In order to simulate this situation it is necessary to find the most threatening ship and take appropriate avoiding action.

A series of tests are carried out, treating each ship in turn as the central vessel and testing whether each of the other ships makes the central ship a give-way or stand-on vessel. Thus vessels outside the arena or vessels which are overtaking are ignored. When two ships are moving apart there cannot be a collision risk as the closest point of approach must have passed. When a ship has the other on her own starboard side she is the give-way vessel. This is determined by comparing the distance between the domain centre of the threatened ship and the actual position of the threatening ship for each pair in turn. The
ship which has the other closest to her own domain centre is the
give-way vessel. When the central ship is the stand-on vessel
the other ship is ignored.

The vessel deemed to be the most threatening at any one time is
dependant upon the courses and speeds of all the vessels involved.
If one ship alters course the whole balance of threatening and
threatened ships can change. In the model it is necessary to
test not only for the current courses, but also for an alteration
of course to port and an alteration to starboard. Vessels which
currently have a closest point of approach to domain centre
(C.P.A.D.) greater than the domain are not considered threatening.
An alteration of course to port or to starboard, in order to
return the ship onto the desired course, which results in the
C.P.A.D. becoming less than the domain is not desirable. To
prevent this happening the C.P.A.D. is calculated for the direction
of alteration onto the desired heading and if this is greater
than the domain the alteration is valid and the ship poses no
threat. If the alteration would create a C.P.A.D. less than the
domain this ship is still regarded as being a threatening ship.

All ships which have proceeded this far through the tests are
regarded as threatening ships. In the multi-ship encounter it
is possible to have more than one ship threatening at any time,
so it is necessary to have a criterion on which to base the most
threatening ship. In the model the definition of the most
threatening ship is the ship which, out of all threatening ships,
has the soonest time of C.P.A.D. If this ship can be safely avoided there must be adequate time to avoid all the other ships as their time of closest point must be later.

When the most threatening ship has been found it is possible to apply the collision regulations to a pair of ships exactly as in the two-ship encounter. Thus the sub-routine developed earlier for the two-ship case can be directly applied to the multi-ship encounter case. (Fig. 5.1, 5.2)

The procedure for finding the most threatening ship is carried out at each iteration. Although this takes computer time, an alteration at one iteration may have stopped one ship from threatening another, and thus caused another ship to become the most threatening. By testing at each iteration the most threatening ship is found and the appropriate action taken. This is imperative as all action to avoid collision should be taken as soon as possible (Rule 8a) and early action reduces the alteration required.
FIG. 5.2 5-SHIP ENCOUNTER
SECTION 5.2
Incorporating a Coastline

Two approaches were tried to the problem of a ship meeting a coastline, the tangential method and the predict-ahead method. After much development the predict-ahead method was found to be more successful, and the tangential method was dropped.

In order to introduce a coastline to the model a series of x and y coordinates were found by drawing the relevant coastline on a grid and selecting a series of discrete points one-tenth of a mile apart. Due to the closeness of the points in the land array in comparison with the size of the land arena the coastline appears to the ship as a continuous line rather than a series of scattered points, and the ship does not therefore try to go between two adjacent points.

A 'land arena' of arbitrary radius of 1.5 n. miles was introduced to the model. This has a similar function to the arena in that when a point of land is found inside a vessel's land-arena the model starts calculating the best action to prevent the land infringing the 'land-domain'. The land domain is the effective area around his ship that a mariner would like to keep free with respect to land and other shallow areas.

THE TANGENTIAL METHOD
The current position of the ship is tested against the points held in the land array to find the closest point to the land-arena.
centre. The angle of the land at this point is then calculated by connecting the point to the next point in the array, producing a line. The angle of this line with respect to north can then be found as the x and y coordinates of the two points lying on it can be used to calculate the tangent of the slope, and hence the slope. As the slope is given in 180 degree notation, but the course of ships in 360 degree notation, the position of the ship is taken into account to convert the coastline to 360 degree notation. Having achieved this it is then possible to work out whether the ship will alter to port or to starboard - the alteration taken being the one which has a smallest turn to enable the ship to run parallel to the land.

This approach worked well for straight coastlines but when the coastline became undulating problems were encountered. By always altering course parallel to the nearest point of land the ship tended to follow a track exactly parallel to the coastline. This is obviously undesirable when a large bay is encountered as it means the ship, instead of heading for the next headland, drives around the bay. When harbour mouths are encountered, or river estuaries, the nearest point of land fluctuates from side to side of the ship and by vacillating between port and starboard alterations the ship ends up with no distance to the coastline, i.e. aground. Various developments of the program were tried to prevent this undesired occurrence which produced another undesired side-effect. When the distance between the ship and the land started to increase the course of the ship became constant, and so the vessel steamed back out to sea again. As bays are usually associated with headlands another approach was sought.
THE PREDICT-AHEAD METHOD

The problems with the tangential method were equivalent to a mariner just navigating with respect to the nearest point of land, and not looking ahead to see what vagaries of coastline were going to occur. The predict-ahead method sought to overcome this by predicting the situation at a series of intervals ahead of the ship, deducing not only from the current position but also from future positions the best method to avoid running aground. In order to reduce the amount of computer time taken for a simulation only half the land array points are considered at each iteration. When the iteration is an odd-numbered interval only the odd-numbered points in the land array are considered. When it is an even numbered time interval the even numbered land array points are considered. In this way the time spent searching through the land array for the nearest point is reduced to half, while the distinctive characteristics of the coastline are retained by using the same number of points. The position of the ship is tested against the land array, as in the tangential method, to find if the land arena is infringed. If the arena is infringed then tests immediately start relating to the land-domain. If the land-arena is currently not infringed, but action has been taken previously to keep the predicted land-domain clear, then testing continues as if the current land arena were infringed. The procedure to determine the optimum alteration of course is as follows.

A "flag" is set up in the model when a ship has altered course
because of land, which has a positive value for a starboard alteration and a negative value for an alteration of course to port. The alteration from the desired course is set to 5 degrees and then the flag for alteration is tested. When the flag is zero either alteration is possible and so testing takes place firstly to starboard and then to port. When the flag is negative the testing for the starboard alteration is missed, and when positive the testing for port alteration is omitted.

With the desired heading altered by a multiple of 5 degrees (the multiples starting at zero and increasing to 36), the model sets a dummy variable in the feasible alteration range for that vessel. The maximum alteration possible at any one iteration is equal to the constant rate of turn used in the two-ship encounter taken from observed ship trials (Shell 1968). Thus the feasible alteration range is the actual ship's heading, plus or minus the rate of turn for one iteration. As the headings tested are relative to that desired and not the actual course the dummy variable is necessary to prevent wild unrealistic course changes.

The desired heading with alteration (D.H.A.) is then used to produce the position of the ship at future ten-interval steps over the area covered by the six-mile range of the ship's radar. Any point of land in the six-mile range that would infringe the land-domain on the D.H.A. is thus found. When all the iterations using the D.H.A. do not have the land domain infringed then that is the heading required to avoid the land and so the model moves on from this section. As soon as one predicted iteration
has the land-domain infringed the testing on that D.H.A. is stopped, and the alteration tried to port instead of starboard when the flag permits. When the flag does not permit, or the alteration to port produces an infringed land-domain at a future iteration, the model increases the alteration by 5 degrees and loops back to the beginning of D.H.A. testing.

When the optimum D.H.A. is found the value stored in the dummy variable is the course nearest to the desired course that it is possible to reach in one iteration. This is in the direction of the course that will give a clear land-domain when it is reached. The heading of the ship is therefore set to the dummy variable. The value of the flag is set as to whether this is a port or starboard alteration relative to the desired course.
SECTION 5.3

Narrow Channels, Harbours and Islands

An island, isolated lighthouse, or similar obstruction can be simulated in the model using the same procedure as for an ordinary coastline but with one proviso. As the number of points will be much smaller than with a coastline the first and last points should be repeated in the land array to prevent a false impression being obtained at an odd or even interval. A series of isolated islands, or one island off a coastline can be stored in one land array as the initial calculations take place with the land arena to find the nearest point. Once the nearest point has been found to infringe the arena the positions predicted ahead are tested against all the points to ensure the land-domain is not infringed.

As has previously been discussed in Chapter 2 there is a hard-core domain that is the smallest to which a mariner will allow his domain to be reduced. This reduction of domain size occurs when the larger domain is not practicable, for instance in narrow channels or at the entrance to harbours. For this reason provision is made in the model for the size of the land-domain to be reduced when certain markers are encountered. These markers can indicate the mouth of the harbour in the land array, or the start of a narrow channel, and allow ships to go where the larger land-domain would otherwise have prevented them. By the same token vessels which are not bound for a certain harbour will treat the
harbour mouth as a bay which they cannot enter because their land-domains are too large.

In practice, when ships approach land they reduce engine speed especially when entering harbour. This allows the navigator more time to take decisions and the ship time to slow down. The reduction of speed is an exponential fall-off curve, (Shell 1968) and this is reproduced in the model by resetting the ship's speed, when markers in the land array are met, at 98% of its previous value. Using this value the model reproduces the behaviour of actual ships. (Fig. 5.3)
Fig. 5.3 Ships approaching land and a harbour
CHAPTER 6

VALIDATION

SECTION 6.1

Concepts of validation

In order to verify physical models it is necessary to expose them to the influences the physical systems are likely to meet and compare their responses. With more complex systems based upon mathematical principles it is more difficult to exert similar influences on the model and the system. It is, therefore, necessary to verify the similarity of logical processes in the behaviour of the system and the model.

When extrapolating results from a model to a system the problem arises whether the model is a valid one, or to what extent it can be considered valid. Vemuri (1978) states that models should be capable of duplicating results produced by the system, and also be capable of being subjected to tests capable of showing them to be false but withstanding the criticism.

In order to check whether the model is producing realistic results there must be a base set of results with which to compare them. Three stage validation of the model has been carried out:--

1. Experienced mariners have a wide knowledge of the types of ship manoeuvres likely to be carried out at sea. By checking that mariners agree the actions taken by model ships are feasible, the logic of the program can be verified.

63.
2. Known data has been extracted from film of shipping in the Dover Strait. By giving the model the same initial conditions the ensuing results should correspond.

3. Long term analysis has been carried out of ship passing distances in the Dover Strait by Curtis and Barratt (1981). By modelling a series of overtaking situations the resultant distribution of passing distances can be compared with the known base.
SECTION 6.2

Survey of mariners

As a first validation method the base used for the comparison was the experience of Master Mariners currently lecturing to nautical students. Randomly selected three ship encounter, and five ship encounter situations were circulated and the lecturers asked to comment whether they thought the action taken by the model was feasible and whether they thought this sort of action would be likely in real life. By unanimous decision both the scenarios were approved as being valid, feasible plots of ships meeting one another, although with a condition that any encounter situation which started with more than three ships on a collision course all at one time was probably pessimistic. Not withstanding this the action taken in the five-ship case was felt to be realistic, providing five navigators all found themselves faced by this task and nobody was to panic.

All those asked were agreed that the course alterations were of the correct sort to avoid collision and of the right size to produce the desired effect of collision avoidance.
SECTION 6.3

The N.M.I. Film

Having been satisfied by experienced mariners that the manoeuvres carried out by the model were realistic the next stage of the validation was to produce a less subjective test of the model.

The National Maritime Institute (N.M.I.), formerly the Ship Division of the National Physical Laboratory, has a library of vessel movements through the Dover Straits built up over the years. This is in the form of 16 mm cine film, exposed one frame per minute, of a radar screen sighted at St. Margaret's Bay coastguard station overlooking the Dover Straits. The screen is a six mile display off-centred to provide a greater area of coverage and shows vessel movements in the inshore English coastal zone and the North-East bound separation lane. (Fig. 6.1). Points which were used to orientate the film for analysis are the South Goodwin Light Vessel situated 3.5 miles away at a bearing of $110^\circ$ from the radar, and the Varne Light Vessel situated 8 miles away at a bearing of $180^\circ$ from the radar.

A copy of a length of film was obtained from the N.M.I. for week 12 of 1974. This period is more fully analysed in a paper by Barratt (1980) and consisted of film taken during varying degrees of visibility. Day 1 to 0600 on day 5 was clear visibility (greater than 10 km. at the Varne Light Vessel), the year, week number and day being shown in the top left-hand corner of the frame, together with the time in Greenwich Mean Time. Figure 6.2 shows
a typical frame of the film and is reproduced here by kind per-
mission of Mr. M.J. Barratt.

In order to analyse the film a projector was obtained which allows
for advancement of the film by a single frame at a time. The
projector was set up in a darkened room projecting onto a sheet of
one-inch squared graph paper hung on a wall. The distance to the
Varne Light Vessel was known to be three miles from the radar
station and the projector was so positioned to give this as three
inches on the graph paper. As a final check the calibration rings
on the radar picture were used to ensure the correct magnification.

The projector showed the film perfectly adequately except when
the direction of travel was reversed, when the film was likely to
jump on the sprockets. To avoid this care was needed so as not
to pass the next desired frame. As the position of the frame
varied slightly in the vertical field in the projector it was
necessary to use some fixed position to adjust the projector's
legs slightly so that successive measurements were taken relative
to the ground. For this the position of the Varne Light Vessel
was used as it gave a good radar image approximately \( \frac{1}{3} \) by \( \frac{1}{10} \) inch
on the paper. By adjusting the position of the Light Vessel
slightly to ensure alignment ships followed a reasonably straight
track, instead of a very irregular one. Despite these precautions
the tracks of the vessels were not completely linear, due perhaps
to small inherent errors in the method used, inaccuracies in auto-
pilots along with wind, wave or current induced motion. The
FIG. 6.2  TYPICAL RADAR PICTURE
courses of all vessels were easily deduced by drawing a line through the points or through the middle of their scatter.

There was a problem when running the film and trying to plot the ship tracks that occasionally ships would merge, or disappear altogether in a blind segment, to re-appear later. Generally these ships were easily identified by extrapolating the track from the early plotting which coincided with the later track with a uniform speed over the plotted and not plotted period. One ship was not noticed as having steamed through a blind spot until the attempted validation using the computer model, when the mistaken belief was easily recognised and rectified.

One other problem with plotting ship tracks from the radar film was trying to ensure that the plots were readable even when more than one ship had occupied the same position on the graph paper. By using a wide range of symbols and not duplicating on any one plot it was possible to do this, although occasionally the time was linked to the ship position by a line up to 4 inches long. This overlapping problem was greatest with the main south-west bound stream of traffic, and sometimes resulted in new ships being excluded from the plot while the old ships finished off their time in the plotting area. If the new ships were then desired to be plotted the film would be rewound and the plot started again at the time the new ships entered the plotting area. As the separation between the ships on one plot and the succeeding plot was in the region of six miles the two would have no visible interaction in the area under consideration and, therefore, no errors are introduced.
SECTION 6.4
Measurements from the film

The film was examined, starting at midnight on day two, for ships taking avoiding action. Midnight on day two was chosen as this is in a period of clear visibility and allowed any previous relevant ship tracks to be plotted as they entered the area covered by the radar screen, rather than having to start plotting with a ship part of the way through the area. The film was projected a number of times. Firstly at full speed to establish the approximate time of ship encounters, then one frame at a time to note when the relevant ships appeared, and finally in steps of two frames and the ships plotted at two minute intervals. As it became apparent that certain ships were well clear of all the other ships and proceeding on a steady course their positions were plotted less frequently to save workload, but the projected track was drawn so that any deviation could be easily recognised leading to more frequent plotting being resumed.
SECTION 6.5
Comparison of the film with the model

In order to validate the model a sufficient number of ship tracks are necessary so as to make a statistically significant sample available. Average daily flow of shipping amounts to 200 vessels per day through the Dover Strait. Due to elimination of certain tracks, as described below, fifty ship tracks were chosen as being sufficient to show any major deficiency in the model. Certain ships were appearing on the plotting sheet for only a short time, so any attempt to describe their behaviour would have been difficult. These ships were therefore discarded, as were other ships that proceeded on a straight course but were sufficiently far from other ships, (4 miles at nearest), that they had no interaction with other ships. Times when hovercrafts were a major portion of the traffic were also discarded as these vessels tend to avoid all shipping whether stand-on or give way while passing close enough to cause echoes to merge and, therefore, difficulties with plotting. This meant that some ships in the sample altered course, while others did not. It was necessary to have a mixture of actions in order to test whether the model over-reacted, under-reacted, or reacted correctly. After the discarding procedure described above the sample consisted of fifty-two ships. After the discovery that one ship was counted twice due to passing through a radar blind sector this left a sample of fifty-one ships which was adequate.
The data collected on the graphs from the radar film was digitised for use in the model in the categories:— Speed, Course, Position of first entering the radar area, Time of first entering the radar area, together with time of altering course and new course if ships altered due to navigational rather than collision-avoidance manoeuvres. This information was input as data for the model for each ship in a particular scenario (figs. 6.3, 6.4, 6.5) and the model then allowed to run until three hours had been simulated or, as was the usual case, all the ships had left the area concerned. In order to keep the graph plotting tidy and stop the pen running against the stops a special method was used. When a ship came to the boundary the speed of that ship was replaced with a value of zero. Initially this caused following ships to carry out manoeuvres as if it was an overtaking ship, which was in fact the case as it had developed. To prevent the following ships altering unnecessarily a conditional statement was incorporated into the program so that ships which had run off the playing area (and therefore been allocated zero speed) were ignored.

The values of domains and arenas input to the model started as standard. The domain radius was 1.5 n. miles, off-centred at an angle of 19° a distance of 0.7 n. miles. The values for the arenas were radius 2.7 n. miles, off-centring 1.7 n. miles and angle of off-centring 19°. The values for the arena were kept constant, and the domain radii altered when manoeuvres were widely different from the film. This value of 1.5 n. miles had been obtained from the questionnaire

73.
FIG. 6.4 SCENARIO VAL. 9 (MODEL)
FIG. 6.5  SCENARIO VAL. 7 (MODEL)
as being the average value of the domain for the open ocean case, but in a congested area like the Dover Straits a smaller value would be expected. Goodwin (1975), deduced the values of 0.82 n. miles for Sector 1 (Starboard), 0.77 n. miles for Sector 2 (Port) and 0.10 n. miles for the astern sector from data gathered from radar simulator exercises purporting to represent the Dover Straits. Using the process described in Chapter 2 these values give a domain of 0.63 n. miles offset 0.54 n. miles at an angle of 41 degrees. The average of the domain values in the model came out to be a radius of 1.2 n. miles, off centred by 0.63 n. miles at an angle of 19°.

When the model had run with the initial starting values derived from the graphs a comparison of the two sets of tracks was undertaken. The first criteria was whether the ships in the model had altered in the same direction as the ships on the radar film. This would show whether the logic for the alteration decision-making process was correct. If every encounter in the film was exactly reproduced by the model there would be a perfect match. However, this would be highly unlikely as the actions observed on the radar film are controlled by humans who have been known to ignore rules or act irrationally. This can be demonstrated by the fact that there are still, on average, four rogue vessels per day reported in the Dover Straits. These rogue vessels are sometimes ships controlled by navigators who willingly break the rules to save fuel or catch the tide, (an example of this type
of ship being the Torrey Canyon, another the Al-Osman (Ratcliffe 1980)), or else vessels with poor navigators who are mistaken as to their exact position. A typical example of the latter was the Al Fahia (Ratcliffe 1980), a Kuwaiti tanker which in 1978 had gyro compass failure and was heading for a sandbank until finally persuaded by the coastguard to alter course.

One rogue ship was found in ship 6 in scenario Val. 7. Not only was this ship heading northwards in the south-west bound lane but when an encounter developed with ships on almost reciprocal courses the ship altered course to port at a very late point and passed ahead of the other ships, completely ignoring the good practice of seafarers. When this scenario was first run in the model the rogue ship altered course to starboard very early on and only a small alteration was required (Figs 6.5, 6.6). By reducing the size of the domain to 0.1 n. mile it was possible for the rogue to avoid the other ships by standing-on, but when a negative alteration of course was input the rogue took a complete round turn out to starboard at the start of the simulation which then allowed the ship to resume course and pass astern and clear of the other ships.

Another ship which could not be simulated perfectly was ship 1 in scenario Val. 9., (Fig. 6.7). On the film this ship showed no apparent alteration of course, but the tracks of Ship 1 and Ship 6 came so close that their echoes on the radar screen were merged into one at time intervals 46 and 48.

Alterations were classified into four collision avoidance categories,
FIG. 6.6  SCENARIO VAL. 7 (RADAR)
FIG. 6.7  SCENARIO VAL. 9 (RADAR)
a category for navigation purposes only and a category of no alteration. The four collision avoidance manoeuvres were:

- Slight Port (up to 15°)
- Port (over 15°)
- Slight Starboard (up to 15°)
- Starboard (over 15°)

Comparing the results from the model with those from the radar film 49 ships out of 51 or 96.1% produced the same sort of alteration both times. This shows that similar procedures are adopted in the model as are used by navigators.

As a more rigorous test of the model, and particularly of the value of the arena, a comparison was made of the times of alteration in the model and in the film. (Table 6.1). Subtracting the time of alteration in the model from the time of alteration on the film produced a distribution of times of alteration in the model relative to the film. The likelihood of these results happening is obtained using the sign test. (Haber & Runyon 1973).

A 95% confidence level was decided as being an appropriate level of significance if the two samples of results are significantly different. Excluding scenario Val. 7 (with the rogue ship), a probability value of 0.608 was produced, and including Val. 7 a probability value of 0.648 was produced. As both of these are greater than the selected value of 0.05 there is no significant
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**Key:**
- N - No alteration
- A/C - Alters course for navigation purposes.
- sl pt - Less than 15° port.
- Port - More than 15° port.
- sl st - Less than 15° starboard.
- stbd - More than 15° starboard.

**No. same alterations:** 49

**No. ships** 51

**% ships correctly simulated** 96.1%

**TABLE 6.1**

Comparison of alterations between the model and radar data.
difference between the model results and the radar results.

The sign test is regarded by statisticians, for example Goodwin & Kemp (1979), as being of low power and only useful as a rough guideline. With the data produced from the model and the film it was possible to use a more powerful statistical test - the Wilcoxon matched pairs signed-rank test. This has the advantage over the sign test of taking into account the amount of difference as well as the direction of the difference. For the two samples to be significantly different the rank value in the tables, which is the smaller absolute value of the addition of the positive and negative rankings added separately, must be greater than, or equal to, the value obtained. Using 95% confidence limit again the appropriate values in the tables are 25 excluding scenario Val. 7, and 46 including scenario Val. 7. The values produced are respectively 34 and 86 indicating there is no significant difference between the model times for alteration and the radar film times for alteration at a 95% confidence limit.

The times of alteration were dependant upon the value of the arena, while the time of resuming course depends largely upon the size of the domain and the relative speeds of the ships, together with the time of initial alteration and the amount of that alteration. There are, therefore, a large number of variables, any one of which could alter the time that the ship resumes course. As before the sign test and the Wilcoxon matched pairs signed-rank test were used on the data, firstly excluding the values for scenario Val. 7 when the rogue ship is present, and then including these.
values. Excluding Val. 7 the sign test gives a probability of 0.226 which is greater than 0.05 and therefore the hypotheses that there is no significant difference between the samples can be accepted. The Wilcoxon test gives the same conclusion, a calculated value of 29 being larger than the tabulated value of 17.

When the results are compared including scenario Val. 7 the sign test gives a value of 0.05 which borders on the significant. When the more powerful Wilcoxon matched pairs signed-rank test is employed, however, the calculated value comes to 39 compared to the tabulated value of 34. The hypothesis is therefore true that there is no significant difference between the model times for resuming course and the radar film times for resuming course at a 95% confidence limit.

The mean of the distribution of differences in the times that the model and radar film vessels alter course excluding Val. 7 is 0.009 minutes with a standard deviation of 3.029 minutes. Including Val. 7 in the distribution gives a mean of 0.26 minutes with a standard deviation of 4.26 minutes. The rogue ship, therefore, greatly increases the spread of results in the distribution.
Observations of overtaking manoeuvres

Curtis and Barratt (1981) compared the overtaking manoeuvres carried out by navigators taking part in radar simulator courses with observations of overtaking manoeuvres at sea. These latter observations were produced from the N.M.I. film of the radar screen covering the Dover Straits, as described in section 6.3. The authors' object was to obtain from the film one hundred overtaking manoeuvres of vessels in fog proceeding through the Dover Straits at a minimum speed of 8 knots, with no external influences, e.g. crossing ships. These were then compared with manoeuvres made by mariners on a radar simulator who were told the visibility was poor and they were in an area of high traffic density. These mariners were told their ship was steering at 16 knots due north, with a 12 knot vessel ahead of them that they were overtaking. The track separation of the two vessels varied from zero to 1.25 miles, as part of the data was allied to a Minimum Safe Overtaking Distance (M.S.O.D.) experiment conducted by Curtis (1977).

Observations of the film were made until the required sample was obtained. Details of the initial track separation of vessels passing Dover are given (Fig. 6.8) together with the passing track separations observed from the film (Fig. 6.9). Details of the expected passing track separation deduced from the radar simulator results are given as a comparison (Fig. 6.10). The passing distances observed for each initial track separation were scaled by the number of ships at that initial separation. The authors
FIG. 6.8 DISTRIBUTION OF INITIAL TRACK SEPARATIONS

SEPARATION (N. MILES)
FIG. 6.9 COMPARISON OF MODEL AND RADAR RESULTS
FIG. 6.10 COMPARISON OF SIMULATOR AND MODEL RESULTS
assumed that vessels with initial passing track separation greater than 1.5 n. miles did not alter course (Curtis 1980), even though some mariners, when presented with a smaller track separation, altered course to give a passing separation of 3 miles or more.

The total number of mariners observed while using the radar simulator were 154, or 24 at each initial track separation up to and including 1.25 miles. The simulator vessels were all 16 knot ships overtaking 12 knot ships, while the average speeds from the radar film show mean speeds of 12 knots for the overtaking ships and 9 knots for the overtaken. No variation in minimum passing track separation has been shown as a function of overtaken ship speed even though the M.S.O.D. varies, (Curtis 1980).
SECTION 6.7

Comparison of radar and simulator observations with the model

In an effort to validate the model by a third method a series of overtaking manoeuvres were simulated by the model. The distribution of passing track distances from the model was then compared with the known distributions of passing track distances obtained from the analysed radar data and simulator results. (Curtis & Barratt 1981).

The flow of traffic through the Dover Straits is not uniform, a histogram of initial passing track separations being given in Fig. 6.8. By using a Monte Carlo simulation it was possible to reproduce these initial passing track separations. The two ships in this particular validation were given speeds of 16 knots and 12 knots with the overtaking ship initially three miles astern of the slower ship. This corresponds to the situation presented to the mariners in the radar simulator experiments. One hundred runs were made of this situation taking values for the domain sequentially from the database and the resulting passing distance distribution compared to the observed distributions.

Initial attempts to validate the model used a fixed average size domain of 1.5 n. miles. This resulted in a very peaked distribution however, so ways were explored whereby the differing actions of mariners could be simulated. As a database comprising over 120 completed questionnaires was available giving details of mariners' reactions in the open ocean in good visibility it was decided to
to make use of this data to give the spread of individuals' actions.

The questionnaire results were pertinent to the open ocean situation with good visibility, while the comparison data was drawn from an area of high density of traffic, many navigational problems and poor visibility. It is therefore necessary to use a scaling factor in order to produce meaningful results from the questionnaire data.

From the questionnaire raw data (Appendix 2), the smoothed domain size for each respondent was found using the technique explained in Chapters 2 and 3. This gave a mean domain size of 1.54 n. miles, and a total of 109 data points consisting of domain radius, and offcentring distance which could both be weighted, using a scaling factor, and offcentring angle. The scaling factor was expected to be less than 1.0 due to the M.S.O.D. results described in detail in Chapter 3. Values used were 1.0, 0.8, 0.5 and 0.41, the latter value being the ratio between Goodwin's (1975) Dover Strait domain and the questionnaire mean, the others are arbitrary scaling factors.

The Kolmogorov-Smirnov two-sample test was chosen as being a suitable statistical test for comparing model data and either radar or simulator data. It has greater power than the Chi-squared test or the median test in all cases. (Siegel 1956). The test is designed to compare two independent samples and tell whether they have been drawn from the same population or from populations with different distributions.
The computer package, Statistical Package for the Social Sciences (S.P.S.S.) which includes this test, was used to analyse the data. The results obtained from the model using scaling factors 1.0 to 0.41 were compared with the observed data from the radar film and simulator experiments (Fig 6.9, 6.10). Using a ten percent confidence limit, as neither sample is sufficiently large to be regarded as a population, there is no evidence that the model results using factors 0.8, 0.5 and 0.41 are any different from the radar observations. Using the same limit there is no evidence that the model results using factors 1.0 and 0.8 are any different from the radar simulator results. In fact the probability of obtaining results with differences as large, or larger, than the results provided by the radar simulator and the model with a factor of 0.8 is 1.00, meaning there is a good fit of results. These results are plotted in Table 6.2.
### PASSING TRACK SEPARATION

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<td>RADAR</td>
<td></td>
<td>0.07</td>
<td>0.55</td>
<td>0.46</td>
<td>0.36</td>
</tr>
<tr>
<td>SIMULATOR</td>
<td></td>
<td>0.70</td>
<td>1.00</td>
<td>0.003</td>
<td>0.011</td>
</tr>
</tbody>
</table>

#### TABLE 6.2

94.
CHAPTER 7

SECTION 7.1

Discussion of Results

The mariners who were shown the manoeuvres produced by the model (Figs. 5.1 and 5.2) all agreed that these were realistic.

Examination of the results used in the second part of the validation (Table 6.1) shows that excluding the data containing the rogue ship there were nine occasions when the model ship resumed course before the ships on the radar film, while the converse is true only four times. This is the skewness of distribution that would be expected, as the computer model should be able to produce an optimum route given the same set of circumstances. The model updates every third of a minute and can perform many calculations in that time exclusively devoted to collision avoidance. The officer of the watch at sea would not be able to undertake the same number of calculations or with the same precision, and must therefore err on the side of safety. When the data for the rogue ship is included the ships in the model resume course early thirteen times while the ships shown in the radar observations resume course only four times before the model ships. All of the differences in resuming course in the rogue ship scenario are in the sense of the model ship altering back onto course before the ships in the radar observations. This then shows the actions taken by the rogue ship not to be the best of all the options available, but rather an early alteration as prescribed in the Collision Regulations would
have been better.

Using the model it is possible to compare various possible courses of action and their results. The domain size can be varied to suit an individual and this can then show how the overall situation changes. Also the size of the arena can be varied to demonstrate to students the benefit of early manoeuvres with small alterations compared to making late manoeuvres with large alterations.

Certain differences between the radar and model results are interesting. In scenario Val. 4 (Page 95) ship number 4 alters course on the film at time 78, while in the model it waits until time 86. This is because the alteration is brought about by ship 6, which does not appear on the film (and therefore in the model) until time 86. Ship 4, being a lot closer, obviously detects ship 6 earlier than time 86 and alters course accordingly. In scenario Val. 9 (Page 80) ship 1 is off-course due to ship 6 for 4 minutes and passes clear. On the film neither ship alters and both vessels become so close that their tracks merge. This shows two things - firstly that the two ships were very close (although as they both produced later tracks they did not sink) and secondly that the radar film is a relatively crude way of collecting data. As the scanner does not produce sufficient brightness on the screen to register on the film with only one scan the film must be exposed for a longer period (40 seconds) in order to produce sufficient light for the correct film exposure. Slightly longer than is necessary is actually used so that weak echoes are not lost. Therefore if at
any time during the filmed scans one ship produces a radar echo which overlaps with any of the echoes for the other ship then the two spots on the screen will appear as one on the film. Due to half-beamwidth extension and pulse length the average echo size is equivalent to 300 metres by 100 metres. The average size of domain observed by Goodwin (1975) is .53 n. miles (1100 metres), therefore ships' domains are severely violated when the radar echoes merge.

In the overtaking portion of the validation various factors were used to scale the data acquired from the questionnaires. Comparing the model results thus produced with the radar data there was no significant difference when using scaling factors between 0.8 and 0.41, see section 6.7. When a factor of 1.0 was used there was a significant difference, which indicates there is a difference between the way navigators react when deep sea with clear visibility compared with in the Dover Straits in fog.

The model results using the scaled questionnaire data were compared with the predicted results from the simulator experiments conducted by Curtis and Barratt (1981). These results showed no significant difference when scaling factors of 1.0 and 0.8 were used. When smaller factors were used the differences between the results became significant. The navigators taking part in the simulator experiments were told they were in an area of high density traffic with restrictions on manoeuvring. No restrictions were actually shown, however, in the form of sand-banks or land so the navigators would have made best use of the
available sea-room.

Goodwin (1975) obtained a domain size which, when smoothed, amounted to a radius of .63 n. miles.

Using the factor of 0.41 in the model no significant difference is found between the radar results and the model results. There is a significant difference between the model results and the simulator results. This can be explained by the difference in constraints upon the navigator and the fact that navigators reduce their domain as the available sea-room decreases due to extra hazards such as sandbanks or dense traffic. If a statistical study of domain size for the simulator situation produced by Curtis were carried out a value of approximately 1.2 n. miles would be expected, corresponding to a scaling factor of 0.8 for the questionnaire data.

The model has therefore been shown to simulate the behaviour of mariners, the size of domain being dependant upon the situation presented. The smoothing routine eliminates the discontinuities associated with the three-sector domain, but retains the offcentred properties which result in a simple and efficient domain. The concept of an arena coupled with that of a domain has meant that a complex situation can be reduced to a series of straightforward tests that can be processed by a computer.
SECTION 7.2

Conclusions

It has been shown that given sufficient information it is possible to model various traffic systems. By applying this model to existing and proposed traffic schemes it should be possible to produce relative merits of safety. There is the need for more examination of the particular criteria which determine the size of the domain and arena under varying conditions. Some analysis of the N.M.I. film has been carried out by Barrett (1980) using a computer linked to a random access film scanner. No data has as yet been published about domain size derived from these results, but a comparison with simulator domain size would indicate the reaction of mariners to the simulator.

When using a radar training simulator to produce results which will be applied in real life care must be taken to provide sufficient initial information and constraints to make the simulation realistic. If insufficient information is given to the participating mariners a different situation will be simulated to that intended.

The computer model could be developed as a training aid for mariners in various different ways. The model could be used to control all the ships shown on a synthesised radar screen of a vessel and a mariner used to control the own ship. In this way various actions could be taken by the mariner and the other ships respond accordingly. Thus the optimum course alteration for a particular situation can be determined by the mariner by using a trial and
error principle. The benefits of the computer model over a radar training simulator is that the vessels can be speeded up once the manoeuvre has been decided upon in order to show the final situation.

Instead of using the model as a training aid it would be possible to use the program as an aid to navigation onboard ship. The positions of vessels encountered could be input to the model and particular problem situations identified. The computer could then select what it considers to be the optimum feasible course to avoid collision. Currently radar plotting is a very time-consuming manual task, but by using an interface it would be possible to input data straight from the radar into a computer carried onboard.

The model has a number of areas of application ashore. Currently traffic routeing schemes are implemented with little idea of the consequences, the only large scale simulation of traffic being carried out by ORION (Degre and Lefèvre 1981) in France. The folly of implementing schemes without fully exploring all the possibilities has been shown by the new Ushant scheme introduced after the Amoco Cadiz disaster. The new scheme has led to head-on encounters between Ushant and the Casquettes due to laden tankers being routed well off-shore at Ushant. A simulation of traffic beforehand would have highlighted this problem, which could perhaps have been averted. More overall integration of traffic schemes is needed in order to prevent a similar situation arising.
A major field that has only been touched upon in this thesis is the variation in behaviour of mariners. By studying the reactions of mariners to various situations the model could be adapted to include the stochastic variation and therefore produce even more reliable results. To this end an expansion of the questionnaire database would increase the amount of information available and the model would therefore be improved. A more comprehensive assessment of the data would then be possible to test the hypotheses that domain varies according to ship type, experience of navigator, size of ship, etc.

Some work has been carried out to determine the capacity of channels and the subsequent need for dredging, regulation, etc. (Glansdorp and Goldsteen 1981). The model could be adapted and extended to reduce the very complicated mathematics involved in Hydro-nautical bottleneck analysis and produce results with relative ease.

A further use of the model could be for the prediction of the routes of ships when they report in to a service such as the Channel Navigation Information Service operated by H.M. Coastguard. By entering the position, destination and speed of vessels into the model areas of high risk could be established. The risk of collision and close encounters could then be reduced by preventative action such as slight adjustment to ship's speed. This advice would be broadcast to the mariners involved who would then be in a position to accept or reject the information in the light of particular details available only onboard ship.
The model therefore has a number of uses which could contribute significantly to marine safety.
REFERENCES


International Regulations for Preventing Collisions at Sea (1972) or Collision Regulations (1972). Final Act of the International Conference on Revision of the International Regulations for Preventing Collisions at Sea, 1972.


APPENDIX 1

Smoothing Routine for the Domain

This computer program converts a three-sector domain into a circular continuous domain. The data required of the three sector domain is the value of the domain for each sector which are input as details from a questionnaire. The details output of the smoothed domain are a circle radius with a distance and direction of offcentring. The results are arrived at by an iterative process which continues until each sector has an error of less than 3 per cent of the original area.

A summary of the distribution of domain radii is output at the end.
The variables used in this program are:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI</td>
<td>3.1415926</td>
</tr>
<tr>
<td>PI2</td>
<td>472.5 degrees.</td>
</tr>
<tr>
<td>VAL</td>
<td>Scaling array giving midpoint values of the questionnaire integer data.</td>
</tr>
<tr>
<td>N</td>
<td>One dimension array containing questionnaire data.</td>
</tr>
<tr>
<td>R1</td>
<td>Radius of sector 1 domain.</td>
</tr>
<tr>
<td>R2</td>
<td>Radius of sector 2 domain.</td>
</tr>
<tr>
<td>R3</td>
<td>Radius of sector 3 domain.</td>
</tr>
<tr>
<td>A1</td>
<td>Area of sector 1.</td>
</tr>
<tr>
<td>A2</td>
<td>Area of sector 2.</td>
</tr>
<tr>
<td>A3</td>
<td>Area of sector 3.</td>
</tr>
<tr>
<td>A</td>
<td>Total area of domain.</td>
</tr>
<tr>
<td>R</td>
<td>Circular domain radius.</td>
</tr>
<tr>
<td>AN</td>
<td>Angular direction of offcentring.</td>
</tr>
<tr>
<td>DIS</td>
<td>Distance of offcentring.</td>
</tr>
<tr>
<td>F2, F3, F4</td>
<td>Areas making up sector 1 of circular domain.</td>
</tr>
<tr>
<td>F</td>
<td>Total of F2, F3, F4.</td>
</tr>
<tr>
<td>G2, G3, G4</td>
<td>Areas making up sector 2 of circular domain.</td>
</tr>
<tr>
<td>G</td>
<td>Total area of sector 2.</td>
</tr>
<tr>
<td>IDOM</td>
<td>Array giving distribution of domain sizes.</td>
</tr>
</tbody>
</table>
DIMENSION VAL(56,9), R(30), IF(70)
P1 = 3.1415926
P2 = 2 * P1 + 1.5635
DO 10 J = 1, 36
10 E = (7.761) * VAL(J + 1) + 1.39
701 FORMAT (15, F9.0)
1 WRITE (6, 602)
551 FORMAT (7, J1)
1 F(4, 1) = 0 TO 88
1 F(3, 5) = 0 TO 15
F(1, 6) = 0 TO 1
I = (15)
1 = VAL(12, 1)
I = (16)
2 = VAL(15, 1)
I = (19)
K = VAL(19, 1)
A1 = P1 + K + 3 + 0.0166
A2 = P1 + K + 2 + 0.0166
A3 = P1 + K + 2 + 0.0066
S = 61 + AP 
R = 50RT
S = -2
50 T = AN = 1.76 + 1.36 + 0.01
F2 = .5 + 2 - (1.863 + ASIN(D1S + SIN(1.9635 - AN) / R) - ASIN(D1S
+ SIN(AN) / R))
F3 = .5 - DIS + SIN(P1 - AN - ASIN(D1S + SIN(AN) / R))
F4 = .5 - DIS + SIN(P1 - 1.9635 + AN - ASIN(D1S + SIN(1.9635 - AN)/ R))
F = F2 + F3 - F4 - A1
G = 2.5 + 2 * (2.356 - ASIN(D1S + SIN(2 * P1 - 2.356 - AN) / R) - ASIN(D1S
+ SIN(AN) / R))
E = 2.5 - .15 - .5 * (2.356 + AN + P1 - ASIN(D1S + SIN(2 * P1 - 2.356 - AN) / R))
E = F3
C = G - K + G + T
IF (B, (12/L)) LT, (.1626, 1.2) LT, 0.03 TO 31
IF = 0
21 ANF = (1.9635 - AN) - 18.0
WRITE (6, 603) P, DIS, AN
601 FORMAT (3F1.5)
15 = 5
1 IF = 1
= 100
= 100
G0 TO 1
WRITE (6, 607) (1.000070), K = 1, 30
602 FORMAT (15, 3F1.5)
STOP
END
APPENDIX 2

The Questionnaire

The questionnaire was given to practicing mariners studying at college. Each respondent was given a copy of pages 1, 2 and 3 with one of the alternative versions of page 4.

The completed questionnaires were then input as coded information to a computer file. As an example, the first respondent had spent 10-12 years at sea, currently holds a Master (F.G.) certificate and is serving as 2/0 F.G..

(Responses 4, 7, 7 to the first three questions respectively.) This respondent received alternative 4B as his last page.
QUESTIONNAIRE

A) PLEASE GIVE DETAILS OF YOURSELF. ALL DATA WILL BE USED PURELY FOR PERSONAL RESEARCH.

<table>
<thead>
<tr>
<th>NATIONALITY</th>
<th>AGE</th>
<th>COMPANY</th>
</tr>
</thead>
</table>

PLEASE TICK ONE BOX FOR EACH QUESTION.

YEARS AT SEA

<table>
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<tr>
<th>3 OR LESS</th>
<th>4 - 6</th>
<th>7 - 9</th>
<th>10 - 12</th>
<th>13 - 15</th>
<th>16 - 20</th>
<th>OVER 20</th>
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PRESENT CERTIFICATE

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<tr>
<th>UNCERT</th>
<th>MTS H.T.</th>
<th>MASTER H.T.</th>
<th>CLASS 4</th>
<th>2ND MATE F.G.</th>
<th>1ST MATE F.G.</th>
<th>MASTER F.G.</th>
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PRESENT RANK

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</table>

PLEASE TICK DETAILS OF YOUR LAST SHIP

SIZE (SUMMER D.W.T.)

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<tr>
<th>BELOW 5,000</th>
<th>5,000-14,999</th>
<th>15,000-24,999</th>
<th>25,000-39,999</th>
<th>40,000-64,999</th>
<th>65,000-79,999</th>
<th>80,000-119,999</th>
<th>120,000-160,000</th>
<th>OVER 160,000</th>
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</table>

FLAG

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<th>E.R.C.</th>
<th>FLAG OF CONV.</th>
<th>COMMONWEALTH</th>
<th>OTHER</th>
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LENGTH O.A. (FT)

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TYPE

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<th>CONTAINER</th>
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ACTUAL OPERATING SPEED (KNOTS)

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<th>BELOW 10</th>
<th>10-12.9</th>
<th>13-14.9</th>
<th>15-17.9</th>
<th>18-20.9</th>
<th>21-25.9</th>
<th>24 OR OVER</th>
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RADARS

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<th>3 CM &amp; 10 CM ANTI-COLLISION</th>
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</tbody>
</table>
IN THE FOLLOWING SITUATIONS YOU ARE OFFICER ON WATCH ONBOARD YOUR LAST VESSEL, DEEP SEA, IN CLEAR WEATHER.

A) YOU ARE BOUND TO QUEBEC FROM LE HAVRE (COURSE 270°). A SHIP IS SIGHTED 4 POINTS ON YOUR STARBOARD BOW, APPROXIMATE COURSE 180°, BEARING STEADY.

<table>
<thead>
<tr>
<th>HOW CLOSE WOULD YOU APPROACH BEFORE ALTERING COURSE (N. MILES)</th>
<th>WHAT WOULD BE YOUR ALTERATION OF COURSE</th>
<th>WHAT WOULD BE YOUR MINIMUM ACCEPTABLE NEW C.P.A.</th>
</tr>
</thead>
<tbody>
<tr>
<td>LESS THAN 1.5 N.M.</td>
<td>15° OR LESS</td>
<td>6 CABLES OR LESS</td>
</tr>
<tr>
<td>1.5 - 2.5 N.M.</td>
<td>16° - 25°</td>
<td>6.1 to 9 CABLES</td>
</tr>
<tr>
<td>2.6 - 3.5 N.M.</td>
<td>26° - 35°</td>
<td>9.1 to 12 CABLES</td>
</tr>
<tr>
<td>3.6 - 4.5 N.M.</td>
<td>36° - 45°</td>
<td>1.21 TO 1.5 N.M.</td>
</tr>
<tr>
<td>4.6 - 5.5 N.M.</td>
<td>46° - 55°</td>
<td>1.51 TO 1.8 N.M.</td>
</tr>
<tr>
<td>5.6 - 6.5 N.M.</td>
<td>56° - 65°</td>
<td>1.81 TO 2.1 N.M.</td>
</tr>
<tr>
<td>6.6 N.M. OR OVER</td>
<td>OVER 65°</td>
<td>2.11 TO 2.4 N.M.</td>
</tr>
</tbody>
</table>

B) YOUR COURSE IS 270°, YOU SIGHT AN OLD TANKER 4 POINTS TO PORT, APPROXIMATE COURSE DUE NORTH BEARING STEADY.

<table>
<thead>
<tr>
<th>HOW CLOSE WOULD YOU LET HER APPROACH BEFORE YOU ALTER COURSE</th>
<th>WHAT WOULD BE YOUR ALTERATION OF COURSE</th>
<th>IN WHICH DIRECTION</th>
<th>WHAT WOULD BE YOUR MINIMUM ACCEPTABLE NEW C.P.A.</th>
</tr>
</thead>
<tbody>
<tr>
<td>LESS THAN 1.5 N.M.</td>
<td>15° OR LESS</td>
<td>ALWAYS PORT</td>
<td>6 CABLES OR LESS</td>
</tr>
<tr>
<td>1.5 - 2.5 N.M.</td>
<td>16° - 25°</td>
<td>ALWAYS STARBOARD</td>
<td>6.1 TO 9 CABLES</td>
</tr>
<tr>
<td>2.6 - 3.5 N.M.</td>
<td>26° - 35°</td>
<td>PREFERABLY PORT</td>
<td>9.1 TO 12 CABLES</td>
</tr>
<tr>
<td>3.6 - 4.5 N.M.</td>
<td>36° - 45°</td>
<td>PREFERABLY STARBOARD</td>
<td>1.21 N.M. TO 1.5 N.M.</td>
</tr>
<tr>
<td>4.6 - 5.5 N.M.</td>
<td>46° - 55°</td>
<td>EQUAL WEIGHTING</td>
<td>1.51 N.M. TO 1.8 N.M.</td>
</tr>
<tr>
<td>5.6 - 6.5 N.M.</td>
<td>56° - 65°</td>
<td></td>
<td>1.81 N.M. TO 2.1 N.M.</td>
</tr>
<tr>
<td>6.6 N.M. OR OVER</td>
<td>OVER 65°</td>
<td></td>
<td>2.11 N.M. TO 2.4 N.M.</td>
</tr>
</tbody>
</table>

P.V. DAVIS/2
c) **You are overtaking a vessel directly ahead of you, closing at 2 - 3 knots.**

<table>
<thead>
<tr>
<th>How close would you approach before you altered to pass.</th>
<th>Which direction would you alter.</th>
<th>What would be your minimum acceptable new C.P.A.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LESS THAN 0.5 N.M.</strong></td>
<td><strong>ALWAYS TO PORT</strong></td>
<td><strong>6 CABLES OR LESS</strong></td>
</tr>
<tr>
<td><strong>0.5 TO 1.00 N.M.</strong></td>
<td><strong>ALWAYS TO STARBOARD</strong></td>
<td><strong>6.1 TO 9 CABLES</strong></td>
</tr>
<tr>
<td><strong>1.01 TO 1.50 N.M.</strong></td>
<td><strong>PREFERABLY TO PORT</strong></td>
<td><strong>9.1 TO 12 CABLES</strong></td>
</tr>
<tr>
<td><strong>1.51 TO 2.00 N.M.</strong></td>
<td><strong>PREFERABLY TO STARBOARD</strong></td>
<td><strong>1.21 TO 1.5 N.M.</strong></td>
</tr>
<tr>
<td><strong>2.01 TO 2.50 N.M.</strong></td>
<td><strong>EQUAL WEIGHTING</strong></td>
<td><strong>1.51 TO 1.8 N.M.</strong></td>
</tr>
<tr>
<td><strong>2.51 TO 3.00 N.M.</strong></td>
<td></td>
<td><strong>1.81 TO 2.1 N.M.</strong></td>
</tr>
<tr>
<td><strong>3.01 TO 3.50 N.M.</strong></td>
<td></td>
<td><strong>2.11 TO 2.4 N.M.</strong></td>
</tr>
<tr>
<td><strong>3.51 TO 4.00 N.M.</strong></td>
<td></td>
<td><strong>2.41 TO 2.7 N.M.</strong></td>
</tr>
<tr>
<td><strong>OVER 4.0 N.M.</strong></td>
<td></td>
<td><strong>OVER 2.7 N.M.</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>What would be your minimum acceptable C.P.A. to a fixed oil platform marked on the chart.</th>
<th>There are tugs attending an uncharted drilling rig.</th>
<th>What would be your minimum acceptable C.P.A. to an isolated lighthouse in deep water.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3 CABLES OR LESS</strong></td>
<td><strong>3 CABLES OR LESS</strong></td>
<td><strong>3 CABLES OR LESS</strong></td>
</tr>
<tr>
<td><strong>3.1 TO 6.0 CABLES</strong></td>
<td><strong>3.1 TO 6.0 CABLES</strong></td>
<td><strong>3.1 TO 6.0 CABLES</strong></td>
</tr>
<tr>
<td><strong>6.1 TO 9.0 CABLES</strong></td>
<td><strong>6.1 TO 9.0 CABLES</strong></td>
<td><strong>6.1 TO 9.0 CABLES</strong></td>
</tr>
<tr>
<td><strong>9.1 TO 12.0 CABLES</strong></td>
<td><strong>9.1 TO 12.0 CABLES</strong></td>
<td><strong>9.1 TO 12.0 CABLES</strong></td>
</tr>
<tr>
<td><strong>1.21 TO 1.50 N.M.</strong></td>
<td><strong>1.21 TO 1.50 N.M.</strong></td>
<td><strong>1.51 TO 1.8 N.M.</strong></td>
</tr>
<tr>
<td><strong>1.51 TO 1.80 N.M.</strong></td>
<td><strong>1.51 TO 1.80 N.M.</strong></td>
<td><strong>1.81 TO 2.10 N.M.</strong></td>
</tr>
<tr>
<td><strong>1.81 TO 2.10 N.M.</strong></td>
<td><strong>1.81 TO 2.10 N.M.</strong></td>
<td><strong>2.11 TO 2.40 N.M.</strong></td>
</tr>
<tr>
<td><strong>2.11 TO 2.40 N.M.</strong></td>
<td><strong>2.11 TO 2.40 N.M.</strong></td>
<td><strong>OVER 2.4 N.M.</strong></td>
</tr>
<tr>
<td><strong>OVER 2.4 N.M.</strong></td>
<td><strong>OVER 2.4 N.M.</strong></td>
<td><strong>OVER 2.4 N.M.</strong></td>
</tr>
</tbody>
</table>
HOW WOULD YOUR ANSWERS TO THE PREVIOUS QUESTIONS FOR MINIMUM ACCEPTABLE C.P.A. DIFFER IF YOUR RADARS HAD FAILED?

<table>
<thead>
<tr>
<th>VESSEL ON STARBOARD SIDE</th>
<th>VESSEL ON PORT SIDE</th>
<th>CHARTED FIXED OIL PLATFORM</th>
</tr>
</thead>
<tbody>
<tr>
<td>DECREASE BY OVER 1.2 N.M.</td>
<td>DECREASE BY OVER 1.2 N.M.</td>
<td>DECREASE BY OVER 1.2 N.M.</td>
</tr>
<tr>
<td>DECREASE BY 9.1 to 12 CABLES</td>
<td>DECREASE BY 9.1 to 12 CABLES</td>
<td>DECREASE BY 9.1 to 12 CABLES</td>
</tr>
<tr>
<td>DECREASE BY 6.1 to 9.0 CABLES</td>
<td>DECREASE BY 6.1 to 9.0 CABLES</td>
<td>DECREASE BY 6.1 to 9.0 CABLES</td>
</tr>
<tr>
<td>DECREASE BY 3.1 to 6.0 CABLES</td>
<td>DECREASE BY 3.0 to 6.0 CABLES</td>
<td>DECREASE BY 3.0 to 6.0 CABLES</td>
</tr>
<tr>
<td>STAY ROUGHLY THE SAME</td>
<td>STAY ROUGHLY THE SAME</td>
<td>STAY ROUGHLY THE SAME</td>
</tr>
<tr>
<td>INCREASE BY 3.0 to 6.0 CABLES</td>
<td>INCREASE BY 3.0 to 6.0 CABLES</td>
<td>INCREASE BY 3.0 to 6.0 CABLES</td>
</tr>
<tr>
<td>INCREASE BY 6.1 to 9.0 CABLES</td>
<td>INCREASE BY 6.1 to 9.0 CABLES</td>
<td>INCREASE BY 6.1 to 9.0 CABLES</td>
</tr>
<tr>
<td>INCREASE BY 9.1 to 12.0 CABLES</td>
<td>INCREASE BY 9.1 to 12.0 CABLES</td>
<td>INCREASE BY 9.1 to 12.0 CABLES</td>
</tr>
<tr>
<td>INCREASE BY OVER 1.2 N.M.</td>
<td>INCREASE BY OVER 1.2 N.M.</td>
<td>INCREASE BY OVER 1.2 N.M.</td>
</tr>
</tbody>
</table>

PVD/4A
HOW WOULD YOUR ANSWERS TO THE PREVIOUS QUESTIONS FOR MINIMUM ACCEPTABLE C.P.A. DIFFER IF VISIBILITY WAS LESS THAN 2 N.M.?

<table>
<thead>
<tr>
<th>VESSEL ON STARBOARD SIDE</th>
<th>VESSEL ON PORT SIDE</th>
<th>CHARTED FIXED OIL PLATFORM</th>
</tr>
</thead>
<tbody>
<tr>
<td>DECREASE BY OVER 1.2 N.M.</td>
<td>DECREASE BY OVER 1.2 N.M.</td>
<td>DECREASE BY OVER 1.2 N.M.</td>
</tr>
<tr>
<td>DECREASE BY 9.1 to 12 CABLES</td>
<td>DECREASE BY 9.1 to 12 CABLES</td>
<td>DECREASE BY 9.1 to 12 CABLES</td>
</tr>
<tr>
<td>DECREASE BY 6.1 to 9.0 CABLES</td>
<td>DECREASE BY 6.1 to 9.0 CABLES</td>
<td>DECREASE BY 6.1 to 9.0 CABLES</td>
</tr>
<tr>
<td>DECREASE BY 3.1 to 6.0 CABLES</td>
<td>DECREASE BY 3.0 to 6.0 CABLES</td>
<td>DECREASE BY 3.0 to 6.0 CABLES</td>
</tr>
<tr>
<td>STAY ROUGHLY THE SAME</td>
<td>STAY ROUGHLY THE SAME</td>
<td>STAY ROUGHLY THE SAME</td>
</tr>
<tr>
<td>INCREASE BY 3.0 to 6.0 CABLES</td>
<td>INCREASE BY 3.0 to 6.0 CABLES</td>
<td>INCREASE BY 3.0 to 6.0 CABLES</td>
</tr>
<tr>
<td>INCREASE BY 6.1 to 9.0 CABLES</td>
<td>INCREASE BY 6.1 to 9.0 CABLES</td>
<td>INCREASE BY 6.1 to 9.0 CABLES</td>
</tr>
<tr>
<td>INCREASE BY 9.1 to 12.0 CABLES</td>
<td>INCREASE BY 9.1 to 12.0 CABLES</td>
<td>INCREASE BY 9.1 to 12.0 CABLES</td>
</tr>
<tr>
<td>INCREASE BY OVER 1.2 N.M.</td>
<td>INCREASE BY OVER 1.2 N.M.</td>
<td>INCREASE BY OVER 1.2 N.M.</td>
</tr>
</tbody>
</table>
HOW WOULD YOUR ANSWERS TO THE PREVIOUS QUESTIONS FOR MINIMUM ACCEPTABLE C.P.A. DIFFER IF VISIBILITY WAS LESS THAN 1 CABLE?

<table>
<thead>
<tr>
<th>VESSEL ON STARBOARD SIDE</th>
<th>VESSEL ON PORT SIDE</th>
<th>CHARTED FIXED OIL PLATFORM</th>
</tr>
</thead>
<tbody>
<tr>
<td>DECREASE BY OVER 1.2 N.M.</td>
<td>DECREASE BY OVER 1.2 N.M.</td>
<td>DECREASE BY OVER 1.2 N.M.</td>
</tr>
<tr>
<td>DECREASE BY 9.1 to 12 CABLES</td>
<td>DECREASE BY 9.1 to 12 CABLES</td>
<td>DECREASE BY 9.1 to 12 CABLES</td>
</tr>
<tr>
<td>DECREASE BY 6.1 to 9.0 CABLES</td>
<td>DECREASE BY 6.1 to 9.0 CABLES</td>
<td>DECREASE BY 6.1 to 9.0 CABLES</td>
</tr>
<tr>
<td>DECREASE BY 3.1 to 6.0 CABLES</td>
<td>DECREASE BY 3.0 to 6.0 CABLES</td>
<td>DECREASE BY 3.0 to 6.0 CABLES</td>
</tr>
<tr>
<td>STAY ROUGHLY THE SAME</td>
<td>STAY ROUGHLY THE SAME</td>
<td>STAY ROUGHLY THE SAME</td>
</tr>
<tr>
<td>INCREASE BY 3.0 to 6.0 CABLES</td>
<td>INCREASE BY 3.0 to 6.0 CABLES</td>
<td>INCREASE BY 3.0 to 6.0 CABLES</td>
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<td>INCREASE BY 6.1 to 9.0 CABLES</td>
</tr>
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<td>INCREASE BY 9.1 to 12.0 CABLES</td>
<td>INCREASE BY 9.1 to 12.0 CABLES</td>
<td>INCREASE BY 9.1 to 12.0 CABLES</td>
</tr>
<tr>
<td>INCREASE BY OVER 1.2 N.M.</td>
<td>INCREASE BY OVER 1.2 N.M.</td>
<td>INCREASE BY OVER 1.2 N.M.</td>
</tr>
</tbody>
</table>
How would your answers to the previous questions for minimum acceptable C.P.A. differ if you were pressed to make the tide?

<table>
<thead>
<tr>
<th>VESSEL ON STARBOARD SIDE</th>
<th>VESSEL ON PORT SIDE</th>
<th>CHARTED FIXED OIL PLATFORM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DECREASE BY OVER 1.2 N.M.</strong></td>
<td><strong>DECREASE BY OVER 1.2 N.M.</strong></td>
<td><strong>DECREASE BY OVER 1.2 N.M.</strong></td>
</tr>
<tr>
<td><strong>DECREASE BY 9.1 to 12 CABLES</strong></td>
<td><strong>DECREASE BY 9.1 to 12 CABLES</strong></td>
<td><strong>DECREASE BY 9.1 to 12 CABLES</strong></td>
</tr>
<tr>
<td><strong>DECREASE BY 6.1 to 9.0 CABLES</strong></td>
<td><strong>DECREASE BY 6.1 to 9.0 CABLES</strong></td>
<td><strong>DECREASE BY 6.1 to 9.0 CABLES</strong></td>
</tr>
<tr>
<td><strong>DECREASE BY 3.1 to 6.0 CABLES</strong></td>
<td><strong>DECREASE BY 3.0 to 6.0 CABLES</strong></td>
<td><strong>DECREASE BY 3.0 to 6.0 CABLES</strong></td>
</tr>
<tr>
<td><strong>STAY ROUGHLY THE SAME</strong></td>
<td><strong>STAY ROUGHLY THE SAME</strong></td>
<td><strong>STAY ROUGHLY THE SAME</strong></td>
</tr>
<tr>
<td><strong>INCREASE BY 1.0 to 6.0 CABLES</strong></td>
<td><strong>INCREASE BY 3.0 to 6.0 CABLES</strong></td>
<td><strong>INCREASE BY 3.0 to 6.0 CABLES</strong></td>
</tr>
<tr>
<td><strong>INCREASE BY 6.1 to 9.0 CABLES</strong></td>
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<tr>
<td><strong>INCREASE BY 9.1 to 12.0 CABLES</strong></td>
<td><strong>INCREASE BY 9.1 to 12.0 CABLES</strong></td>
<td><strong>INCREASE BY 9.1 to 12.0 CABLES</strong></td>
</tr>
<tr>
<td><strong>INCREASE BY OVER 1.2 N.M.</strong></td>
<td><strong>INCREASE BY OVER 1.2 N.M.</strong></td>
<td><strong>INCREASE BY OVER 1.2 N.M.</strong></td>
</tr>
</tbody>
</table>

PVD/4D
You are overtaking a vessel steaming 4 knots slower than your own on a parallel course. What is the minimum track separation at which you would pass without altering course.

<table>
<thead>
<tr>
<th>In Clear Visibility cc.35</th>
<th>In Visibility of 1 cable cc.36</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-5 Cables</td>
<td>3-5 Cables</td>
</tr>
<tr>
<td>6-8 Cables</td>
<td>6-8 Cables</td>
</tr>
<tr>
<td>9-11 Cables</td>
<td>9-11 Cables</td>
</tr>
<tr>
<td>1.2-1.6 N.M.</td>
<td>1.2-1.6 N.M.</td>
</tr>
<tr>
<td>1.7-2.0 N.M.</td>
<td>1.7-2.0 N.M.</td>
</tr>
<tr>
<td>Over 2.0 N.M.</td>
<td>Over 2.0 N.M.</td>
</tr>
</tbody>
</table>

P.V. Davis 4/E
APPENDIX 3

The program

To facilitate programming the simulation model is divided into a master segment and a series of subroutines.

The master segment is altered slightly, depending upon the desired simulation. The master segment shown here produces a simulation of up to six ships, together with a coastline. In order to run the program without coast the call of the Coast subroutine is omitted together with the read statements referring to Format label 701 and 702 where the coast coordinates are input.

In order to simulate a series of one hundred overtaking encounters as described in Chapter 6 it is necessary to add instructions for the following:-

(1) The data concerning the initial track separation must be input.

(2) The model must be controlled by a loop simulating the required number of encounters.

(3) The starting track separation is determined using a random number generator and the data input at (1).

(4) The output data is arranged into classes in order to facilitate drawing a histogram.

A brief description of the symbols used in each section are given at the beginning of the section.
**Master Segment**

This part of the program controls the calls to the subroutines, and the general flow of the model, e.g. calling a setting-up subroutine near the start and a graph plotting subroutine near the end.

The following variables are used:

- **DIST(K)**: One line function to determine the distance from the first ship of each successive ship.
- **XYZ, XYY**: Seed for random number generator.
- **FF1(M), FF2(M)**: Arrays storing the coastline as coordinates.
- **IBERT**: Counting 'flag' for when all vessels are back on course.
- **START, DELTA**: Initial and incremental values for graph plotting.
- **LENX, LENY**: Length of axes (inches) for graph.
- **INTL**: Frequency of plotting symbols on graph.
- **TOTLX, TOTLY**: Largest X and Y values plottable.
- **PI**: $3.141592653$.
- **PI2**: $\pi/180$.
- **ITIME**: Time counter for simulation period.
- **SHIPDA(I,J)**: Data about 5 types of ships, e.g. speed.
- **X(I,J), Y(I,J)**: Coordinates of ship J at time I.
- **ITURN(IB)**: Flag set to 1, 0, or -1 to indicate type of alteration.
- **DISTAP(N,K,L)**: Distance apart 3-N intervals ago of ship L from ship K domain centre.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>R(IJ), S(IJ)</td>
<td>Coordinates of domain centre for ship IJ.</td>
</tr>
<tr>
<td>ARENAT(IJ, J)</td>
<td>Distance of ship J from centre of ship IJ's arena.</td>
</tr>
<tr>
<td>U(IJ)</td>
<td>Speed of ship IJ.</td>
</tr>
<tr>
<td>TCPA</td>
<td>Time of closest point of approach.</td>
</tr>
<tr>
<td>THREAT</td>
<td>Earliest time of CPA so far.</td>
</tr>
<tr>
<td>IDEG(IJ)</td>
<td>Course of ship IJ in degrees.</td>
</tr>
<tr>
<td>A1(J)</td>
<td>Initial course of ship J.</td>
</tr>
<tr>
<td>ALT(J)</td>
<td>Rate of turn of ship J.</td>
</tr>
<tr>
<td>AREDIR(J)</td>
<td>Direction of offcentre of arena.</td>
</tr>
<tr>
<td>AREBD(J)</td>
<td>Distance of offcentre of arena.</td>
</tr>
<tr>
<td>ARBDIN(J)</td>
<td>Arena radius.</td>
</tr>
<tr>
<td>ARENR(J), ARENS(J)</td>
<td>Coordinates of centre of arena.</td>
</tr>
<tr>
<td>COURSE(J)</td>
<td>Course of ship J.</td>
</tr>
<tr>
<td>D(J)</td>
<td>Distance of offcentre of domain.</td>
</tr>
<tr>
<td>DIR(J)</td>
<td>Direction of offcentre of domain.</td>
</tr>
<tr>
<td>DOM(J)</td>
<td>Domain radius.</td>
</tr>
<tr>
<td>DOML(J)</td>
<td>Land domain radius.</td>
</tr>
<tr>
<td>E(N, I, J)</td>
<td>Distance apart 3-N intervals ago of ships I and J.</td>
</tr>
<tr>
<td>RADAR(6,6)</td>
<td>Matrix showing which vessels are within 10 miles of each other.</td>
</tr>
<tr>
<td>RL(J), SL(J)</td>
<td>Centre of land domain.</td>
</tr>
<tr>
<td>T(I, J)</td>
<td>Distance apart of ship I from ship J domain centre.</td>
</tr>
</tbody>
</table>
RL(IJ)  Distance from land of ship IJ.
ZLONG(J)  Length of ship J in n. miles.
IFL(J)  Flag to indicate time of altering for coast.
JJ(I)  Maximum alteration required to clear land.
IFLAG(J)  Flag to delay start of turn.
C(IJ)  Collision possibility or half the distance covered in one iteration by a vessel.
CSIMULATION TAKES PLACE WITH MAX DURATION OF 3 HOURS, 546 INTERVALS
REAL XYZ,XYX+0.05662
REAL LUX,JETY

C PROGRAM WRITTEN TO COPE WITH MAXIMUM OF SIX SHIPS
DIMENSION A(6),ALT(6)
DIMENSION ARENS(6),AREDIR(6),AREND(6),ARND(6),AREX(6),AREY(6)
DIMENSION ARENS(6),C(6),COURSE(6),DIR(6),TL(6),DOM(6)
DIMENSION DML(6),C(3,6),F(160),F2(160),R(6),RADIUS(6,6)
DIMENSION SL(6),S(6),SHPIDA(3,6),SL(6),T(6,6),TL(6),U(6)
DIMENSION 2DONG(6)
DIMENSION IFLAS(6),IDEC(6),IFL(6),ITURN(6),JU(6)
COMMON X(540,6),Y(540,6),DISTAP(3,6,6)
DIST(X,Y)=SRT((X(1,J)-X(K,1))**2+(Y(1,1)-Y(K,1))**2)

C A ONE-LINE FUNCTION TO DETERMINE DISTANCE APART FROM SHIP NO. 1
XYZ=0.6

C THIS IS A SEED FOR THE RANDOM NUMBER GENERATOR
C READ IN THE LAND ARRAY
READ(7,7001)(F1,M),F2(M),M=1,152
READ(7,7002)M1,M2
7C1 FORMAT(15F5.0)
7C2 FORMAT(15F5.0)
N=1

C VALUES FOR GRAPH PLOTTING ROUTINE
START=0.0
DELTA=0.0
LNX=0.0
LDY=0.0
ITL=9
TOTLX=START+DELTA*LENY
TOTLY=START+DELTA*LENY

C PLT=3.141592653
PLT=PLT/180.0
ITIME=1

C READ IN THE NUMBER OF SHIPS IN THIS RUN
READ(5,102)N
165 FORMAT(12)

C READ IN DATA FOR FIVE DIFFERENT SHIP TYPES
READ(5,101)((SHPIDA(I,J),J=1,5),I=1,3)
READ(5,102)M
161 FORMAT(5F5.0)

CALL PLOTS(5,6,16)

C OPEN GRAPH PLOTTER FILE
CALL PLOTS(5.0,1,0,-1)

C THIS MOVES PLOT OFF THE BOTTOM OF THE PAPER
DO 400 I=1,N
1 CALL SETUP(FI,IF,IF, AREND(18), FIR(18), AREND(18), DML(18),
    . AREND(18), B(18), C(18), SHPIDA(18), SHPIDA(18), F1)
C CHECK TO SEE IF STILL WITHIN HOURS
X2=AREX(I)+DML(I)**2
Y2=AREY(I)+DML(I)**2
IF (X2+Y2)**0.5.EQ.0 GO TO 1
IF (Y2+T**0.5.EQ.0 GO TO 1

C THIS KEEP THE SHIP ON L.H.S. OF LAND
400 CONTINUE
WRITE(S,601)IP,COURSE(IP),X(IP),Y(IP),ZLONG(IP),ALT(IP),U(IP)

FORMAT(9,601)I0,*12,COURSE,*F4.0,INITIAL X,*F5.2,INITIAL Y
*F5.2,LENGTH,*F4.2,ALERTATION/MIN,*F4.1,SPEED,*F5.2
CALL KISHL(COURSE(IP),U(IP),ALT(IP),C(IP),A1(IP),J,ZLONG(IP),
S(IP),AREND(IP),IFL(IP))
ITURN(IP)=2
CALL UPDATE(2,IS,U(IP),COURSE(IP),DL(IB),D(IB),DIR(IB),R(IB),S(IB)
X(S(IP)),SL(IP),AREN(IP),ARENS(IP),AREND(IP),AREND(IP))
IF(IS.EQ.1)GO TO 400
IF(2IST(1).LT.2)G0 TO 1
11(X(1,IP),AT.12,0)G0 TO 1
400 CONTINUE
DC 404 ITIME=2.000
THIS USUALLY HAS VALUE 538 FOR LOOP COUNTER UP TO 3 HOURS
DO 491 IJ=1,N
CALL UPDATE(ITIME,IP,U(IP),COURSE(IP),DL(IP),D(IP),DIR(IP),R(IP)
S(IP),SL(IP),AREN(IP),ARENS(IP),AREND(IP),AREND(IP))
UPDATE POSITION OF ALL SHIPS
401 CONTINUE
DO 402 IJ=1,N
DO 402 J=1,N
UPDATE CURRENT 5 PAST DISTANCES APART.
DISTAP IS DISTANCE APART FROM DOMAIN CENTRE
DISTAP(1,1J,J)=DISTAP(2,1J,J)
DISTAP(2,1J,J)=DISTAP(2,1J,J)
DISTAP(3,1J,J)=SQRT((X(IP,1J)-X(IP,1J))**2+(S(IP,1J)
-X(1J,1J)**2)
C IS DISTANCE BETWEEN SHIPS
C(1,1J,J)=C(2,1J,J)
C(2,1J,J)=C(3,1J,J)
C(3,1J,J)=SQRT((X(1J,1J)-X(1J,1J))**2+(Y(1J,1J)
-X(1J,1J)**2)
402 CONTINUE
DO 403 IJ=1,N
CHECK IF SHIP IN PLAYING AREA
IF(X(1J,1J),LT.STAT,LX.OR.Y(1J,1J),LT.START)U(IP,1J)=6.0
IF(X(1J,1J).LT.TOLX,OR.Y(1J,1J),LT.TOLY)U(IP,1J)=6.0
IF(U(IP,1J).EQ.6.0)GO TO 413
IF SHIP IS OFF PLAYING AREA SET SPEED TO ZERO, IF SPEED IS ZERO SHIP TO 403
CALL COAST(U(IP,1J),COURSE(IP),X(IP,1J),Y(IP,1J),FF1,FF2,
Z(IP,1J),DOL(IP,1J),DL(IP,1J),SL(IP,1J),ALT(IP,1J),TL(IP,1J),IFL(IP,1J),ITIME
CALL(IP,1J,M1,F1,F1,TURN(IP,1J),A1(IP,1J))
CHECK DISTANCE OFF LAND
IF (TL(IP,1J),LT.DOL(IP,1J),OR.IFL(IP,1J),GT.ITIME)GO TO 405
IF SHIP HAS ALTERED FOR COAST IT DOES NOT ALTER FOR OTHER SHIPS
SUBPROGRAM TO FIND MOST THREATENING SHIP
T(IP,1J) IS THE TARGET DISTANCE OF J FROM I,THREAT(IP) IS CLOSEST DISTANCE
THREAT=1000
M=1J
DO 405 IJ=1,N
18.
IF (IJ .GT. J) GO TO 400
IF (AREAT (IJ , J) .GT. 30000 (IJ)) GO TO 400

C IF SHIP IS OUTSIDE ARENA BOUNDARY SKIP TO 406

C TO FIND THE MOST THREATENING SHIP
IF (ARBS (COURSE (IJ) .EQ. COURSE (J)) .AND. U (IJ) .LT. U (IJ))
X (IJ) = 0 GO TO 406

C IF OTHER SHIP IS OVERTAKING MY SHIP STANDS ON
IF (IJ .GT. J) .GE. (I, J) .GE. E (I, J) .GE. E (1, I, J)
X (IJ) .EQ. DISTAF (Z, I, J) .GT. DISTAF (Z, I, J)) GO TO 406

C IF SHIP'S MOVING AWAY FROM OTHER SHIP'S DOMAIN, MORE THREATENED SKIP OVER
CALL CRCAL (X (TIME, J), Y (TIME, J), X (TIME, I, J), Y (TIME, I, J),
U (IJ), V (IJ), COURSE (IJ), COURSE (J), V (IJ), DIR (IJ), CPA, FALS)

C CALCULATES CLOSEST POINT OF APPROACH TO DOMAIN CENTRE
CALL DISTA (IJ) - ALT (IJ)
CALL CRCAL (X (TIME, J), Y (TIME, J), X (TIME, I, J), Y (TIME, I, J),
U (IJ), V (IJ), COURSE (IJ), COURSE (J), V (IJ), DIR (IJ), CPA, FALS)

C CALCULATES CPA FOR ALTERATION TO PORT
CALL DISTA (IJ) - ALT (IJ)
CALL CRCAL (X (TIME, J), Y (TIME, J), X (TIME, I, J), Y (TIME, I, J),
U (IJ), V (IJ), COURSE (IJ), COURSE (J), V (IJ), DIR (IJ), CPA, FALS)

C CALCULATES CPA FOR ALTERATION TO STARBOARD
CALL DISTA (IJ) - ALT (IJ)
CALL CRCAL (X (TIME, J), Y (TIME, J), X (TIME, I, J), Y (TIME, I, J),
U (IJ), V (IJ), COURSE (IJ), COURSE (J), V (IJ), DIR (IJ), CPA, FALS)

415 TCPA = TIME - FALS

C MOST THREATENING SHIP IS ONE THAT INFRINGES DOMAIN AND HAS EarLIEST CPA
IF (TCPA .LT. PT. THTAT) = J
IF (TCPA .LT. LT. THTAT) THTAT = TCPA

406 CONTINUE

C ALTER COURSE FOR THREATENING SHIP
CALL CCHG (COURSE (IJ), A (I, J), ALT (IJ), PORT (IJ), T (IJ, J), TIME,
LAT (IJ), LON (IJ), LAT (IJ), LON (IJ), AREAT (IJ), U (IJ), R (IJ), S (IJ), U (IJ),
TILS, X (IJ), TUB (IJ))

407 X (IJ) = 1

C CHANGE COURSE TO DECREASE BEFORE WRITING
400 CONTINUE

464 CONTINUE

100 IF (T (IJ, J) .LE. 00.0) GO TO 160

160 CONTINUE

C THIS PART OF PROGRAM STOPS THE MODEL WHEN ALL VESSELS HAVE RESUMED COURSE
IF (IJ .LE. 10.0) COURSE (IJ), 10.0, (IJ, L) .EQ. 10.0 GO TO 464

463 CONTINUE

100 CONTINUE

404 CONTINUE

412 = INCH - 1
DO 410 = 1, 10
CALL TABC (IJ, L, STAB, DELTA, LLX, LLY, XL, YL, FF1, FF2)
CALL TABC (IJ, L, STAB, DELTA, LLX, LLY, XL, YL, FF1, FF2)

417 CONTINUE

CALL PLOT (IJ, X (IJ), Y (IJ), X (IJ), Y (IJ))
SUBROUTINE CHANGE

When the most threatening ship has been found in the master segment, this subroutine is called to determine and carry out the evasive action.

Variables are:-

A  Course of own ship.
Al Desired course of own ship.
ALT Rate of alteration of own ship.
ARENA Arena radius of own ship.
B  Course of most threatening ship.
Bl Desired course of most threatening ship.
DOM Domain.
I  Time counter.
IFLAG Interval at which last alteration occurred.
ITURN Direction of alteration flag either +1, -1 or 0.
M  Central ('My') ship number.
N  Nearest ship number.
NGPA Closest point of approach on course A-Alt.
NNCAPA Closest point of approach on course Al.
QT Distance from arena centre to other ship.
R,S Coordinates of domain centre.
T  Distance from domain centre to other ship.
U  Speed of own ship.
U2 Speed of other ship.
Ll Logical tests if my ship is nearest ship.
| **L2** | Logical tests Ll and time of last alteration of course. |
| **E(IJ)** | Distance from one ship to the other at time IJ. |
| **Z(IJ), W(IJ)** | Coordinates of nearest ship at time IJ. |
| **AA** | Dummy course allowing for alterations to port or starboard. |
| **FALSE** | Time to or from CPA. |
| **FA** | Dummy. |
| **SNCPA** | New CPA with starboard alteration. |
| **XDA, YDA** | Coordinate distance of my vessel at next iteration on desired course. |
| **ZDA, WDA** | Coordinate position of other vessel at next iteration on current course. |
| **PREDIS** | Predicted distance apart at next iteration. |
SUBROUTINE CHANGE(A, A1, ALT, DOM, T1, ARENA, B, S1, GT, U, R, S2, U2, IFLAG, N, M, I)
C THIS SUBROUTINE TAKES ACTION TO AVOID COLLISION
C THIS SUBROUTINE IS CALLED IF THE LAND ARENA IS NOT INFRINGED
REAL NCFA, NCPA
COMMON X(540, 6), Y(540, 6), DISTAP(3, 6, 6)
DIMENSION IFLAG(20)
DIMENSION E(540), W(540), Z(540)
LOGICAL L1, L2
L1 = M, E, N
L2 = L1, AND (IFLAG(M), LT, I = 1)

C SHIP ALWAYS TURNS TO STARRBOARD TO AVOID ANOTHER SHIP
C SHIP TURNS BACK ONTO ORIGINAL COURSE WHEN DISTURBING INFLUENCE IS OVERCOME
IF(L1 = E, 6) RETURN
DOMAIN = DOM
NCPA = 0.0
PI = 3.141592653
IF(L1 GT A1 + 2 * F) A = A1
C THIS KEEPS SHIP'S COURSE IN 360 DEGREE FORMAT
C IF(L1 OR L2 EGT A1) I = 0
C THIS FREES THE CONSTRAINT ON SENSE OF TURN WHEN NO THREAT OR ON COURSE
IF(GT, GT, ARENA, AND, E, F0, A1) RETURN
C IF NO SHIP IS INSIDE THE ARENA AND SHIP ON COURSE THEN NO THREAT
IF(L2 AND A, LTE, A1) GO TO 4
C IF NO THREAT FOUND AND SHIP OFF CO. TO STARR AND DELAYED THEN ALTER BACK
IF(L2 AND A, LTE, A1) GO TO 7
C IF NO THREAT FOUND AND OFF CO. TO PORT AND DELAYED THEN ALTER BACK
IF(L1) RETURN
C IF NO THREATENING SHIP FOUND THEN RETURN TO MASTER SEGMENT
I1 = I - 6
I2 = 7
DO 1 I = 11, 12
Z(I,J)=X(I,J)+N
W(I,J)=Y(I,J)+N
E(I,J)=SQRT((X(I,J)-Z(I,J))^2+(Y(I,J)-W(I,J))^2)

1 CONTINUE
AA=A-ALT
CALL CPACAL(X(I+1,M),Y(I+1,M),Z(I+1,W(I+1),U+2,A,B,0.9,0.7,0.331,CFA,FA)
TCPA=FALSE+FLOAT(I)

6 CALL CPACAL(X(I+1,M),Y(I+1,M),Z(I+1),W(I+1),U+2,A,B,0.9,0.7,0.331,CFA,FA)

TCPA=FALSE+FLOAT(I)

601 FORMAT(CPA. IS **F6.2** AT TIME **F6.2** MY SHIP **F6.2**)

C CHECK FOR CPA IF ALTERING BACK
AA=A-ALT
CALL CPACAL(X(I+1,M),Y(I+1,M),Z(I+1),W(I+1),U+2,A,B,0.9,0.7,0.331,NCPA,FA)
CALL CPACAL(X(I+1,M),Y(I+1,M),Z(I+1),W(I+1),U+2,A1,B,0.9,0.7,0.332,NCPA,FA)
AA=A+ALT
CALL CPACAL(X(I+1,M),Y(I+1,M),Z(I+1),W(I+1),U+2,A,B,0.9,0.7,0.332,SNCPA,FA)

YD=A/(X(I+1,M)+U*SIN(A1))
YD=Y(I+1,M)+U*COS(A1)

ZD=Z(I+1)+U2*SIN(E)
WD=W(I+1)+U2*COS(E)

PREDIS=SQRT((XD-ZD)^2+(YD-WD)^2)
IF(PREDIS.GE.E(I).OR.NCPA.GE.DOM).AND.ALT.UA1)GO TO 4
IF(CPACAL.GT.DOM.AND.ALT.UA1)GO TO 4
IF(CFSAK-A.LT.0.AND.BT U2.AND.CPACAL.LT.DOM.AND.TCPA.GT.1)
X=(X(I+1,M)+U)*T
Y=(Y(I+1,M)+U)*T
Z=(Z(I+1)+U2)*T

C IF I AM OVERTAKING FROM STARBOARD THEN ALTER TO PORT
5 IF(CPACAL.GT(A1+0.501).AND.(TCPA.LT.1))GO TO 4
5 IF SHIP OFF CO. TO STERN AND TCPA HAS PASSED ALTER BACK
GO TO 5
4 A=A-ALT
IFLAG(N)=I
ITURN=-1
C THIS IRONS OUT ANY MINOR DISCREPANCIES WHEN RETURNING TO COURSE
IF(AALT)ITURN=-1
C SET ITURN TO NEGATIVE WHEN SHIP OFF CO. TO PORT
GO TO 5
5 IF(PREDIS.GE.E(I).OR.NCPA.GE.DOM.OR.CPACAL.GE.DOM).AND.ALT.A1)
GO TO 7
C IF SHIP IS MOVING APART OF DOMAIN CLEAR OR ALTER BACK DOMAIN CLEAR
C AND SHIP OFF COURSE TO PORT THEN ALTER BACK
IF(CPACAL.GE.DOM.OR.TCPA.LT.1)GO TO 6
C IF DOMAIN NOT THREATENED OR TIME OF THREAT HAS PASSED SKIP OVER ALT
7 A=A+ALT
IFLAG(N)=1
ITURN=-1
IF(AALT)ITURN=-1
C IF SHIP IS OFF COURSE TO STARBOARD SET ITURN POSITIVE
GO TO 8
8 CONTINUE
DOM=DOM+1
IF((ALT.GT.6).AND.ALT.A1).Or.(ALT.LT.0.5).AND.(ALT.GT.A1))A=A+ALT
IF((ALT.A1+ALT.GT.8)).And.(ALT.A1-ALT.5.6)<A1
RETURN
END
SUBROUTINE COAST

This subroutine is called every iteration when land is included in the simulation, and seeks to keep the land domain clear of all points of land. The subroutine statement includes the following variable list:-

U  Speed of ship.
A  Course of ship.
X,Y  X and Y coordinates of ship.
FF1,FF2  X and Y arrays of land.
J  Dummy.
DOM  Land domain radius.
RL,SL  X and Y coordinates of land domain centre.
ALT  Alteration of course per iteration.
TL  Distance to land.
IFLAG  Flag to indicate time of altering course.
D  Distance of offcentring of land domain.
MOUTH1, MOUTH2  Entrance points to harbour.
ITURN  Indicates direction of alteration.
Al  Desired course of ship.

In the subroutine a one-line function is used TLD(K) gives distance of ship off the land at a future interval. Variable names used within the subroutine are:-

IRAD6  Distance shown on ship's 6-mile radar range.
RI  Real value of ITIME/2.
INT Interval of looking at values in land array.
I Integer value of ITIME/2.
CX Five degree alteration in radians.
II Counter of total number of CX values.
XI Equal to II minus 1.
XX Dummy course equal to Al plus or minus XI\times CX.
US Distance travelled in X-direction in one iteration on dummy course.
UC Distance travelled in Y-direction in one iteration on dummy course.
DUM Dummy variable set equal to XX.
XCAL, YCAL Calculated X and Y positions at a number of iterations ahead.
MOUTH1,MOUTH2,ITURN,DOM)

DIMENSION FF1(160),FF2(160)

TL(K)=SORT((YCAL-FF1(K))**2+(YCAL-FF2(K))**2)

DOM=DOM
IRA6=(6.0-DOM)/U
IT=TIME/2
RI=FLOAT(ITIME)/2.0
INT=2
IF((RI-1).LT.0.40)INT=1
PI=3.141592653
DO 9 K=1,149
9 CONTINUE
IF(SORT((X-FF1(K))**2+(Y-FF2(K))**2).LT.0.1)U=0.0

CONTINUE
IF(U.EQ.0.0)RETURN
DO 14 I=1,150
TL=SORT((RL-FF1(M))**2+(SL-FF2(M))**2)
14 CONTINUE
RETURN

C CX=5.0+PI/180.9
IF(Y.LT.FF2(MOUTH1).OR.Y.GT.FF2(MOUTH2))GO TO 19
C U=U*0.98
D=DOM
A1=DOM/C
DO 10 II=1,36
XI=II-1
XX=A1*X1+CX
IF(ITURN.LT.0.6)GO TO 13
US=U*SIN(XX)
UC=U*COS(XX)
DUM=XX
IF((XX.GT.A+ALT)UM=A+ALT
IF((XX.LT.A-ALT)UM=A-ALT
DO 12 J=2,IRA6,10
XI=J
XCAL=X*XJ*US*COS(XX)
YCAL=Y*XJ*UC*Sin(XX)
11 CONTINUE
12 CONTINUE
ITURN=II+1
GO TO 26
C IF(X1.FG.0.0)GO TO 16
13 IF(ITURN.GT.0.0)GO TO 16
X=X1-XI+CX
US=U*SIN(XX)
UC=U*COS(XX)
DUM=XX
IF((XX.GT.A+ALT)UM=A+ALT
IF((XX.LT.A-ALT)UM=A-ALT
DO 17 J=2,IRA6,10
XI=J
XCAL=X*XJ*US*COS(XX)
YCAL=Y*XJ*UC*Sin(XX)
26.
DO 15 K=INT*142*2
IF(TLD(K)*LT.DUM)GO TO 10
15 CONTINUE
17 CONTINUE
ITURN=-1
GO TO 20
10 CONTINUE
20 CONTINUE
IF(X1.EQ.0.0)ITURN=0
IFLAG=ITIME
IF(A.AND.DUM.AND.(Y.GT.FF2(MOUTH1).AND.Y.LT.FF2(MOUTH2))))U=U*0.98
A=DUM
25 RETURN
END
SUBROUTINE CPACAL

This subroutine calculates the closest point of approach of one ship from another's own domain centre, and calculates the time to get there. By using a subroutine the results of various course alterations can be easily assessed.

Variables listed in the call are:-

X X coordinate of own ship.
Y Y coordinate of own ship.
Z X coordinate of other ship.
W Y coordinate of other ship.
U Speed of own ship.
U2 Speed of other ship.
A Course of own ship.
B Course of other ship.
D Distance of domain offcentring.
DIR Direction of domain offcentring.
CPA Closest Point of Approach to domain centre.
FALS Time to or from CPA.
SUBROUTINE CPACAL(X,Y,Z,W,U2,A,B,D(DIR),CPA,FALS)
S=Y*D*SIN(A+DIR)
S=Y*U*COS(A+DIR)
ZZ=Z-U2*SIN(B)+U*SIN(A)
WW=W-U2*COS(B)+U*COS(A)
     IF((ZZ-Z).LT.0.000001)RETURN
     IF((Z-R).LT.0.000001)RETURN
ALPHA=ATAN((WW-W)/(ZZ-Z))
THETA=ATAN((W-S)/(Z-R))-ALPHA
SIDE=SQR((R-Z)**2+(S-W)**2)
CPA=ABS(SIDE*SIN(THETA))
FALS=ABS(SIDE*COS(THETA))/SQR((Z-ZZ)**2+(W-WW)**2))
RETURN
END
SUBROUTINE INISHL

The variable names used in the call to this subroutine are given in order below. This subroutine converts the data previously acquired into a form suitable for iterations of one-third of a minute, and angles into radians:

A  Course.
PI  3.141592653.
U  Speed.
ALT  Rate of alteration.
C  Collision area.
Al  Desired Course (equal to A).
J  Flag set to zero.
L  Length of ship.
DIR  Direction of offcentring for domain.
QDIR  Direction of arena offcentring.
IFL  Flag set to zero.
SUBROUTINE INITIAL(A,P1,U,ALT,C,AL,J,L,DIR,DIRF,IFL)
C SUBROUTINE SETS ALL VALUES EQUAL TO DESIRED EQUIVALENT FOR THE UPDATING IN
REAL L
IFL=0
C=A*PI/180.0
AL=4.
U=U/180.0
C=(U+L)/2.
U=U/2.
ALT=ALT/2.
ALT=ALT*PI/180.
DIR=DIR/PI/180.
DIR=DIR*PI/180.
J=J.
RETURN
END
SUBROUTINE SETUP

This subroutine initialises values in the model with angles in degrees, and speeds in knots.

Variables used in the call are:-

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DL</td>
<td>Land domain offcentre distance.</td>
</tr>
<tr>
<td>D</td>
<td>Domain offcentre distance.</td>
</tr>
<tr>
<td>QDR</td>
<td>Arena offcentre direction.</td>
</tr>
<tr>
<td>DR</td>
<td>Domain offcentre direction.</td>
</tr>
<tr>
<td>QD</td>
<td>Arena offcentre distance.</td>
</tr>
<tr>
<td>DML</td>
<td>Land domain radius.</td>
</tr>
<tr>
<td>DM</td>
<td>Domain radius.</td>
</tr>
<tr>
<td>QDM</td>
<td>Arena radius.</td>
</tr>
<tr>
<td>U</td>
<td>Speed.</td>
</tr>
<tr>
<td>A</td>
<td>Course.</td>
</tr>
<tr>
<td>ZL</td>
<td>Length.</td>
</tr>
<tr>
<td>ALT</td>
<td>Alteration.</td>
</tr>
<tr>
<td>SHIPDA</td>
<td>Ship type details.</td>
</tr>
</tbody>
</table>
SUBROUTINE SETUP (CL, O, DOR, DR, GO, DML, OM, ODM, U, A, ZL, ALT, SHIPDA)
REAL * S XY, YY, G05CAF
DIMENSION SHIPDA (3, 5)
D L = 1.5
D = 1.7
DOR = 19.0
DR = 19.6
G0 = 1.7
DML = 1.5
OM = 1.7
OM = 2.7
R = G05CAF (XY)
X0 = R * 5 + 1
U = SHIPDA (1, MO)
FA = G05CAF (YY)
A = FA * 360.5
ZL = SHIPDA (2, MO)
ALT = SHIPDA (3, MO)
RETURN
END
SUBROUTINE TRACK 1

This subroutine draws the axes for a graph, then draws the ship tracks and finally labels the ship tracks and notates the symbols with the time. Variables passed across in the call are:-

IBUF          Dummy variable.
M             Maximum period of plotting.
START         Starting coordinate.
DELTA         Increments per inch.
LENX          Length of X axis.
LENY          Length of Y axis.
INTL          Plotting interval between symbols.
ISYMB         Calcomp Symbol number.
FF1           Land X-array.
FF2           Land Y-array.

Common Variables are:-

A             X-coordinates of all ships.
B             Y-coordinates of all ships.
DISTAP        Dummy variable.

One line function is:-

U(v)          Function for positioning symbols on the graph, converting X and Y coordinates into inches.
SUBROUTINE TRACK1(H, M, START, DELTA, LEX, LNY, INTL, SYMB, 
XFF1, XFF2)
C THIS SUBROUTINE PLTS THE TRACKS AND LAND
REAL LEX, LNY
COMMON A(B40, 6), B(B40, 6), CISTLEF(3, 6, 6)
DIMENSION X(541), Y(541)
DIMENSION FF1(160), FF2(160)
U(V) = (V-STAR)/DELTA
CC.
J=1;
X(J)=A(J, SYMB)
Y(J)=B(J, SYMB)
IF (J, SYMB) .GE. A(J+2, SYMB) AND E(J, SYMB) .LE. B(J+2, SYMB)) GOTO 6
CONTINUE
6. ASYM=ASYMB
H=J-2
N1=J-1
N2=J
Y(M1)=START
Y(M2)=DELTA
X(M1)=START
X(M2)=DELTA
C DRAW THEY AND Y AXIS
C
IF (ASYMB .GE. 1) CALL AXIS(0, 0, 0, 0, 12, HX IN N.MILES*12, LEX,
NO. .X(Y(M1)), X(Y(M2))
IF (ASYMB .GE. 1) CALL AXIS(0, 0, 0, 0, 12, HY IN N.MILES*12, LNY,
NO. .Y(Y(M1)), Y(Y(M2))
CALL LINE(X, Y, X, 1, INTL, SYMB)
CALL SYMBOL(U(X(N))+0.1, U(Y(N))+0.1, 0.1, 0.1, RSHIP NO. .G.6, 0.1)
CALL NUMBER(U(X(N))+0.1, U(Y(N))+0.1, 0.1, 0.1, SYMB=0.1, 0.1, 0.1)
CALL PLOT(0.05, 0.05, -3)
C PLOT THE TIME AGAINST THE SYMBOLS
TO 10 THT = 1, INTL
41=FLOAT((ITIM-1)/1)
CALL NUMBER(U(X(1+M)), U(Y(1+M)), 0.05, 0.1, 0.0, -1)
CONTINUE
CALL PLOT(-0.05, -0.05, -3)
FF1(151)=START
FF2(151)=START
FF1(152)=DELTA
FF2(152)=DELTA
IF (ASYMB .GE. 1) CALL LINE(FF1, FF2, 15, 1, 1, 2)
C THIS PLTS THE LAND
RETURN
END
SUBROUTINE UPDATE

This subroutine updates the position of each ship at each iteration.

Details required are, in order:

I  Time interval.
J  Ship Number.
U  Ship Speed.
A  Course of ship.
DL Distance of offcentring of land domain.
D  Distance of offcentring of domain.
DIR Direction of offcentring of domain.
R  X-coordinate of domain centre.
S  Y-coordinate of domain centre.
RL X-coordinate of land domain centre.
SL Y-coordinate of land domain centre.
QR X coordinate of arena centre.
QS Y coordinate of arena centre.
QDIR Direction of offcentring of arena centre.
QD Distance of offcentring of arena centre.
COMMON X(546, 6), Y(546, 6), DISTAP(3, 6, 6)
PI=3.141592653
C THIS SUBROUTINE UPDATES POSITIONS OF ONE SHIP EVERY 1/3 OF A MINUTE
X(I, J) = X(I-1, J) + U*SIN(A)
Y(I, J) = Y(I-1, J) + U*COS(A)
RL = X(I, J) + 1.5*SIN(A)
SL = Y(I, J) + 1.5*COS(A)
GR = X(I, J) + GD*SIN(A+DIR)
GS = Y(I, J) + GD*COS(A+DIR)
R = X(I, J) + D*SIN(A+DIR)
S = X(I, J) + D*COS(A+DIR)
RETURN
END
APPENDIX 4

Extracts from the International Regulations for Preventing Collisions at Sea, 1972

Rule 7
Risk of Collision

(a) Every vessel shall use all available means appropriate to the prevailing circumstances and conditions to determine if risk of collision exists. If there is any doubt such risk shall be deemed to exist.

(b) Proper use shall be made of radar equipment if fitted and operational including long-range scanning to obtain early warning of risk of collision and radar plotting or equivalent systematic observation of detected objects.

(c) Assumptions shall not be made on the basis of scanty information, especially scanty radar information.

(d) In determining if risk of collision exists the following considerations shall be among those taken into account:
   (i) such risk shall be deemed to exist if the compass bearing of an approaching vessel does not appreciably change;
   (ii) such risk may sometimes exist even when an appreciable bearing change is evident, particularly when approaching a very large vessel or a tow or when approaching a vessel at close range.

Rule 8
Action to avoid collision

(a) Any action taken to avoid collision shall, if the circumstances
of the case admit, be positive, made in ample time and with
due regard to the observance of good seamanship.

(b) Any alteration of course and/or speed to avoid collision
shall, if the circumstances of the case admit, be large
enough to be readily apparent to another vessel observing
visually or by radar; a succession of small alterations
of course and/or speed should be avoided.

(c) If there is sufficient sea room, alteration of course alonge
may be the most effective action to avoid a close-quarters
situation provided that it is made in good time, is substantial
and does not result in another close-quarters situation.

(d) Action taken to avoid collision with another vessel shall be
such as to result in passing at a safe distance. The
effectiveness of the action shall be carefully checked until
the other vessel is finally past and clear.

(e) If necessary to avoid collision or allow more time to assess
the situation, a vessel shall slacken her speed or take all
way off by stopping or reversing her means of propulsion.

Rule 10

Traffic separation schemes

(a) This Rule applies to traffic separation schemes adopted by
the organisation:

(b) A vessel using a traffic separation scheme shall:
(i) proceed in the appropriate traffic lane in the general
direction of traffic flow for that lane;
(ii) so far as practicable keep clear of a traffic separation
line or separation zone;

39.
(iii) normally join or leave a traffic lane at the termination of the lane, but when joining or leaving from the side shall do so at as small an angle to the general direction of traffic flow as practicable.

(c) A vessel shall so far as practicable avoid crossing traffic lanes, but if obliged to do so shall cross as nearly as practicable at right angles to the general direction of traffic flow.

(d) Inshore traffic zones shall not normally be used by through traffic which can safely use the appropriate traffic lane within the adjacent traffic separation scheme.

(e) A vessel, other than a crossing vessel, shall not normally enter a separation zone or cross a separation line except:
   (i) in cases of emergency to avoid immediate danger;
   (ii) to engage in fishing within a separation zone.

(f) A vessel navigating in areas near the termination of traffic separation schemes shall do so with particular caution.

(g) A vessel shall so far as practicable avoid anchoring in a traffic separation scheme or in areas near its terminations.

(h) A vessel not using a traffic separation scheme shall avoid it by as wide a margin as is practicable.

(i) A vessel engaged in fishing shall not impede the passage of any vessel following a traffic lane.

(j) A vessel of less than 20 metres (65 feet) in length or a sailing vessel shall not impede the safe passing of a power-driven vessel following a traffic lane.
Rule 13

Overtaking

(a) Notwithstanding anything contained in the Rules of this Section any vessel overtaking any other shall keep out of the way of the vessel being overtaken.

(b) A vessel shall be deemed to be overtaking when coming up with another vessel from a direction more than 22.5 degrees (2 points) abaft her beam, that is, in such a position with reference to the vessel she is overtaking, that at night she would be able to see only the sternlight of that vessel but neither of her sidelights.

(c) When a vessel is in any doubt as to whether she is overtaking another, she shall assume that this is the case and act accordingly.

(d) Any subsequent alteration of the bearing between the two vessels shall not make the overtaking vessel a crossing vessel within the meaning of these Rules or relieve her of the duty of keeping clear of the overtaken vessel until she is finally past and clear.

Rule 14

Head-on situation

(a) When two power-driven vessels are meeting on reciprocal or nearly reciprocal courses so as to involve risk of collision each shall alter her course to starboard so that each shall pass on the port side of the other.
(b) Such a situation shall be deemed to exist when a vessel sees the other ahead or nearly ahead and by night she could see the masthead lights of the other in a line or nearly in a line and/or both sidelights and by day she observes the corresponding aspect of the other vessel.

(c) When a vessel is in any doubt as to whether such a situation exists she shall assume that it does exist and act accordingly.

Rule 15

Crossing situation

When two power-driven vessels are crossing so as to involve risk of collision, the vessel which has the other on her own starboard side shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel.

Rule 16

Action by give-way vessel

Every vessel which is directed to keep out of the way of another vessel shall, so far as possible, take early and substantial action to keep well clear.

Rule 17

Action by stand-on vessel

(a) (i) Where one of two vessels is to keep out of the way the other shall keep her course and speed.

(ii) The latter vessel may however take action to avoid collision by her manoeuvre alone, as soon as it becomes apparent to her that the vessel required to keep out of the way is not taking appropriate action in compliance with these Rules.
(b) When, from any cause, the vessel required to keep her course and speed finds herself so close that collision cannot be avoided by the action of the give-way vessel alone, she shall take such action as will best aid to avoid collision.

(c) A power-driven vessel which takes action in a crossing situation in accordance with sub-paragraph (a)(ii) of this Rule to avoid collision with another power-driven vessel shall, if the circumstances of the case admit, not alter course to port for a vessel on her own port side.

(d) This Rule does not relieve the give-way vessel of her obligation to keep out of the way.

**Rule 19**

**Conduct of vessels in restricted visibility**

(a) This Rule applies to vessels not in sight of one another when navigating in or near an area of restricted visibility.

(b) Every vessel shall proceed at a safe speed adapted to the prevailing circumstances and conditions of restricted visibility. A power-driven vessel shall have her engines ready for immediate manoeuvre.

(c) Every vessel shall have due regard to the prevailing circumstances and conditions of restricted visibility when complying with the Rules of Section I of this Part.

(d) A vessel which detects by radar alone the presence of another vessel shall determine if a close-quarters situation is developing and/or risk of collision exists. If so, she shall take avoiding action in ample time, provided that when such action
consists of an alteration of course, so far as possible the following shall be avoided:

(i) an alteration of course to port for a vessel forward of the beam, other than for a vessel being overtaken.

(ii) an alteration of course towards a vessel abeam or abaft the beam.

(e) Except where it has been determined that a risk of collision does not exist, every vessel which hears apparently forward of her beam the fog signal of another vessel, or which cannot avoid a close-quarters situation with another vessel forward of her beam, shall reduce her speed to the minimum at which she can be kept on her course. She shall if necessary take all her way off and in any event navigate with extreme caution until danger of collision is over.
I note with interest the paper by Dr Curtis and Mr Barratt in this issue of the Journal concerning validation of radar simulator results. At Plymouth we are constructing a computer model of ship behaviour, the initial values in the model being extracted from data amassed from questionnaires. These questionnaires were given to practising navigators studying for Department of Trade examinations, one question being 'In fog you are overtaking a vessel steaming 4 knots slower than your own on a parallel course. What is the minimum track separation at which you would pass without altering course?' A range of answers was provided between 3 cables and 2 miles. By extracting the results of those respondents who were serving on board 16-knot vessels (as used in the simulator experiments) the following 'probability acceptance' graph is drawn for comparison.

The minimum safe overtaking distance (MSOD) given by Dr Curtis for this situation is 8 cables; nearly all questionnaire respondents said they would leave greater track separation than this while 43% of the simulator navigators were prepared to pass at the MSOD.

The comparisons point towards the difference between how mariners do react under pressure (the simulator) and how they think they react or would act ideally (questionnaire response). Both lines produce similar slopes, so the answers would appear to vary in a similar fashion in both sets of data, indicating the spread of consensus in both situations.

REFERENCES
Dr Curtis comments:

Mr Davis's questionnaire results are very interesting and I wish to comment on the comparison with my radar simulator results. The 'probability acceptance' graph indicates that the questionnaire results were not in agreement with those obtained from the simulator. The results show that when questioned nearly all mariners say they would pass another vessel at a safe distance in fog (greater than 8½ cables). Yet in the more realistic environment of a radar simulator mariners are roughly 40 per cent more likely to accept a particular passing track separation. This illustrates the importance of validating a source of data before it may be relied upon.
A Computer Simulation of Multi-Ship Encounters


ABSTRACT. In a previous paper (1) a model was outlined for an encounter between two vessels. This paper shows how the model has been developed to include the simulation of the behaviour of more than 2 ships, the entrance to harbours, and narrow channels.

1. INTRODUCTION. In a previous paper by the authors (1) the concept of a domain was examined. Goodwin's definition of a domain (2) was used, viz. "the effective area around a ship which a navigator would like to keep clear with respect to other ships and stationary objects'. The concept of distinct sectors for sidelights and sternlight (2) was modified mathematically so that an area equal to the total of the segments was contained within a circle. By off-centering the position of the ship within this circle, the weighting of the differing areas for the various sectors was retained (Fig.1.) A second circle with the ship off-centre was introduced called an arena or "sphere of influence". When a ship is inside the arena a navigator becomes aware of the other ship and decides what action, if any, is needed to keep his own domain unviolated. This resulted in a model which obeyed the collision regulations.

2. CURRENT WORK. The ships in the original model initially altered course beyond the reciprocal course of the stand-on vessel. This was overcome by incorporating a test of distance between the ships at each updating interval. When two ships were found to be moving apart the alteration of course was halted. This created the situation where the give-way vessel steadied onto a reciprocal of the other ship's relative course. What was required in the updated model was to reduce the alteration of course to a minimum so that the domain is just kept clear. This was achieved by testing
for the time of closest point of approach (C.P.A.) so that if the time of C.P.A. had already passed, then it was unnecessary for ships to continue altering as the distance between them must now be increasing.

To achieve a reduction in the size of required alterations, calculations ahead for C.P.A. to the centre of the domain are made (Fig.2). If the C.P.A. is greater than the domain then no action is taken as the navigator does not feel threatened. However, if the C.P.A. is found to be less than the domain, then avoiding action is taken as before unless the time of C.P.A. has already passed.

In the preliminary model ships were only allowed to alter course to starboard. In some overtaking situations this was found to cause problems and prolong the encounter. An examination of various overtaking incidents showed that it was the situations with a ship originating on the starboard quarter which were causing problems. These ships, when on collision or close encounter courses, can best avoid collision by altering course to port and steering around the stern of the stand-on vessel (Fig.3) rather than altering to starboard and paralleling the course; waiting until she has outrun the stand-on vessel before altering back. A simple test for an overtaking situation comparing courses and speeds thus allowed for this variation.

3. MORE THAN TWO SHIPS. The Regulations for Prevention of Collision at Sea deal only with the two ship encounter, any meeting of ships larger than this is assumed to be broken down into a series of two-ship encounters. The model has been developed along these lines, with each ship finding the ship which is considered as the most threatening and then applying the model rules to these two ships as in the previous two ship encounter. The model has been tested and shown to work for up to and including five ships all on initial courses such that all ships would collide at the same point if no avoiding action were taken. If the action taken to
avoid one ship causes another ship to be deemed more dangerous at the next up-dating interval (1/3rd of a minute) then the model acts with the new most threatening ship. An example of a four-ship encounter is shown in fig. 4. Table 1 shows the major decisions taken during the course of this simulation.

4. METHOD USED TO CHOOSE MOST DANGEROUS SHIP. Calculations take place in the model to decide which of the other ships is considered the most dangerous by each ship in turn. For one ship to appear threatened by another, two criteria must be satisfied – firstly that the arena is infringed and secondly that the predicted C.P.A. must be less than the domain. When these conditions both exist the central ship then carries out a test to find which of the threatening ships is most dangerous by virtue of the time of C.P.A. When the C.P.A. has passed the ship is no longer threatening, so the next earliest time of C.P.A. is chosen. Where a ship finds that the most threatening ship is the give-way vessel, deduced by distances from the domain centres, then a delay is incorporated to allow the give-way vessel time to alter course. If no alteration takes place within five minutes then the stand-on vessel is at liberty to take action as in Rule 17 of the Collision Regulations, usually by taking a round turn.

5. LAND. Land is input to the model as a set of discrete latitude and longitude co-ordinates selected from a map or chart, etc., of the coastline; hence any coast can be easily represented. Initially the model navigated the ship so that it ran parallel to the tangent of the land closest to the land domain centre. This meant that the ship would navigate parallel to the land, no matter what the shape. Obviously with large bays or headlands this was not suitable so a similar prediction approach to that used in the two-ship encounter was used (Fig. 5).
Since there are many points in the land array it is inefficient to construct the relative velocity triangles (Fig.2) for each point in turn. Instead the ship is projected on its present course at 10, 20, 30, 40 and 50 time intervals ahead. If the land domain is not infringed then the calculations take place for 5 degree interval alterations to port and starboard. By computing alternately between port and starboard alterations the first calculation which gives a clear land domain at all time projections is the one with the least alteration to clear the obstructions.

Vessels navigating in channels with land or other obstructions on either side start off with the initial land domain size. If it is impossible to keep this domain clear and still navigate in the desired direction then the size of the land domain is reduced in stages until it reaches the 'hard-core domain' (3). This domain size depends upon the situation, and could be as small as the width of a lock gate.

By means of the domain off-centering the ships can be directed to keep to the right side of the channel and so allow vessels going in the opposite direction to pass. In order to prevent the size of land domain being reduced too early the land array co-ordinates for the mouth of the channel are specified. Reduction of land domain size only takes place when the point of land infringing the ship's land domain lies within this mouth. By this arrangement it is possible to navigate a ship into a channel, (Fig.5) or else direct the ship past, treating the entrance as a large bay if the desired destination is elsewhere.

REFERENCES


Fig 1: Position of Domain and Arena Relative to Ship
$R, S$ is centre of domain for ship A

$x_{t-1}, y_{t-1}$ to $x_t, y_t$ is distance traveled by ship A

$z_{t-1}, w_{t-1}$ to $z_z, w_w$

$z_{t-1}, w_{t-1}$ to $z_e, w_e$ is distance traveled by ship B

$\lambda = \tan^{-1} \left( \frac{w_w - w_e}{z_z - z_e} \right)$

$\phi = \tan^{-1} \left( \frac{w_e - S}{z_e - R} \right)$

$\theta = \phi - \lambda$

$CPA = \text{distance}(R, S$ to $z_e, w_e) \times \sin \theta$

$R^*, S^*, z_{z^*}, w_{w^*}$ correspond to $R, S, z_z, w_w$ after alteration of course of ship A.

**Figure**

*Closest Point Calculations*
<table>
<thead>
<tr>
<th>TIME OF START OF MANOEUVRE</th>
<th>SHIP NUMBER</th>
<th>COURSE ALTERATION FROM</th>
<th>COURSE ALTERATION TO</th>
<th>REASON</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2</td>
<td>24°</td>
<td>354°</td>
<td>Overtaking ship 1.</td>
</tr>
<tr>
<td>13</td>
<td>3</td>
<td>87°</td>
<td>99°</td>
<td>Crossing ship 1.</td>
</tr>
<tr>
<td>19</td>
<td>3</td>
<td>99°</td>
<td>161°</td>
<td>Crossing ship 2.</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>46°</td>
<td>101°</td>
<td>Crossing ship 4.</td>
</tr>
<tr>
<td>20</td>
<td>2</td>
<td>354°</td>
<td>40°</td>
<td>Overtaking ship 1.</td>
</tr>
<tr>
<td>23</td>
<td>3</td>
<td>161°</td>
<td>87°</td>
<td>Clear</td>
</tr>
<tr>
<td>27</td>
<td>2</td>
<td>40°</td>
<td>86°</td>
<td>Crossing ship 4</td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>101°</td>
<td>46°</td>
<td>Clear</td>
</tr>
<tr>
<td>33</td>
<td>2</td>
<td>86°</td>
<td>24°</td>
<td>Clear</td>
</tr>
</tbody>
</table>

1: MANOEUVRES IN FIGURE 4.
Fig. 5. Coast with Harbour Mouth.
A Computer Simulation of Marine Traffic Using Domains and Arenas

P. V. Davis, M. J. Dove and C. T. Stockel

(Plymouth Polytechnic)

This paper outlines the concept of a domain and an evasion area, called an arena, around a ship which are then applied to produce a computer model of ship behaviour. The arena determines when a ship takes avoiding action, as does the land arena which reacts with a discrete series of coastal points to prevent the ship running aground.

1. INTRODUCTION. The increase in the number and size of ships has resulted in the introduction of traffic routing schemes and the need to understand ship behaviour more thoroughly. The concept of 'the effective area around a ship which a navigator would like to keep clear with respect to other ships and stationary objects' has been used by various authors including Goodwin, Fujii and Lewison with varying names such as domain, collision diameters and encounter area. There has been no fixed shape for these areas. Some are circular, others elliptical, while Goodwin's has three segments each with its own portion of a circle. By developing the theory of the domain, it was hoped to be able to produce a model of traffic behaviour which could be used to simulate traffic flows, or specific incidents, in order to study them more fully.

2. CURRENT WORK. Goodwin's concept for a domain (Fig. 1) gives the idea of different weightings to the different directions from which ships approach. The largest area is on the navigator's own starboard side, as this is the region where he must take avoiding action. However, Goodwin's area is discontinuous, with sudden jumps at the boundaries. Thus a ship from $112^\circ$ on the starboard side enters the domain at 2.35 miles, while at $113^\circ$ on the same side the domain boundary is only 0.85 miles in open sea conditions.

It is obviously desirable to smooth the domain edges in some way if the domain concept is to be used in any realistic modelling of marine traffic. As a starting-point for the work at Plymouth an initial attempt was made to smooth the domain boundary by taking the areas enclosed in the three sectors (Fig. 1) summing them and using a circle with an equivalent area as the effective domain. This, however, lost the original benefit of the weighting of the different sectors by placing the ship at the centre of the circle. By moving the ship from the centre in such a way that the areas in the sectors are equivalent to the areas produced by the discontinuous domain, the concept of weighting is retained (Fig. 2).
new domain is therefore a desired, smoothed version of the original. It was found easiest to produce the domain as a circle around a 'phantom' ship which was at the centre of the circle, the real ship being fixed by a distance and an angle (relative to ship's head) from the phantom ship. Distances can be directly compared from the phantom ship between the domain size and the distance to the target ship. As the domain is a circle about this fictitious point, if the target is closer than the domain radius then the domain is infringed.

A preliminary attempt was made at producing a computer model of a two-ship encounter situation using the domain to decide the ship's alterations of course. This is effected by constructing the domain and then
testing for the distance from the phantom ship. If phantom-to-target
distance is less than the radius of the domain, then the domain is infringed
and the ship will alter course to starboard. When the danger is over and
the two ships are clear of one another they both resume their original
courses. When this model was tried with ships approaching at varying
angles, it was found that the ships were manoeuvring too late to avoid a
close-quarters situation. Generally the stand-on vessel would also have
to take avoiding action although not quite so severely as the give-way
vessel.

This situation, with a small CPA, was not considered realistic, so the
theory of domains was re-examined. The domain, as defined in the intro­
duction, is the area the navigator wishes to keep vacant, but he feels
threatened by an approaching ship in a much larger area than this. Action
would be taken well before the domain is infringed in order to keep it
clear of other ships. Therefore the idea of a larger domain, based upon
the distance from another ship at which a mariner would start to take
action in order to avoid a close quarters situation, was considered. This
super-domain is called the 'arena' (Oxford Dictionary definition: 'sphere
of action'), and when it is infringed the mariner will make his decisions
as to appropriate action. Only when there is a future position where the
domain is infringed will the ship alter course, and the alteration will be
such as to bring the closest approach of the other ship just outside his own
domain. By virtue of the ofT-centring and the give-way vessel, leaving the
stand-on vessel just outside his own domain, the domain of the stand-on
vessel is not infringed.

In order to obtain information from mariners for the computer model
a questionnaire was devised. This presents a definite collision situation to
the mariner: constant bearing, deep-sea with no restrictions and the
respondent as OOW onboard his last vessel. A preliminary survey was
carried out with sea-going personnel studying for DOT certificates, with
the hope of obtaining results which could be scaled using known data and
thus reduce the subjectivity of the questionnaire.

The mariners who took part were given two cases: (a) with a vessel on
their starboard side and (b) with a vessel to port.

They were asked to fill in a multiple-choice ('tick one box') answer
for, amongst other things, the distance at which they would alter, and
their desired new CPA (Fig. 3). When a comparison of the CPA answers
was made with published observed data, the starboard-side average was
1.8 nm with a decision distance of 4.3 nm. These compare with the
domain of 2.35 nm suggested by Goodwin and the decision distance
suggested by Limbach of 5.6 nm. These discrepancies could be accounted
for by the fact that the comparison data quoted were taken from radar
simulators where the mariner assumes he is in dense fog. Thus the results
obtained are of the correct order of magnitude.

The port-side average for CPA was found to be 1.6 nm with a decision
distance of 2.6 nm (Fig. 3) so a similar smoothing technique to that used
for the domain was tried out for the arena. By calculating the area enclosed on each side of the ship, summing, and then equating the total with a circle, a figure of 2.7 nm was obtained for the radius. Using the concept of a 'phantom' ship again to obtain the benefits of off-centring the real ship is off-centred by 1.7 nm at a relative clockwise angle of 199° from the phantom ship (Fig. 4). This is approximately double the domain size, and when applied to the model produced realistic results (Fig. 5). The model logic is such that if the arena is infringed, the predicted CPA infringes the domain, and the infringing ship has not altered course then the threatened ship alters. There is also a built-in safety factor, such that as soon as the domain is infringed the ship alters course, irrespective of the other ship's actions. With ships coming from all points of the compass on a collision course with the reference ship, steaming at 090°, the give-way vessel keeps out of the way of the stand-on vessel. Only in certain special circumstances do both ships have to alter, e.g. end-on or nearly end-on encounters.

As the model was producing realistic results with two ships, land was
introduced. The coastline was drawn on a grid and discrete points selected one-tenth of a mile apart on the coastline. These points were then input to the computer where their latitudes and longitudes were stored in an array. The ships were given a 'land arena' of arbitrary radius 1.5 nm with real ship displaced 1.5 nm astern of the phantom (Fig. 6). Due to the size of the land arena relative to the closeness of the points in the land array the coastline appears as a continuous line rather than a series of scattered points. It is impossible for the ship to pass between two adjacent points as action will have been taken earlier when the land arena is first infringed, as this has priority over any risk of collision.

Once the model was found suitable for a straight coastline an irregular coast was introduced, and later other obstructions. In a two-dimensional model the obstructions could be land, forbidden areas or areas of sea too shallow for that particular ship, e.g. a five-fathom line for a ship with 30-feet draft.

The questionnaire has been extended to cover the situations of a ship meeting an oil rig, isolated lighthouse and a fixed oil platform. From the replies it is hoped to find whether the land domain varies with the type of obstruction. If this proves to be the case the ship in the model will need to be equipped with a series of domains, the appropriate data being
selected by a code on the obstruction met. The area around Land's End is shown (Fig. 7) using the values for arena, land arena, etc., previously specified. By altering the coastline data a first approximation for any stretch of coast could be obtained.

Fig. 5. (In the figure the give-way vessels are erroneously shown as altering past reciprocal course of stand-on vessel)

Using the prior details, ships of varying speeds were directed in collision situations in the model. The results show that for equal speeds the model works satisfactorily but when the speeds are dissimilar anomalies occur. From the questionnaire replies it is hoped to establish to what extent the arena and domain vary with the size or speed of the ship.

3. FUTURE DEVELOPMENTS. Having obtained realistic results with two ships encountering one another and then a coastline the computer model is now being developed to include more ships, the simulation of a narrow channel and the variation of arena values about the mean. From the pilot questionnaire it can be seen (Fig. 3) that mariners react in an individual way to similar situations, and so the use of fixed values for arena and domain values is limited. By using a statistical model of mariners' reactions it is hoped to emphasize the human factor in navigation. The questionnaire has been expanded to provide data for reduced visibility, overtaking situations and closeness of approach to land, amongst other
factors. In this way it is hoped to obtain improved knowledge of the size and shape of the domain and arena as the speed and size of the ship, and the experience of the navigator, vary.

At present the rate of turn of the ships is constant after a 20-second delay, but it is hoped to link the rate of turn with other factors while also allowing for a drop in speed due to the turning effect. To enable this to be done, the angle of applied rudder will need to be found and then applied to a control model, consisting of steering gear, rudder and ship handling characteristics, that is currently being developed at Plymouth. The resultant model, incorporating traffic flows and queueing theory, could then be used to simulate traffic systems and allow for detailed study of alternative proposals before any regulations are brought into force. The model can produce collisions if the rate of turn is small, especially in the end-on or nearly-end-on case as often happens in 'radar assisted collisions', and so can be used to investigate or demonstrate these occurrences.
Fig. 7. The modelled ship reduces speed when the land arena is infringed so as to create a realistic effect.

REFERENCES