Comments on Ship Domains

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The ship domain is a very important and useful concept in marine traffic engineering. It has been widely used in traffic simulation models, for encounter criteria, traffic lane design criteria, VTS planning, risk assessment, collision avoidance, and for other applications.

Dr Y. Fujii, Dr E. M. Goodwin and Dr T. G. Coldwell have done a lot of work on this subject. The differences between their ship domain concepts are described in the second part of this paper. In the third part, the authors have used a new branch of social psychology – the theory of Proxemics – to analyse the factors which affect the ship domain, and point out that the basis of producing ship domains is in the field of Proxemics. Finally, in the fourth part of this paper, some problems in ship domains are analysed.

1. INTRODUCTION. Geometrically, a ship collision occurs when the passing distance between two ships becomes zero. To prevent a collision accident, a safe distance must be kept between two ships. The safe distance in the COLREGS is the concept of keeping 'well clear'. In marine traffic engineering, it is the radius of the ship domain.

The concept of a ship domain was presented first in the early sixties by Dr Y. Fujii and others, who established the ship domain model in Japanese waters, and introduced it to Europe. Further, Dr E. M. Goodwin in England confirmed the existence of the ship domain, and established a model of a ship domain in the open sea. In the eighties, Dr T. G. Coldwell established models of ship domains for end-on encounters and overtaking situations in restricted waters. By this time, the theory and models of ship domains had become generally established. In that period, and in the following ten years or so, many scholars modified the ship domain, and carried out practical researches. Since then, the ship domain has been widely used in ships' collision avoidance, marine traffic simulation, calculation of encounter rates, appraisal of collision risk, VTS design, the design of harbour water areas and anchorages, channel dredging, etc.

Even so, the theory of ship domains itself still has to be studied in the following aspects:

(1) The causes of ship domains;
(2) The problems that exist in present ship domains;
(3) The computer simulation of ship domains.

In this paper, the first two of the above problems will be discussed. The last question will be discussed in another paper.

2. SIMILARITIES AND DIFFERENCES IN THE CONCEPTS OF SHIP DOMAINS. Fujii, Goodwin and Coldwell defined the ship domain from various points of view. The definition of a ship domain made by Fujii is: 'Most of the navigators of the following ships avoid entering the surrounding domain of the

fore-going ship'. The domain boundary is defined as the distance from the central ship at which the density of passing ships reaches a local maximum value (see Fig. 1), the model of his domain is an ellipse (see Fig. 2)[1]. The definition

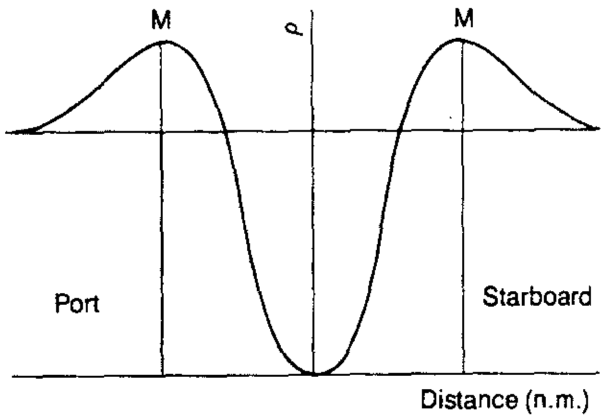

Fig. 1. Determination of ship domain size in narrow channel

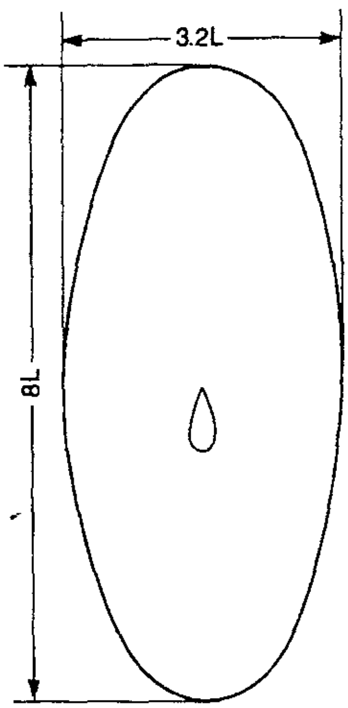

Fig. 2. Ship domain model (Japan)

of a ship domain made by Goodwin is: 'The surrounding effective waters which the navigator of a ship wants to keep clear of other ships or fixed objects'. The domain boundary is defined as x'_A in Fig. 3; thus, the total number of ships in $x < x'_A$ is less than the number would be if the domain did not exist. The condition that $x = x'_A$ corresponds to a condition of homogeneous traffic density. The boundary of her ship domain is divided into 3 sectors (see Fig. 4)[2] according to the arcs of a ship's sidelights and stern light. The definition of a ship domain made by Coldwell is: 'The surrounding effective waters which the typical navigator actually keeps clear, considering the existence of other ships'. The size of his

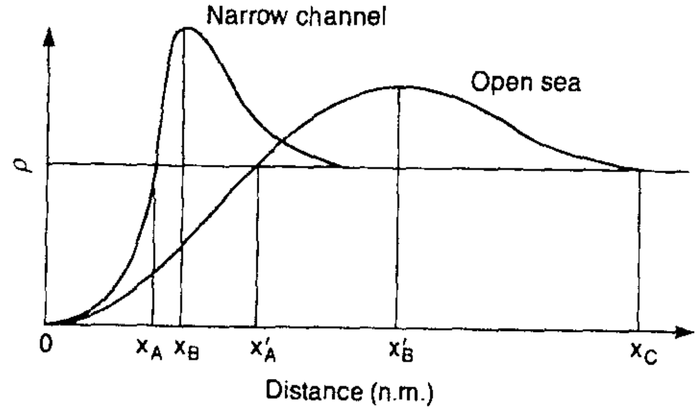

Fig. 3. Determination of ship domain size

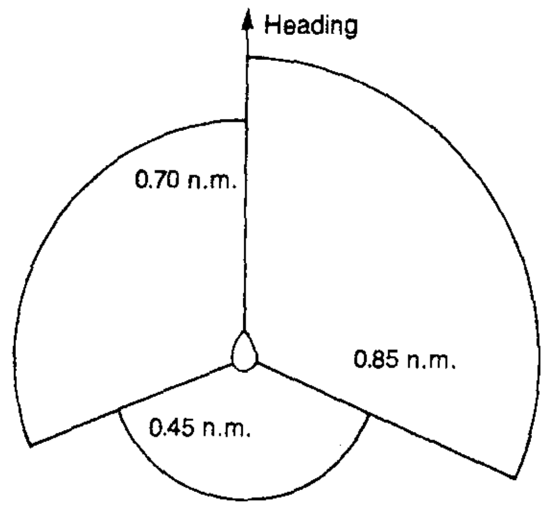

Fig. 4. Ship domain model in open sea

domain boundary is defined as the distance of a local maximum density value from the central ship; that is, x_B in Fig. 3. Coldwell's model for end-on meetings is shown in Fig. 5[3].

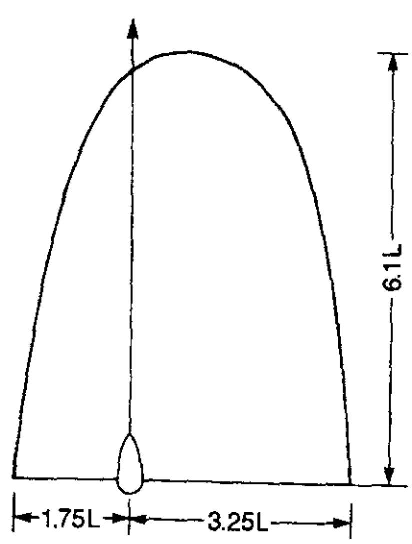

Fig. 5. Ship domain for head-on encounter

From the above, we can see that the definitions and models of Fujii, Goodwin and Coldwell are different. We analyse their similarities and differences as follows, and we consider their similarities first.

(i) The essential aspects of the concepts of these ship domains are the same. They all refer to a water area around a vessel which is needed to ensure the safety of navigation and to avoid collision.

(ii) From the models of ship domains as presented, we can see that the COLREGS have an important role in guiding a ship's behaviour.

(iii) From the definitions we can see that they all recognize the ship domain as being kept by one navigator of two meeting ships.

(iv) Considered formally, a ship domain as presented is around one of the two meeting ships. However, the safe navigation water area within the domain is shared by both ships.

(v) The purpose of all the ship domains is for research in marine traffic engineering.

(vi) The study methods the researchers used were marine traffic investigations and simulator experiments.

(vii) They all recognized that the ship domain dimensions would be affected by the length and speed of the central vessel, traffic density, conditions in the sea area, etc., especially the influence of ship length and sea area. They pointed out that a ship domain is not a fixed boundary around the central vessel, but is a water area adopted by the Officer of the Watch based on the varied circumstances.

Despite the above similarities in concepts and models, they also had the following differences due to investigating different sea areas, having different purposes, and thinking along different lines.

(i) The domain around a central ship (an overtaken ship) presented by Fujii is mostly formed by the actions of the navigators of the overtaking ships. The ship domain as presented by Goodwin around ownship is mostly formed by the actions of its own navigator. The ship domain (which is shown for an end-on model in Fig. 5) as presented by Coldwell is around ownship, and is mostly formed by the actions of its own navigator, but it is emphasized that the conditions reflected by the model are for typical navigators.

(ii) Considering the sea areas and encounter situations studied, the ship domain model presented by Fujii is suitable for overtaking situations in a channel; the ship domain model presented by Goodwin is suitable for various encounters in the open sea; and the ship domain model presented by Coldwell is suitable for end-on situations in restricted waters or harbours. Therefore, due to the influence of the COLREGS, the ship domain model presented by Fujii is symmetrical right and left, and the models of ship domain presented by Goodwin and Coldwell are non-symmetrical. This is reasonable and to be expected.

(iii) Considering the methods used to determine the position of the boundary of a ship domain, Fujii and Coldwell adopted the position of a local maximum value of ship density, and Goodwin adopted the position when the actual density of surrounding ships was equal to the local mean density for the first time. Of these two methods, the former is suitable for the study of traffic capacity and navigation safety in a channel, and the latter is suitable for the study of traffic risks.

(iv) Consider now the ship data used for ship domain models. The vessels observed by Fujii were mainly small coastal vessels of 20 ~ 500 g.t. The vessels observed by Goodwin were large and medium ships of various tonnages. Coldwell did not indicate the observed ships' sizes in his study, but his table 3 in reference [3] includes categories for ship length less than 50 m and ship length between 50 and 100 m.

(v) Considering the influence of visibility, Fujii held that: "It looks as if decreasing visibility will increase the range of an effective domain, but that further deterioration of visibility will not affect the range of a domain". Yet the domain obtained from experimental data (the visibility is supposed to be 0·25 n.m.) in a simulator by Goodwin showed an obvious influence of visibility. There was nothing concerning visibility in Coldwell's report.

3. THE PHYSIOLOGICAL BASIS OF SHIPS' DOMAINS. Why should a ship domain come into being? With the emergence and development of the theory of Proxemics, there is a possibility of our finding the reason.

3.1. *The concept of personal space.* One of the fundamental aspects of human behaviour is the use of one's surrounding area. How far apart do people stand from one another? What is the significance of the distance between them? Which factors affect it? What will be the reactions when the actual distance does not coincide with the required value? All these problems relate to the quality of a person's domain, which is one of the aims of the study of Proxemics.[5] Proxemics is a new branch of social psychology which was established by anthropology Professor E. T. Hall of the American North-East University in the late fifties. It is a science to study the use which people make of their surrounding area. The study showed that people are the same as most other animals: they need a certain clear space surrounding their bodies. When the actual space is less than some required minimum value, they make some reaction to preserve the space they feel comfortable with. This space is known as 'personal space', but sometimes we call it a person's 'domain'. A domain is an area or a space said to belong to oneself, rather like an extension of one's body. Personal space can be divided into four areas: the intimate area, the private area, the social area and the public area. For Americans, the sizes of these four areas are shown in Fig. 6.

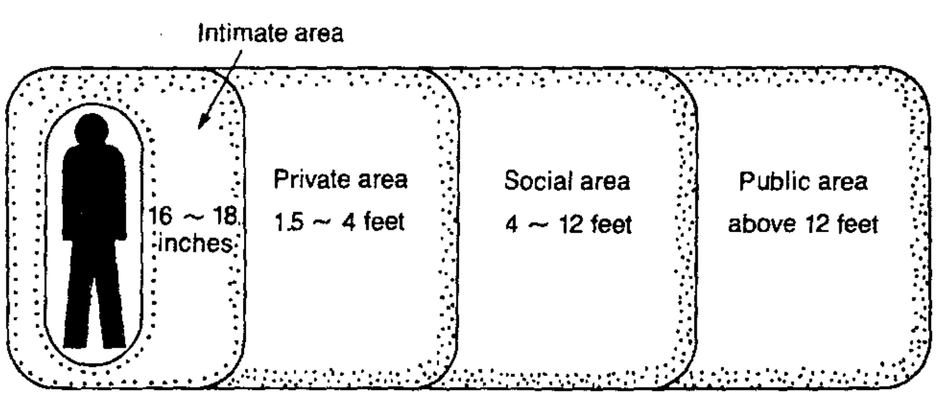

Fig. 6. Size of personal space

Personal space is affected by many factors, the main aspects being as follows:

First, persons with different cultural backgrounds have different concepts of personal space. The personal space of American, British and Swiss people is relatively large. For South Europeans (Italian and Greek), it is comparatively small. For South American, Pakistani and Arabian people, it is even smaller.

Secondly, the personal space of an adult and a child is different, the adult's being larger and the child's being smaller.

Thirdly, if the other person or the surroundings are safe and familiar, then one's personal space will be smaller. Otherwise, if the other person or the surroundings are seen as dangerous or unfamiliar, then one's personal space will be larger.

Fourthly, the relative speed of an approaching object affects one's personal space; the higher the speed, the larger will be the personal space.

Fifthly, the density of the surrounding persons affect one's personal space; the higher the density, the smaller the personal space.

Sixthly, the bearing of the surrounding persons will also affect one's personal space; generally, the personal space in front of one is larger than behind.[6]

In addition, sexual distinction, social position, relationships with the surrounding persons, disposition and sentiments, etc., will markedly affect personal space.

On the other hand, personal space will sometimes extend to include surrounding objects. For example, when bathing in the sea, people may spread a towel on the beach so that their personal space is not only a space around themselves, but also extends to the space around the bath towel. Moreover, when riding in a car, one's personal space extends to the space around the car. Psychologists have discovered that: 'The reaction of a driver in a territorial sense is different from that of individual people. A car seems to have a magnifying function – it will magnify one's personal space so that the driver considers that $12 \sim 15$ feet in front of and behind the car are his territory'.

3.2. *The causes of a ship domain.* Essentially, a ship's behaviour is a reflection of the navigator's behaviour. We can therefore personify a ship and look upon it as a special 'person' (a 'ship person') with a behavioural capability. It compromises a navigator's 'brain' and a ship's 'body'. The personal space of this ship-person is the ship domain. As for the personal space discussed above, the personal space of a ship-person is the extended personal space of the navigator. Therefore, the production of a ship domain is not only required for navigation safety, the basic cause is the domain concept of Proxemics; that is, the concept of personal space.

Now that a ship domain is identified as the personal space of a ship-person, it follows that it should have the characteristics of personal space. At the same time, it is not the personal space of a natural person, so there must be some peculiarities. In the follow sections, we will discuss the relationship of the various factors of ship domains.

Firstly, a ship domain is affected by the nationality of the ship personnel, and this is related to the ship's flag. Ships of different flags have different sizes of domain. This is mainly because the regulations formulated by various countries and companies which affect ships' behaviour are different, but also because of different training and requirements for seamen and different standards of ships' manning, equipment and management.

Secondly, the size of a ship affects its domain. The bigger the ship, the larger will be the domain. Fujii[5] obtained a relation between the ship size and domain size in an overtaking situation in Japanese waters, as follows:

$$\ln r = \ln L + 0{\cdot}85 +/- 0{\cdot}6, \tag{1}$$

$$\ln s = \ln L + 0{\cdot}48 +/- 0{\cdot}7, \tag{2}$$

where L is ship length, r and s are the long and short semiaxes of the ship domain respectively, and the units are metres.

Thirdly, the size of a ship domain is affected by the ship type. If ownship and the approaching ship are general cargo ships, the ship domain is relatively small. If they are passenger ships or ships carrying dangerous cargo, the domain is relatively large.

Fourthly, the size of a ship domain is affected by the character of the surrounding waters. If the ship navigates in open water, the ship domain is relatively large. From table 1[8], this can be clearly seen.

TABLE 1. THE BOUNDARIES OF DOMAINS IN DIFFERENT CONDITIONS. UNITS: NAUTICAL MILES

Sea area	Starboard sector	Port sector	Stern sector
Dover Strait	0·8	0·8	0·1
Ocean	2·4	2·4	0·9

Fifthly, the size of a ship domain is affected by the relative speed of the two ships. The higher the relative speed, the larger will be the ship domain.

Sixthly, a ship domain is affected by the traffic density in the navigating area. The higher the traffic density, the smaller will be the size of domain. This can be clearly seen from table 2[6].

TABLE 2. THE SIZE OF DOMAIN IN DIFFERENT TRAFFIC DENSITY. UNITS: NAUTICAL MILES

Index of traffic density	Starboard Sector	Port sector	Stern sector
20·9	0·5	0·5	0·4
11·3	0·7	0·6	0·5
7·5	0·9	0·9	0·8

Seventhly, the bearing of approaching ship will effect a ship domain. Goodwin's ship domain model (Fig. 4) showed this clearly. But how is this produced? P. Davis and others[9] explained it as: 'Because if the approaching ship is in the starboard sector, then the ownship must take avoiding action'. That is to say, when the target comes from the starboard side, the ownship is a giving way vessel, therefore the starboard sector will be larger. When the target comes from the port side, the ownship is a stand-on ship, therefore the port sector will be smaller. This explanation is open to question. Actually, the fact that the starboard sector is bigger than the port sector results from the COLREGS requirement that ships should pass port to port. If the navigator's avoiding action will result in passing port to port, and the passing distance is safe, then his psychological burden is light. If by any chance a collision happens, his responsibility will be small. On the contrary, if the navigator's action will result in passing starboard to starboard, it violates the COLREGS, and if by any chance a collision happens, his responsibility will be large, and his psychological pressure will be heavy also. In such a case, the passing distance of 'safe' is not sufficient - it must be 'very safe' and, as a reflection of this, the starboard sector is bigger than the port sector. This is a result of the psychological influence on navigation by the COLREGS.

In the ship domain of Goodwin (Fig. 3), the stern sector is smaller than the port or starboard sectors, but in the ship domains of Coldwell[3] and Fujii, the ahead sector is larger than the port or starboard sectors. How does this happen? We believe it is caused by the navigator's psychological factor. The study of Proxemics shows that: 'The requirement for space forward of a person is larger than the requirement for space behind them, and this is a common phenomenon'.[6] Therefore, the forward section of a ship domain, the personal space of a ship-person, should be larger than the after-space. But the actual ship domain is affected by the COLREGS and the COLREGS prescribe that the give-way vessel should avoid crossing ahead of the other vessel. That is to say, crossing astern is conforming with the regulations, and crossing ahead is violating the regulations. For this reason, the ahead sector should be smaller, and the astern sector should be larger. If the influence of the former factor is bigger than the latter, then the ahead sector will be bigger than the after sector overall, and that is the result shown by actual observation.

The above discussion is only an analysis from the aspect of a ship-person, and does not include the influence of different navigators. Such influences would be similar to those discussed in Section 3.1. Since the concept of a ship-person has no sexual distinction and social position, these influences do not exist.

4. ANALYSIS OF SHIP DOMAINS. We consider that, of the concepts and models of ship domains as presented by Fuijii, Goodwin and Coldwell, that of Goodwin is the most representative. In this section, we analyse Goodwin's ship domain especially.

4.1. *The definition of the ship domain.* Just as in paragraph 1, we start by considering the definition of a ship domain. Each of the three researchers holds that the ship domain is kept by one of the two meeting ships. Considering the form of a ship domain, they all recognize that safe navigation water is contained encircled within the ship domains as possessed by both ships. We consider now the situation where two meeting ships each hold that the initial DCPA$_0$ is not safe, and one of the ships takes avoiding action to reach a new DCPA$_1$. If the other ship now takes avoiding action, it is because the navigator of that ship considers that DCPA$_1$ is also not safe. If that other ship does not take avoiding action, it is because the navigator of that ship considers that the DCPA$_1$ is safe. The safe navigation water area is determined by the actions of the two ships; therefore, we consider the ship domain is defined by navigators of both meeting ships, and is not defined by just one of the navigators.

4.2. *The stern sector of a ship domain.* Speaking from a technical point of view, the essence of the boundary of ship domain is the locus of the extremity of the DCPA radius. Because the models of ship domain presented by Fujii, Goodwin and Coldwell were obtained from investigations after statistical processing, the models themselves can only demonstrate their objective existence, and cannot demonstrate anything else. Therefore, the discussion hereafter is on the basis of recognizing the objective reality noted above and discussing the subjective explanations of Goodwin's model.

Supposing that Goodwin's theory of ship domains is tenable (we assume that the internal part of a domain is empty, ideally) we consider the case as in Fig. 7: ship B astern of ship A, $\text{DCPA}_0 = 0{\cdot}45$ n.m. From ship A, the situation appears

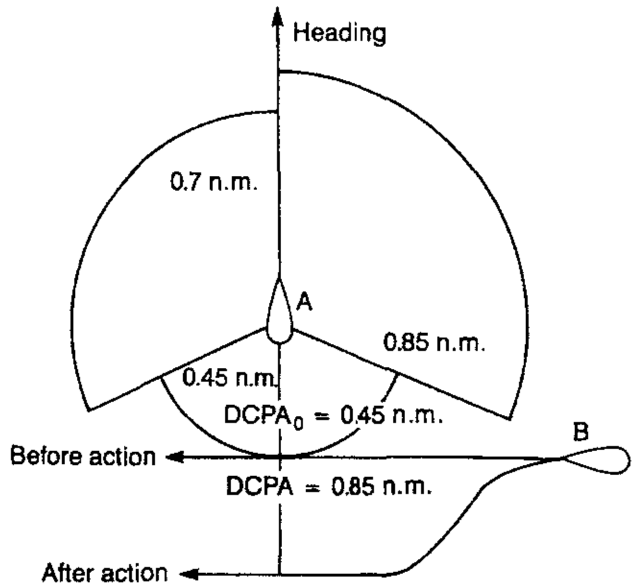

Fig. 7. Relative motion line passed astern

safe, and no action should be taken. But look at the situation from ship B, which also has a domain supposed similar to ship A. At this time, ship A is in the starboard sector of the domain of ship B, therefore ship B should take action to displace ship A outside the starboard sector. As a result, the astern sector of ship A should also become empty, so the observed stern sector radius should not be 0·45 n.m. but nearly 0·8 n.m. This does not coincide with Goodwin's actual observation, so we believe that the original supposition is untenable, and that the explanation of the results of observations made by Goodwin is not satisfactory.

4.3. *How the phrase 'in sight of one another' affects the ship domain.* Goodwin stated that: 'The COLREGS require that, when the threat comes from different bearings, ships should take different actions. This is why the domain around the central ship is not symmetrical'. This is the reason why Goodwin thought that the starboard sector should be larger. Davis and others gave the same explanation of Goodwin's model: 'Goodwin's domain concept presented the idea that when

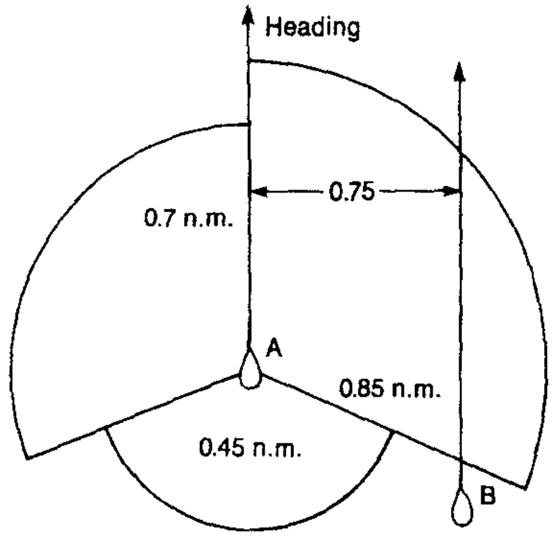

Fig. 8. Relative motion line passed starboard

ships come from different directions, they should be given different weights. The largest area is on the starboard side of the navigator, because in this area he must take avoiding actions.' This is not satisfactory. Generally speaking, when ships are in sight of one another, the regulations require that they should be passing port to port. Passing starboard to starboard is violating the regulations, so that the passing distance should be larger. To cope with this, Coldwell and James[10] made some explanations. As stated above, a turn to the right conforms with the regulations, so that the DCPA should be smaller, satisfying the 'safe' criterion. A turn to the left violates the regulations so that the DCPA should be larger. Therefore, a ship domain is not expected to be symmetrical; the starboard sector must be larger than the port sector. But one cannot conclude that the larger sector corresponds to bearings from 0° to 112·5°, and that the smaller sector corresponds to bearings from 247·5° to 360°. Besides which, the domain radii of different bearings are continuously changing, and they cannot change suddenly as in Fig. 4.

4.4. *The shape of a ship domain in restricted visibility.* Although Goodwin considered the influence of the COLREGS on the shape of a ship domain, she ignored the fact that the requirements for avoiding actions for ships in sight of one another and in restricted visibility are different. Therefore, she ignored the reality that the shapes for a ship domain in good visibility and in restricted visibility are different.

4.5. *The problem of calculating encounter rate.* Suppose Goodwin's ship domain model is correct, then let us see what happens when we use it to calculate the encounter rate.

In Fig. 8, ship A and ship B navigate on parallel courses, and ship A is in the starboard side of ship B, DCPA = 0·75 n.m. According to Goodwin's definition, taking one ship entering another ship's domain as one encounter, then, in this case, it allocates one encounter to ship A, due to ship B entering the starboard sector of the domain of ship A. But it does not allocate an encounter to ship B, because ship A is outside of the port sector of the domain of ship B. An encounter is a special meeting circumstance which is closely related to a collision and it indicates the traffic risk at sea to a certain extent. But we can see from the above example that, in the same situation, it may result in a collision with ship B for ship A, but it will not relate in a collision with ship A for ship B. This is contradictory, and so we will deduce that the original hypothesis is not true.

4.6. *The problem of determining collision risk.* In addition to the above example, there is another situation which illustrates the problem existing in Goodwin's ship domain. Goodwin and others considered that the size of a domain changes with the speed and size of the central ship, so that a larger ship has a larger domain, and a small ship has a smaller domain. If a small ship is situated in the starboard sector of a large ship's domain, and the large ship is outside the port sector of a small ship's domain (see Fig. 9), then according to the theory of ship

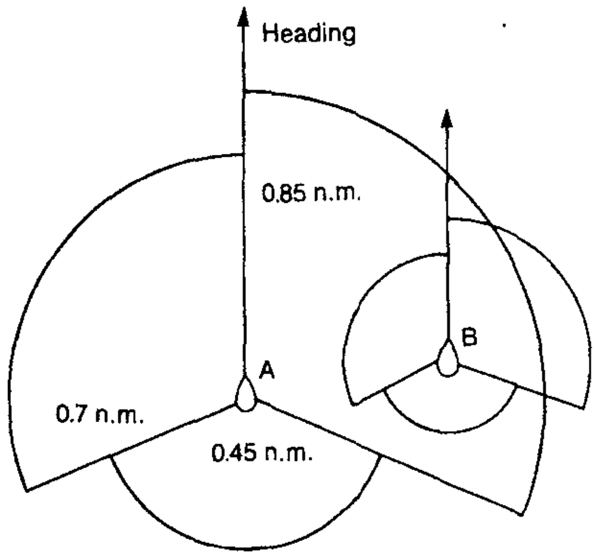

Fig. 9. Small target

domains, it is dangerous to ship A, but it is safe to ship B. This is also contradictory.

4.7. *The problem of ship domain size in restricted visibility.* The ship domain size in restricted visibility as presented by Goodwin is the result of simulator experiments. It is quite different compared with the ship domain size for ships in sight of one another. But investigations of live collision avoidance at sea[9] have shown that, in the open sea, the mean value of DCPA for ships in sight of one another is 1·24 n.m. and 1·32 n.m. in restricted visibility. They do not differ by much. Fujii also pointed out that the further worsening of visibility will not affect the size of ship domain.[1] We consider that the ship domain in restricted visibility should be investigated practically, and that the results of simulator experiments should not be investigated practically, and that the results of simulator experiments should not be trusted excessively. Also, the condition of visibility being less than 0·25 n.m. is very rare at sea, so it is doubtful how much experience of this will have been accumulated. Besides, the psychological factors may be affected by the experimental situation which will also affect the results.

4.8. *The boundary of a ship domain should be fuzzy*. According to the definition of a ship domain, navigators want to keep other objects out of the ship domain. f the relative motion line of an approaching ship intersects the ownship's domain, then the ownship's navigator will take action to keep it out of his domain. But, if the estimated DCPA differs very little from the radius of the ship domain – for example, the estimated DCPA is on the port side, and $DCPA_0 = 0{\cdot}69$ n.m. (see Fig. 10) – then, according to ship domain theory and the model

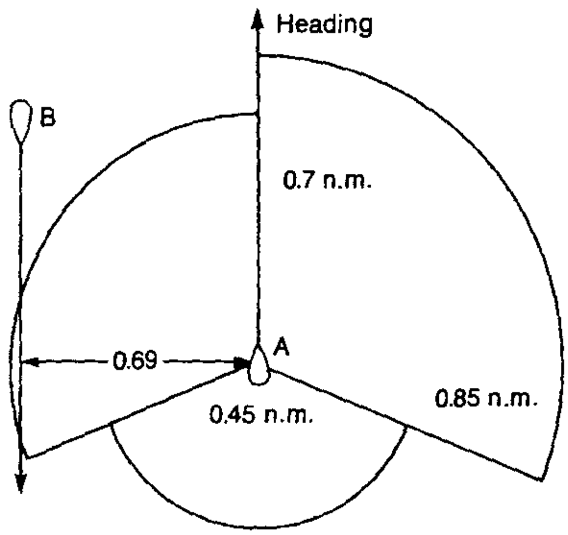

Fig. 10. The difference between DCPA and $DCPA_0$ IS SMALL

in Fig. 4, the navigator of ship A will feel unsafe and will take action to keep the relative motion line of his ship B out of his ship domain. This is not conforming with normal practice. Generally speaking, if the estimated DCPA differs very little from a safe DCPA, the navigator will not take action. This conforms with the normal psychological state of a human. Then what is the value of differing 'very little'? This is a fuzzy concept. We put the difference of estimated DCPA ($DCPA_0$) and the safe DCPA (that is, the radius of the domain) as y:

$$y = |DCPA - DCPA_0|. \tag{3}$$

Thus, the diagram to indicate the subordinate function of 'not very little' fuzzy set S, is as in Fig. 11. Its equation is:

$$\begin{aligned} \mu_s(y) &= \lambda_1 y^{\lambda_2}; \quad y \leqslant y_1, \\ \mu_s(y) &= 1, \quad y > y_1, \end{aligned} \tag{4}$$

where y_1 is the value of y in $\lambda_1 y^{\lambda_2} = 1$; λ_1, λ_2 are positive parameters, which change with critical conditions, and reflect the navigator's attitude.

The concept of a fuzzy boundary for domain (FBD) is: the FBD is fuzzy; if the relative motion line of a target is outside of the fuzzy boundary, it is safe, no action need be taken; if the relative motion line is just inside the fuzzy boundary, it is not certainly safe, but not certainly dangerous either, action need not be taken; if the relative motion line is inside the fuzzy boundary, it is dangerous, action must be taken to keep it out of the fuzzy boundary (see Fig. 12).

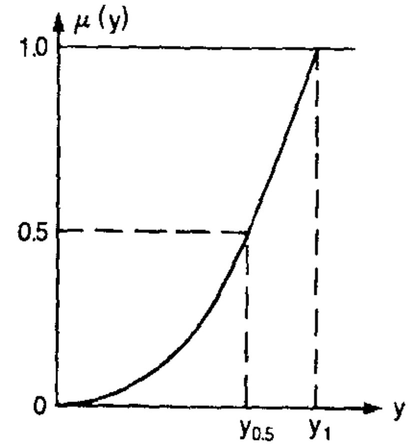

Fig. 11. The membership of fuzzy set S

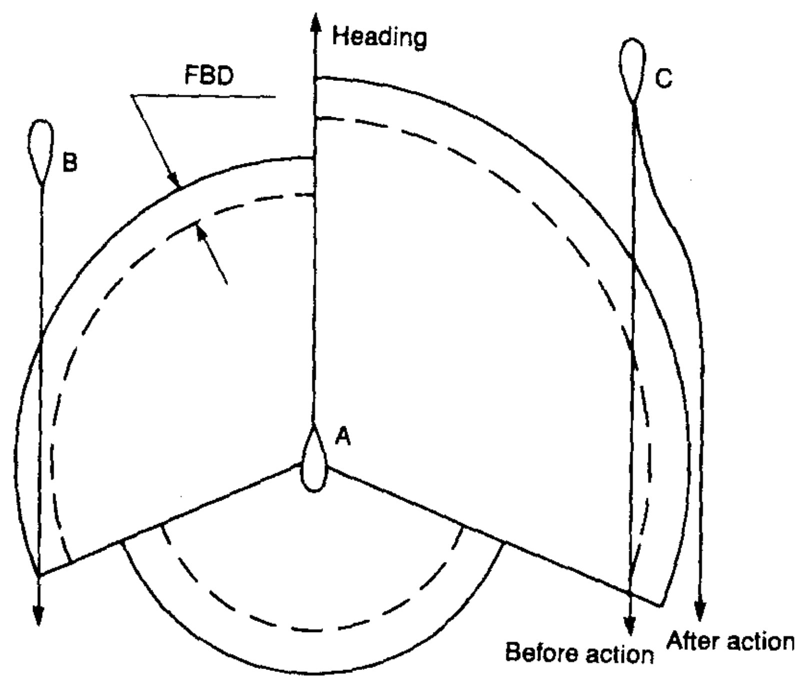

Fig. 12. The fuzzy boundary of ship domain (FBD)

The mathematical expressions of the above concept are:

(i) the width of FBD is $y_{0 \cdot 5}$.
(ii) if $\text{DCPA}_0 \geqslant \text{DCPA}$, it is safe. No action shall be taken.
(iii) if $\text{DCPA} - \text{FBD} \leqslant \text{DCPA}_0 < \text{DCPA}$, it is not safe, but the degree of risk is small, and action need not be taken.
(iv) if $\text{DCPA}_0 < \text{DCPA} - \text{FBD}$, it is dangerous, and action must be taken to keep the actual passing distance not less than DCPA.

5. CONCLUSION. The ship domain, since it was first presented by Fujii and others, has developed theoretically and practically, and made encouraging achievements. In this paper, the causes of ship domains have been analysed to help us understand the ship domain more deeply. The problems which existed have been discussed, and the next step is to study how to solve these problems.

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KEY WORDS

1. Marine traffic. 2. Risk analysis. 3. Collision avoidance.

Dr E. M. Goodwin *writes*:

1. In this paper the authors have very helpfully discussed some important practical aspects in the modelling and subsequent use of the concept of the ship domain. It will be interesting to follow the future work of these authors in this area.

2. The difference in definition between Fujii, Coldwell and Goodwin reflects the sea areas and traffic densities being modelled. In practice, the definitions adopted by all three authors in restricted waters are likely to yield similar results because, in narrow channels and high density traffic, the navigator has less room to manoeuvre and is also able to leave less room around his vessel. In open sea conditions, which were those modelled by Goodwin, the navigator has more effective sea room.

3. Certainly, the navigators of each ship will be keeping their own domain, but as these vary from ship to ship and person to person, there will be many encounter cases when one of the ship domains is breached. The work of Goodwin was done by observing the behaviour patterns from outside the ships and it was not possible to talk to the navigators to discuss if a breach of a ship domain for one of them was threatening.

4. The results obtained by Goodwin were all based on a series of observations of ships, and differences in radii of the three sectors were obtained. The results were obtained with ships passing each other on a range of relative bearings and aggregated over all ships in the area. Clearly, in practice, any one ship will not have the discontinuities in ship domain boundary as produced in the model but the three sector domain was used to illustrate the differences in risk.

5. Unfortunately, when the original study was done, time and other practical considerations prevented a full study of ship domains in restricted visibility in real life. Certainly the differences in navigators' behaviour in real-life and simulated conditions needs to be investigated.

Because of the difference between two ships with two different navigators, an encounter for one navigator/ship will not be an encounter necessarily for the other ship/navigator. Some encounters cannot be avoided and are deliberate manoeuvres. They are only likely to turn to collision risk when human error is involved. The use of ship domains for the calculation of collision risk is only a modelling tool, although for many practical applications it has proved to be an extremely useful one.

A Note on the use of the Global Positioning System (GPS) for the Identification of Marine Radar Contacts

W. B. Stawell

1. INTRODUCTION. The Global Positioning System (GPS) is a cheap, accurate (± 100 m), satellite-based position fixing system. These qualities suggest that it might be used in the identification of marine radar targets. The first application of such a system on any scale will probably be as part of a Vessel Traffic Service (VTS) and here GPS would seem to be ideally suited. Vessels entering the VTS control zone would need to be fitted with GPS interfaced with either a dedicated VHF receiver or a 'guard' channel on their normal receiver A VTS radar operator needing to identify an echo would work out the echo's position from the radar range and bearing and transmit that position as the interrogating signal. Only the vessel in the control zone with that position (derived from its GPS interface) would respond with its identity. There would thus be no possibility of interference between responses or garbling that can be a problem in interrogation systems based on secondary radar. Even if the VTS had several radars, these could easily be synchronized to prevent simultaneous interrogations. However, outside VTS zones there is a clear need for a universal identification system that would allow any ship to identify any other. It would be unfortunate and wasteful if a system developed for VTS was found to be unsuitable for this general application. This note will therefore discuss the adequacy of GPS as the basis of a universal marine identification system.

2. POSSIBLE METHODS. There would seem to be two possible ways of applying GPS to marine identification. The first, which might be called 'individual interrogation', could operate in very much the same way as in a VTS as described above. A ship wishing to identify a radar echo would work out the echo's position from its own position, derived from GPS and the echo's radar range and bearing, and transmit this as the interrogating signal. Only the ship in that position would repond with its identity. In the second method, which might be called 'broadcast', all ships would transmit their positions and identities as often as needed to keep their position up-to-date, and this information could be received and recorded by all ships within VHF range: a simple inexpensive matter with modern computers. Subsequently, any echo could be identified by working out its position and 'looking up' its identity from the stored information. The rest of this note, though not pretending to full mathematical rigour, will attempt to make some estimate of the possible performance of these two methods. It will appear, even from this elementary treatment, that the use of GPS as the basis of an interrogation system may suffer from severe operational limitations. Certainly

further work, including computer simulation, is essential before any such system is considered for operational use.

3. INDIVIDUAL INTERROGATION. Though an individual ship will only respond to an interrogation if it receives a signal coded with its own position, performance will be limited by the possibility of mutual interference caused by simultaneous interrogations and by the responses of different ships within VHF range of each other. In order to assess the effect of this interference it is necessary to make some assumptions as to how the system will be operated. It is assumed then, that all ships will attempt to establish the identity of all new echoes appearing on their radars, making as many attempts as needed to do so, but once an identity has been established, no attempt will be made to interrogate the same target again. A ship will either transfer the identity to its ARPA or keep a manual record.

Now if the average speed of a ship in a particular areas is $\bar{v}$, and the maximum radar range is R_r, the ship will in time T sweep out an area of $2R_r\,\bar{v}T$ of new radar coverage. If the density of shipping in the area is D this will contain:

$$2R_r\,\bar{v}TD \quad \text{new radar targets}$$

and this will be the average number of identifications that a ship must make in time T. If the maximum VHF range is R_v, then mutual VHF interference can occur over an area of πR_v^2 containing $\pi R_v^2 D$ ships. Thus the total number of identifications which must be made by all ships in this area in time T must be:

$$2\pi R_v^2\, R_r D^2 \bar{v} T. \tag{1}$$

Now if the probability that a single attempt at identification will fail due to interference is p_i, then the probability that the second attempt will fail is p_i^2 and the third p_i^3 and so on and the average number of interrogations required to establish an identity on each occasion will be:

$$\sum_{n\to\infty} 1+p_i+p_1^2+,\dots,+p_i^n \quad \text{or} \quad \frac{1}{1-p_i} \quad (\text{as } 0 < p_i < 1). \tag{2}$$

Thus the total number of interrogations performed in the VHF area πR_v^2 in time T is, from (1) and (2):

$$\frac{2\pi R_v^2\, R_r\, D^2 \bar{v} T}{1-p_i}. \tag{3}$$

Now if each interrogation and response takes a time t_i then from (3):

$$p_i = \frac{2\pi R_v^2\, R_r\, D^2 \bar{v} T}{(1-p_i)} \cdot \frac{t_i}{T} \tag{4}$$

or

$$p_i^2 - p_i + A = 0. \tag{5}$$

Where

$$A = 2\pi R_v^2\, R_r\, D^2 \bar{v} t_i. \tag{6}$$

Solving (5) for p_i gives:

$$p_i = \frac{1 \pm \sqrt{(1-4A)}}{2}. \tag{7}$$

If $4A > 1$ equation (7) has no real roots, so the maximum value of p_i when $4A = 1$ is 0·5. The physical significance of this is that if $p_i = 0{\cdot}5$ then half the available time is filled with initial interrogations and responses, but, as under these conditions from equation (2), the average number of interrogations needed to establish an identity is given by $1/(1-p_i) = 2$ (for $p_i = 0{\cdot}5$) all the available time is filled by initial and subsequent interrogations and any further increase in ship density, D, will result in a catastrophic failure as the system 'locks out' and it will become impossible for any interrogator to obtain an identity. The critical traffic density D at which this lock-out occurs can be estimated by making reasonable assumptions of the factors in equation (6) and solving for D in $A = \frac{1}{4}$ ($p_i = 0{\cdot}5$ in equation (7)).

Hence assuming:

$$\text{Max VHF range } R_v = 35 \text{ n.m.},$$
$$\text{Max radar range } R_r = 12 \text{ n.m.},$$
$$\text{Average speed } \bar{v} = 12 \text{ knots}.$$

For the interrogation response time t_i, assume that a discrimination of $\pm 0{\cdot}5$ n.m. is required and that a unique position in a hundred-mile square is sufficient to identify a local target without the possibility of triggering a response from a source outside the square. This means $200 \times 200 = 40\,000$ addresses or, say, 20 bits allowing for check bits. For the response, six decimal digits should be enough to provide a unique identity. Allowing a further 6 bits for checking and type of ship indication gives a total response code of 30 bits or a total of 50 bits for interrogation and response. If the available bandwidth is 1 khz this means a t_i of around 50 ms. In the expression for A, as $\bar{v}$ is in knots, t_i must be expressed in hours; that is, $50 \times 10^{-3}/60 \times 60$. Solving for D in $A = \frac{1}{4}$ gives $D = 0{\cdot}13$ vessels/sq n.m. or a ship in roughly every 8 square miles. This is equivalent to about three miles between ships: a high, but hardly excessive, traffic density.

4. BROADCAST. In the broadcast use of GPS all ships, rather than waiting to be interrogated, would broadcast their identities and positions. Clearly, some method is needed to stop all ships broadcasting at once. If the system is to discriminate between ships 0·5 n.m. apart, then the position provided in the broadcast position identity message must be to that accuracy or better. It would be reasonable then, if a ship broadcast a new position identity message when she had travelled 0·25 n.m. (this would involve an interface with the log but that is not difficult). With the same symbols, this means a transmission $4\bar{v}$ times/hour or a total of:

$$4\pi R_v^2 D\bar{v} \quad \text{transmissions/hour for the VHF area.} \tag{8}$$

As the transmission consists of a position and an identity, the time required would be the same – 50 ms – as that for the interrogation and response derived above. To ensure that its transmission had registered and that the accuracy of its position was maintained, a ship would need to listen out for interfering transmissions (detected by a transmission of < 50 ms after its own transmission had ceased) and if it detected any, retransmit until an interference-free transmission was obtained. Thus we can again derive an equation for p_i similar to (4) above. That is:

$$p_i = \frac{4\pi R_v^2\ D\bar{v}t_i}{1-p_i}. \tag{9}$$

And again the critical value – 0·5 – of p_i when the system locks out is given by:

$$4\pi R_v^2\ D\bar{v}t_i = \frac{1}{4}. \tag{10}$$

Solving for D using, as before, 35 n.m. for R_v and 12 knots for $\bar{v}$, gives $D = 0{\cdot}1$ or a vessel every 10 sq n.m. This is the same order of magnitude for traffic density as the critical density for the individual interrogation method.

5. POSITION ERRORS. The analysis so far has taken no account of the interrogator's uncertainty of its target's position. Such uncertainty will arise from three sources: GPS error in determining the interrogator's own position, GPS error in the target's position and uncertainties in the interrogator's radar range and bearing of the target. If these errors are sufficient to place the target outside the half-mile square the interrogator believes it to be in, then the interrogation will fail. The target will appear to be outside the half-mile square if either the error across the interrogator target line of sight or along it places the target outside the corresponding half-mile side of the square. The possible error across the line of sight will be a combination of the ±100 m of GPS errors in position of the interrogator and target and the possible error due to the finite beamwidth of the interrogator's radar. Taking the GPS errors as approximately 0·1 n.m. each and a radar beamwidth of 0·5 at 12 n.m. also producing an error of 0·1 n.m., the total RMS error is $\sqrt{(3\times 0{\cdot}1^2)} = 0{\cdot}17$ n.m. If, to simplify the arithmetic, it is assumed that this error has a rectangular rather than a gaussian distribution, it can be shown that the probability that this error will place the target outside the half mile side is $0{\cdot}17/(4\times 0{\cdot}5) = 0{\cdot}08$. If the possible radar range error is 0·1 n.m. then the error along the line of sight is again 0·17 n.m. and the probability that the target is outside the half mile side is again 0·08. Combining these two by the normal rule for the addition of probabilities gives a probability of $0{\cdot}08+0{\cdot}08-0{\cdot}08\times 0{\cdot}08 = 0{\cdot}15$ that the target will be placed in the wrong square and the interrogation fail. The probabilities of failure to obtain an interrogation from interference (p_i) and position error (p_e) gives an overall probability that an interrogation will fail as

$$p_t = p_i + p_e - p_i\,p_e. \tag{11}$$

Equation (4) can then be rewritten as:

$$p_i = \frac{A}{(1-p_t)}. \tag{12}$$

Combining equations (11) and (12) and substituting for p_i and p_e gives the critical value of A when lock-out occurs as $A = 0{\cdot}85^2/4$ for the individual interrogation method. This decreases the critical traffic density (D) to $D = 0{\cdot}11$ vessels/sq n.m. Thus positioning errors cause a degradation of performance of around 15 percent. Similar results can be expected from the broadcast method.

6. CONCLUSIONS. The conclusion is then that either of the two methods considered for using GPS as a marine identification system will suffer catastrophic failure at high (but not impossible) traffic densities. It is, of course, at these high traffic densities that the mariner has the greatest need for reliable identification. It will doubtless be argued that some of the assumptions in this note are unrealistic. For instance, in the individual interrogation method does a ship need to identify *every* new radar contact? Or again, will not high traffic densities only occur in restricted waters where much of the πR_V^2 of a VHF area will be dry land devoid of shipping? There may be something in these arguments; nevertheless, any system that is capable of catastrophic failure under any possible circumstance cannot be regarded as satisfactory. The fundamental flaw in a GPS-based identity system is its lack of discrimination: every ship in VHF range receives the transmissions of every other whether it needs it or not. By their ability to use bearing information, secondary radar-based systems such as Midar[1] can provide discrimination better by some two orders of magnitude.

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KEY WORDS

1. Radar. 2. Satellite navigation. 3. Vessel traffic services.