EVALUATION OF AN AUTOMATIC MARINE RADAR PLOTTER

W.C. van den Hoed

Koninklijke/Shell-Laboratorium, Amsterdam (Shell Research B.V.)
Amsterdam, The Netherlands

and

H.J.G. Zwaga

Psychological Laboratory, University of Utrecht,
Utrecht, The Netherlands

Summary

To help determine the operational value of computerized automatic plotters as a major marine navigational aid, Koninklijke/Shell-Laboratorium, Amsterdam, has carried out a field test on Iotron´s Digiplot. In this paper results are presented on that part of the evaluation on board the ss "Methane Princess" in which special attention was paid to: (i) the use of Digiplot in watchkeeping and (ii) the role of Digiplot in the decision process in situations where there is a direct threat of collision.

For this assessment an analysis was made of the utilization of the data supplied by Digiplot and the conventional sources of navigational information. The sequence of consultation of the different sources of information was also studied and structured interviews were held. The latter were used to determine how a navigator arrived at a particular decision under a direct threat of collision and the way in which Digiplot assisted him in the decision making.

1. Introduction

For navigation under conditions of reduced visibility, radar information is of the utmost importance. It is doubtful, however, whether in congested traffic areas the navigator will always be able to extract from the data presented on a conventional plan position indicator (PPI) all the relevant information he requires to take adequate collision avoidance actions (Jones et al., 1975). It was for this reason that Shell Research was requested to look into the operational limitations of conventional PPI´s and to investigate the possible improvements to be gained by the use of modern automatic plotters.

From an extensive survey of commercially available automatic plotting systems, Iotron´s Digiplot was selected for a field test for the following reasons:

(i) At the time of ordering, Digiplot was the only marine radar plotter available with automatic target acquisition. This facility was considered an essential requirement for the system to function as a data extractor.

(ii) Iotron claimed that Digiplot could be interfaced with any type of marine radar system.

(iii) Digiplot is built around a general-purpose minicomputer that could also be used for other navigational tasks.

In February 1972, one of Iotron´s first production units was installed on board the liquid natural gas carrier ss "Methane Princess", which maintains a regular service between Canvey Island (UK) and Arzew (Algeria). At our request this Digiplot unit was extended with a data output bus to enable data to be collected for later evaluation. For this purpose, a data logger based on a Nova 1200 computer (Data General Corp.) was developed and coupled to the Digiplot.

The actual evaluation of the Digiplot was begun in April 1973 and took place during round trips between the UK and Algeria. The Digiplot/Nova system was subsequently used for traffic analysis at Europoort over the period October 1973 to February 1974 (van den Hoed, 1976) and is now installed permanently on board ms "Niso".

2. The collision avoidance operation

The block diagram in Figure 1 illustrates the navigational task as far as collision avoidance (CA) is concerned. Two levels of activity can be distinguished:

(i) A watchkeeping duty to confirm in a continuous updating mode that the ship is not involved in a close-approach encounter situation either at the present time or in the near future. (See dashed line "no threat" in Figure 1).

(ii) A decision-taking duty in situations where there is a potential risk of collision in the near future. This situation is represented in Figur 1 by the outer loop.

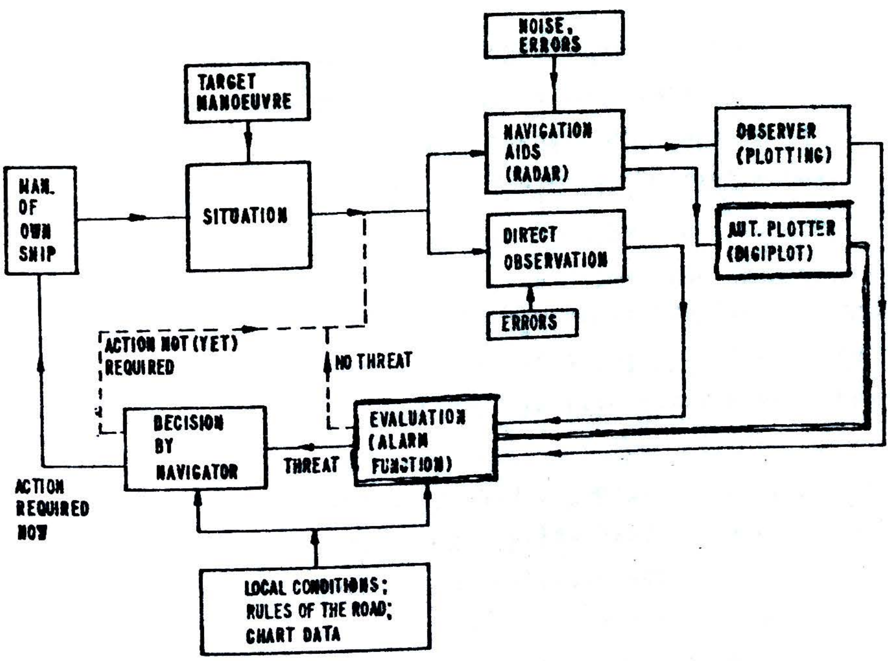


FIGURE 1

NAVIGATOR's ACTION LOOP FOR COLLISION AVOIDANCE

The navigator updates his knowledge concerning the traffic situation by making use of the radar, plotting, direct observation, etc and evaluating the data. From this evaluation he may or may not recognize a direct threat. On recognizing a threat he decides whether any action has to be carried out immediately or not. In the absence of a threat the sequence of information collection is repeated.

In neither case will the navigator use absolute standards; local conditions such as the weather, visibility and sea state, traffic recommendations and traffic patterns known from previous experience will influence his decision as regards acceptable minimum distances (Goodwin, 1975). Moreover, he will observe the appropriate "rules of the road" that apply under the given conditions.

To perform each of his two duties the navigator requires different information (Jones, 1973):

(i) For watchkeeping he primarily needs the closest point of approach (CPA) and, for targets with a short CPA, also the time of CPA (TCPA).

(ii) In situations where there is a direct threat of collision, the true course, speed and aspect are required, both of dangerous targets and of targets which could become part of the problem should a manoeuvre be carried out.

Two types of information are available to the navigator: data obtained by direct observation when visibility is good and radar data obtained under nearly all conditions.

The information collected by direct observation, though wide-ranging, is merely qualitative. The navigator can obtain information on the range, bearing, aspect and type of ship, and he may get indications of the speed, the course and even of the rate of turn of a target. For estimating the risk of collision the navigator analyses the change in bearing. However, it is difficult to determine the CPA from direct observations with confidence, but with good visibility it is not necessary to work to hard and fast limits. A navigator will accept CPA's of a few cable length as long as he feels that he has full control over the situation.

The data presented on a conventional radar can, after manual plotting, provide the navigator with a certain amount of quantitative information. Since the operating range of a modern radar set is wider than the visual horizon, radar can also be used as a forewarning aid. On a PPI operating in relative motion, the CPA and TCPA can easily be obtained by a simple procedure of extrapolation. However, to extract the course and speed of a target the navigator has either to plot a vector triangle or to switch the PPI to true motion. In true motion, owing to the persistence of the PPI, the trails of the echoes give a direct indication of the true course and speed, but in this mode the CPA and TCPA cannot be obtained directly. This is, of course, the reason for the recommendation by Wylie (1966) 'that, with duplicated radar installations, one PPI be used in the relative-motion mode and the other in the true-motion mode.

3. The contribution from automatic plotters

During the last decade manufacturers of radar equipment and computers have recognized the problems concerning workload and fatigue (see Davies and Tune, 1970) that are encountered in navigation in areas with a high traffic density. A number of solutions have been found in the use of automatic plotters, which may or may not be based on computers (see, for example, Watt and Piercy, 1969; Wylie, 1972; Riggs, 1975). At the present state of the art, the accuracy of operation and the reliability of tracking of computerized automatic plotters is limited (Van den Hoed, 1976). Moreover, these systems are only capable of extrapolation from the actual data, so they cannot give indications of the intentions of other ships.

As regards these intentions, which are of the utmost significance for collision avoidance, the navigator is expected to continuously update his knowledge of the actual situation and to generate hypotheses about what is going to happen. Automatic plotters, however, can make a contribution in this respect; the immmediate availability of the range and bearing, the course and speed and the CPA/TCPA of a particular ship makes it easier for the navigator to assess the situation, and this will greatly improve the speed and quality of his decisions. On the other hand the navigator still has to verify the data presented by the automatic plotter in order to compensate for its limitations.

We may include from the above that automatic plotters should be particularly useful under conditions of heavy traffic and in situations where CA manoeuvres have to be carried out. In respect of watchkeeping the automatic plotter might be considered a luxury. However, while watchkeeping the navigator could form a well-balanced opinion of the system and would learn from experience that there is a possibility of the system presenting him with erroneous information.

4. Features of the Digiplot system

Iotron's Digiplot, which is a computerized system, has the following features:

(i) Automatic acquisition of targets and detection of land masses.

(ii) Vectorial display of up to 40 targets, presenting positions, speeds and courses of targets on a fully synthetic display (neither PPI data nor a rotating scan).

(iii) The persistence of the display is very short and updating takes place at mains frequency (60 Hz). The range, display mode and orientation of the screen can be changed without any noticeable afterglow. This enables the navigator to switch quickly and frequently between relative and true motion.

(iv) A predicting facility (trial manoeuvre) for testing the feasibility of a proposed manoeuvre for own ship only. In this mode the vectorial picture develops step-wise in a time scale 30 times faster than real time.

(v) Numerical read-out of data for any target tracked. Target selection is accomplished by the use of a flashing symbol controlled by a joystick. The following combinations of data can be displayed on the twin three-digit display unit: range/bearing (DMO); speed/course (DM1); CPA/TCPA (DM2).

Photographs of the display in the true modes are presented in Figure 2. The figure clearly shows the layout of the control panel.

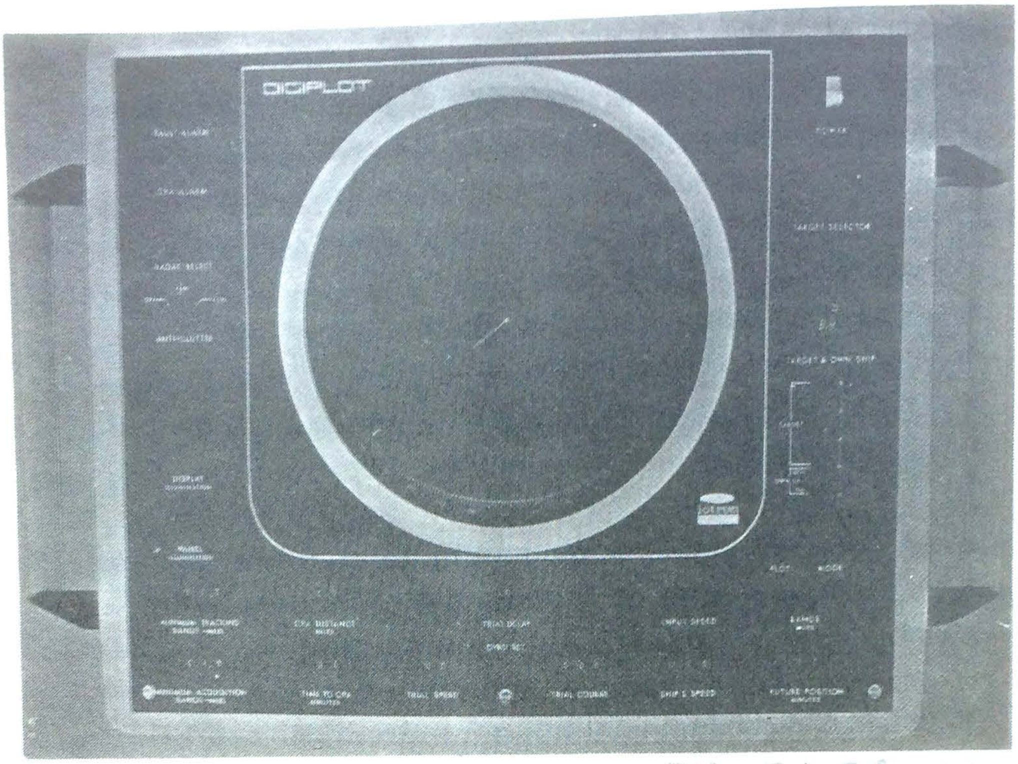
5. Aims of the evaluation

The aims of the evaluation can be considered under two headings:

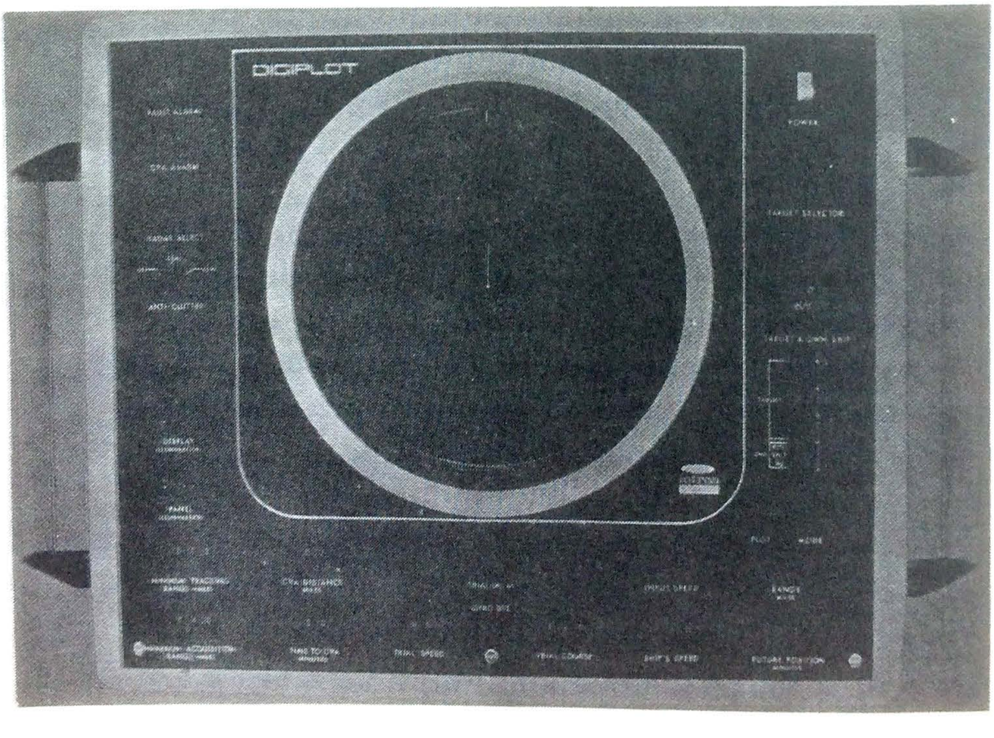
5.1 Assessment of the use of the Digiplot in watchkeeping

Whether or not the navigator regards the Digiplot as the main source of information for his watchkeeping duty is a leading question. In the affirmative case a marked decrease in consultation of the radar, visual inspection of the sea and the use of charts would be expected. Alternatively, the navigator could integrate the system in a comprehensive procedure of information collection encompassing radar, looking out and charts. A third possibility might be that the navigator decides to neglect most of the information made available by Digiplot and prefers the conventional means and methods.

FIGURE 2



NORTH-UP – TRUE VE



HEAD-UP – TRUE VECTORS

THE DIGIPLOT DISPLAY AND CONTROL PANEL

5.2 Analysis of the decision process under direct threat of collision with special emphasis on the role of Digiplot

This refers to the use of Digiplot displays and features in situations where decisions aimed at collision avoidance have to be made. More specifically, we wished to determine how the navigator arrives at a particular decision and in which way Digiplot assists him in the decision making.

6. Methods used in the evaluation

6.1 Analysis of information collection during watchkeeping

The assessment of the value and role of Digiplot relative to other available sources of information was based on an analysis of the frequences of utilization of information supplied by the Digiplot and the conventional sources of information (For a discussion of the techniques used see Chapanis, 1962 and de Greene, 1970). The sequence of consultation of the different sources of information was also studied in order to find out how the use of the Digiplot system is integrated in the complete procedure of information collection.

The data base for these studies consisted of records made of the actions of the navigator. Two groups were distinguished:

(i) actions involving the use of features of the Digiplot;

(ii) consultations of the radar, inspection of the Digiplot displays, visual scanning of the sea (with or without binoculars) and the use of charts.

In respect of the Digiplot, the Nova computer was programmed to record the use of all its features. For the recording of the other actions a set of push buttons was interfaced with the Nova and these were operated by an observer on the bridge. Although the recording of data was based on an activity sampling method, the registration can be considered to be a continuous recording since an extremely short time base (two seconds) was used. The advantage of such a continuous recording is that it indicates not only the frequency with which the different sources of information are consulted but also the sequence.

During an observation period a complete action string was recorded. For the analysis of the data the string of each observation period was broken up into pairs of subsequent actions and the totals for each period were aggregated in the form of a transition matrix. This matrix shows the frequency of occurrence of all the possible pairs of actions.

6.2 Analysis of the decision provess under direct threat of collision

Operationally a situation with a direct threat of collision is defined as any situation in which a change of course occurs or a trial manoeuvre is carried out. For the analysis of situations with a direct threat of collision the data base consisted of the following information:

(i) The action records made on the bridge and the record of the use of Digiplot ffeatures.

(ii) The computer record of the information displayed on the Digiplot. Thus accelerated play-backs of the display round about the time of significant events could be obtained.

(iii) The navigators' recollections of the situatiions and their actions.

(iv) The observers' notes on activities on the bridge.

After each watch, the significant events that had occurred were reconstructed with the aid of these four sources of information. This was done in structured interviews based on the scheme presented in Figure 3. Subsequently, these situations were extensively described on standardized sheets, after which the sheets were edited and approved by the navigator. Polaroid pictures of a slave display were taken at the most critical points in time. An example of a sequence of these pictures is shown in Figure 4.

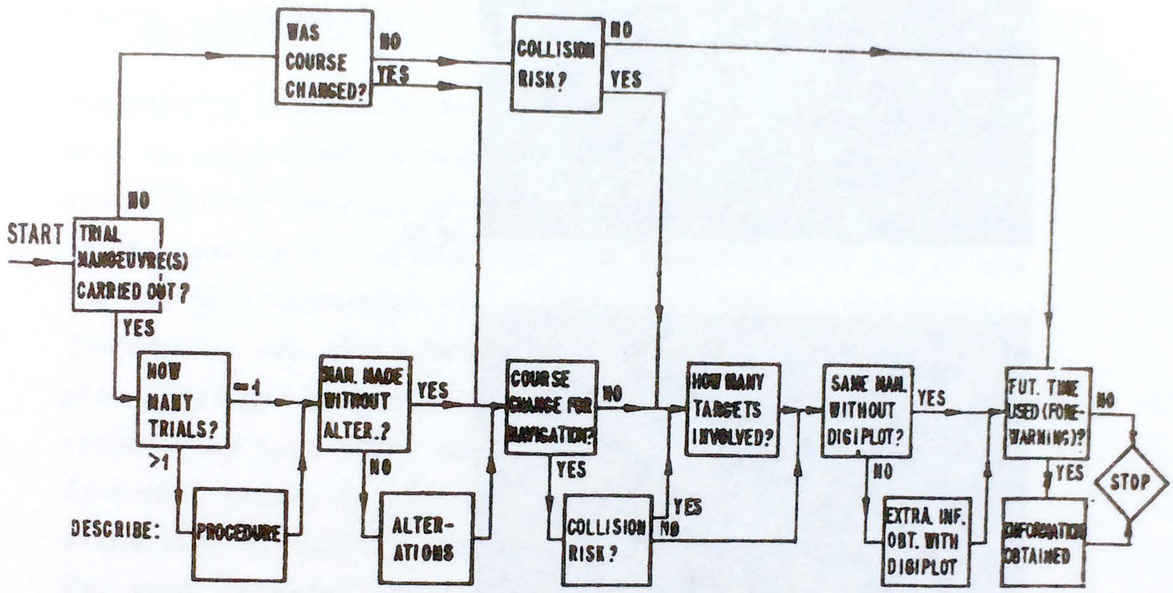
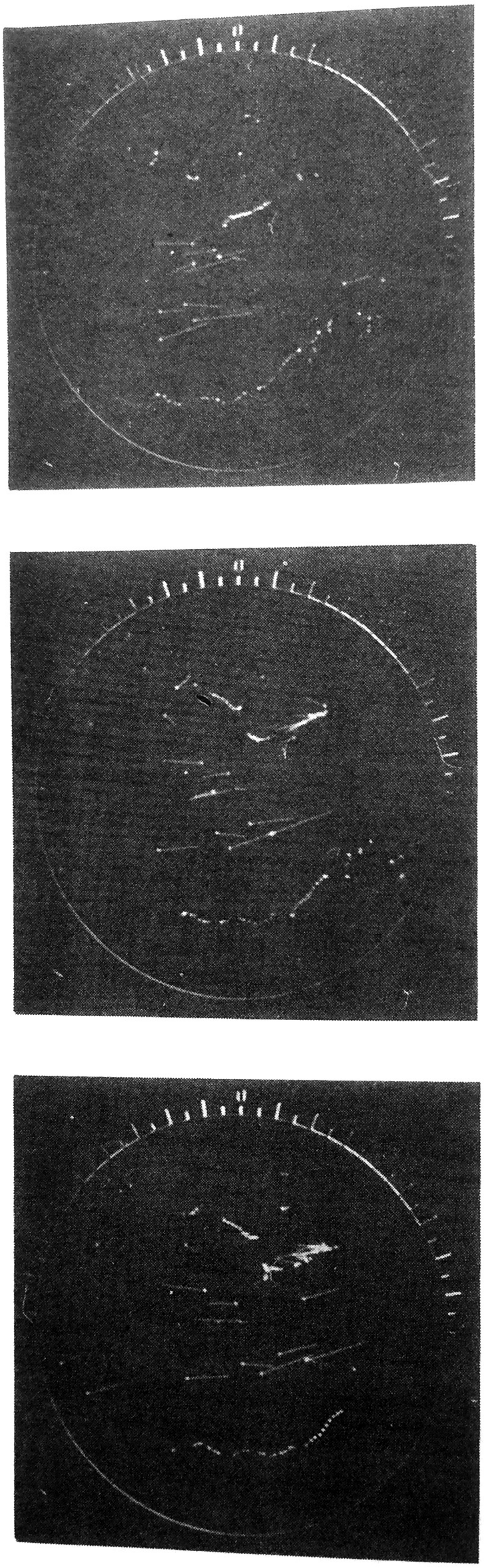


FIGURE 3

SCHEME FOR STRUCTURED INTERVIEWS

FIGURE 4



NORTH-UP
TRUE VECTORS
RANGE 12 miles
FUTURE TIME 12 min

08.30

08.38

08.42

POLAROID PICTURES OF AN ENCOUNTER SITUATION
STRAITS OF GIBRALTAR 1 SEPTEMBER 1973

7. Results of the evaluation

The results presented here are based on the data collected during a number of observation periods which added up to a total of 20 hours and 35 minutes. These periods only relate to a few parts of the trip, in the English Channel and around Gibraltar.

7.1 The use of Digiplot in watchkeeping

The results concerning the use of Digiplot in watchkeeping will be considered in two ways: frequency of utilization of the different sources of information and the sequence of use of the sources of information. The frequencies of use of the sources of information are presented in Table 1. The Digiplot frequencies are given in the table under two headings; "Digiplot displays" comprises only the visual inspection of the cathode-ray tube (CRT) and the digital read-outs; "Digiplot features" refers to the use of Digiplot controls for the extraction of information not already displayed at the time. The entry "Charts" stands for both the inspection of charts and work in the chartroom.

Table 1

Source of information	Use
Looking out (LOK)	314
Radar (RAD)	203
Digiplot displays (DIG)	125
Digiplot features	172
Charts	93

The frequencies record suggest that the Digiplot was not regarded as the main sournce of information about the situation at sea. Even combining the two Digiplot entries in Table 1 (to give 297) does not give a figure that greatly deviates from "Looking out" and "Radar". If we disregard the time taken to consult the radar and the Digiplot, for this tends to be rather short particularly in the latter case, an average consultation interval can be calculated for these courses (see Table 2).

Table 2

Source of information	Consultation interval, minutes
Radar	6
Digiplot displays	10
Digiplot features	7
Digiplot displays + features	4

A more detailed analysis of the use of Digiplot is given in Table 3, in which the frequences of utilization of the individual features are shown. From Tables 1 and 3 one can conclude that the average number of actions performed during a single consultation amounts to 2.2 when all the Digiplot consultations are considered. If the consultations with only visual inspection of the data already displayed are disregarded, the average number increases to 3.8 per consultation.

Before any conclusions can be drawn from Table 3, the data should be viewed in the light of the length of time that the respective features were in use. As regards the relation between DMO and DM1, the system was on DMO for 78 % of the total time. As far as TRU and REL are concerned, the Digiplot was practically always in the TRU mode and the same preference was also shown for R12. The future time control was normally set at 12 minutes; the frequency of 64 for F refers to F being lengthened or shortened and set back to the 12 minute position in a single action.

Table 3

Digiplot Features		Use
Ref.	Function	
DMO	range and bearing of target	130
DM1	speed and course of target	119
DM2	speed and course of own ship	6
DM3	CPA/TCPA for target	130
TRU	true motion	18
REL	relative motion	18
TM	trial manoeuvre	33
TC	trial course	31
R03	range: 3 miles	0
R06	range: 6 miles	0
R12	range: 12 miles	5
R24	range: 24 miles	5
F	future time changed	64
S	trial speed changed	4
TAR	target tagged with joystick	166
DT	delay time changed	9
	TOTAL	738

The most significant variables concerning a target are DMO, DM1 and DM3. Considering both the frequencies and the periods of use, one sees that these features are often employed.

The reason why the short ranges of 3 and 6 miles were not used might be that under normal weather conditions the visual horizon is roughly 12 miles. This hypothesis is supported by the navigator having a distinct tendency to check the radar information against the visual picture of the sea and vice versa. Another explanation may be that the noise content of the Digiplot image does not diminish when the range is reduced. The change to 24 miles occurs occasionally and appears to serve a forwarning purpose.

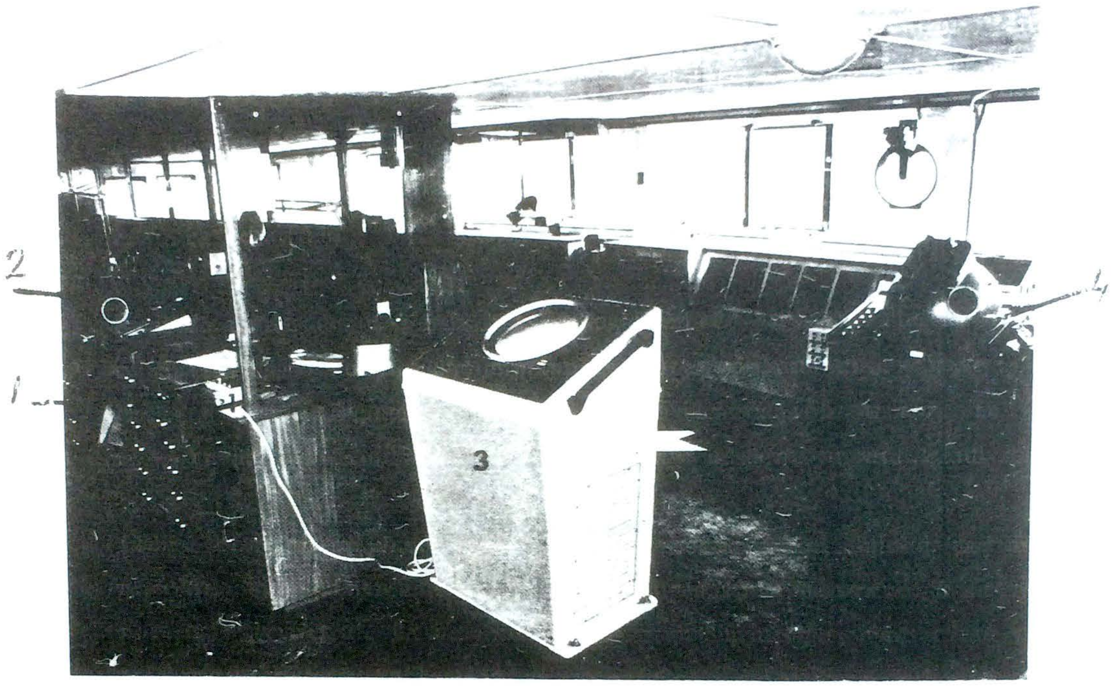
The results regarding the sequence of use of the different sources of information are summarized in Table 4, in which the transition frequencies from one source of information to the next are given. The most frequent transitions are DIG-LOK (194), LOK-DIG (160) and LOK-RAD (124). (The total of 194 for DIG-LOK is obtained by adding the transitions from each of the features of Digiplot to LOK to the frequency DIG-LOK). The data indicate a tendency to make more use of Digiplot information than radar information. Apparently, inspection of the Digiplot image is closely connected with visual inspection of the sea and it is not normally verified against the radar (DIG-RAD = 69, including the transitions from Digiplot features).

The frequencies for RAD-DIG (86) and DIG-RAD (69) differ very little, which indicates that the navigator works to a certain extent on the basis of a double-check system. The relatively high frequency for CHART-DIG (51) might be attributable to the position of the Digiplot on the starboard side of the bridge (see Figure 5). After consulting the charts,the navigator is inclined to walk to the right and he passes the Digiplot on his way to the front of the bridge.

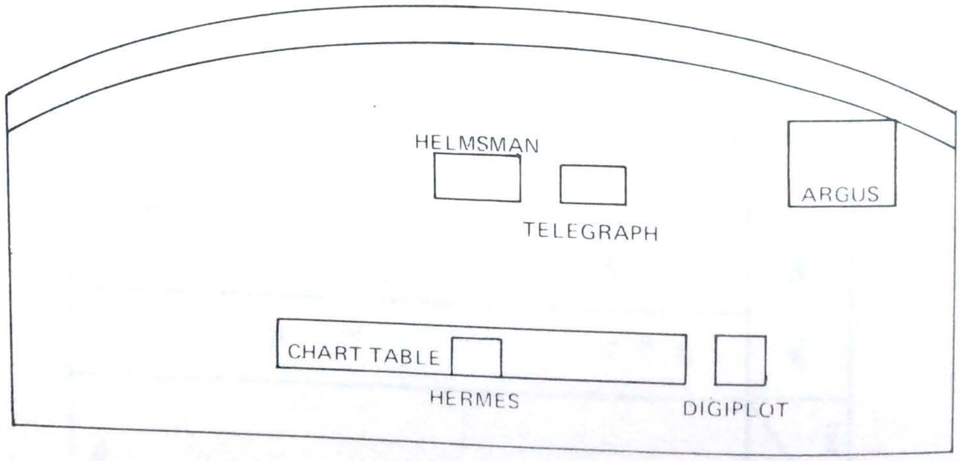
Table 4

from: \ to:	DMO	DM1	DM2	DM3	TRU	REL	TM	TC	R12	R24	F	S	TAR	DT	LOK	RAD	DIG	CHART
DMO		17	1	24				4			7		25		38	9		6
DM1	29		1	33		3	1	4		1	1		17		17	8		4
DM2	3			1									1					1
DM3	37	26				1		1			24		25		11	3		2
TRU						2					5		1		5	3		2
REL					14						4							
TM	3	2		1		1	2	9			1	1	4	2	7			
TC	1		1				18				1		4	1	2	2		1
R12											2				1	1		1
R24									3		1		1					
F	16	5		4	5	4	1		1	2		1	11	1	5	6		2
S							2							1		1		
TAR	28	43	1	44		2	1	4	1		5	2		3	23	5		4
DT							6	1			1		1					
LOK																124	160	29
RAD															89		86	29
DIG	16	26	2	22		5	1	8		2	12	1	76	1	85	31		10
CHART															31	10	51	

FIGURE 5



1. TERMINAL FOR ERGONOMIC OBSERVATIONS
2. MARCONI HERMES
3. IOTRON DIGIPLOT
4. MARCONI ARGUS



BRIDGE LAYOUT OF ss "METHANE PRINCESS"

Figure 6 gives an idea of the way in which the conventional sources of information interlock with some significant Digiplot features. The data are based on Table 4 and the numbers in the flow diagram refer to the highest and the second highest frequences in the raw data. We may conclude that not only the action of looking at the Digiplot displays, but also the use of its features are always succeeded by LOK. In fact the diagram clearly shows a tendency for both the Digiplot and the radar to be used to verify (lower half of diagram) and to extend (upper half) the data obtained by visual inspection of the sea.

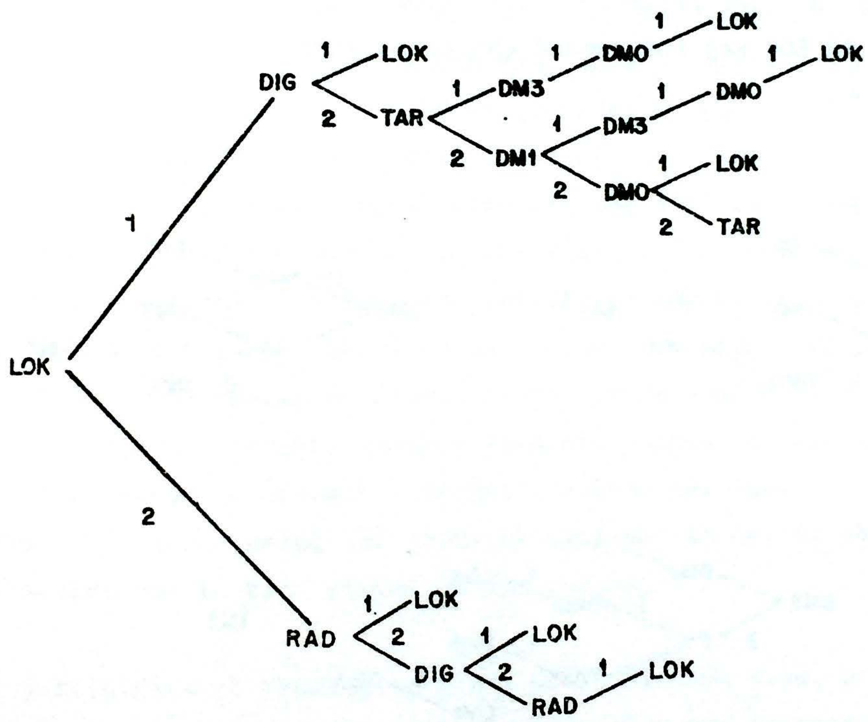


FIGURE 6

INTERLOCKING OF CONVENTIONAL SOURCES OF INFORMATION WITH DIGIPLOT

Of the features of Digiplot, we have already seen that DM3 is one of the most important. An explanation for this is that assessment of the CPA/TCPA on the basis of LOK and RAD involves a time-consuming procedure. Figure 7 shows the transitions made by the navigator starting from DM3. Since the row for DM3 in Table 4 shows three second choices (DM1, TAR and F) which hardly differ in frequency, three separate diagrams (A, B and C) are shown. The first choice after DM3 is DMO; this enables the navigator to follow possible changes of the range and bearing of a particular target. Probably the navigator prefers to store information about targets on the basis of their DMO. By leaving the system in DMO after DM3 he can follow the change in these parameters with time. The first choice after DMO is LOK and the second choice in Figure 7A, DM1, also ends in LOK.

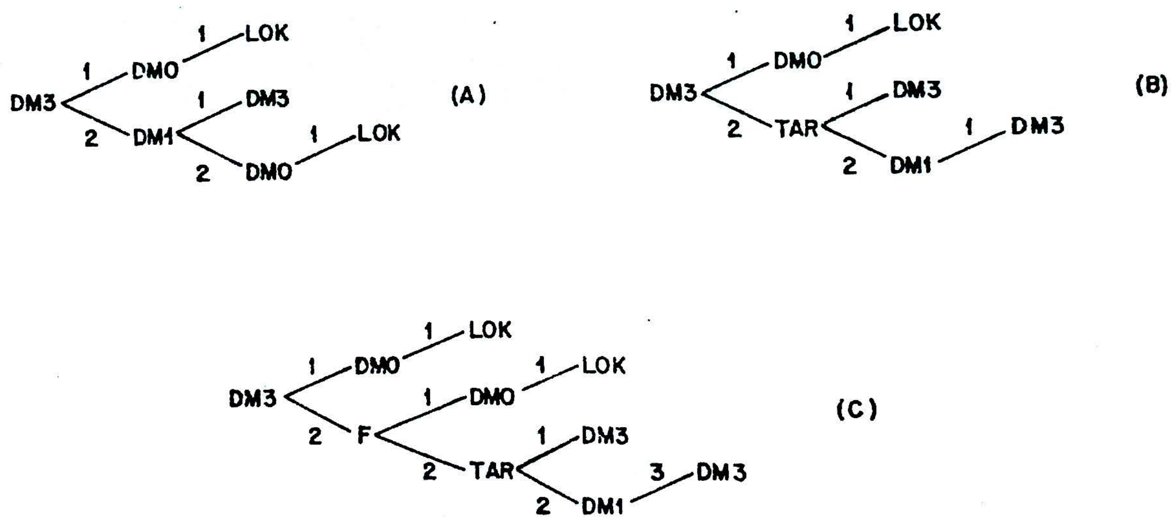


FIGURE 7

SOURCES OF INFORMATION USED AFTER DM3

In Figure 7B the second highest frequency is that of TAR, which leads back again to DM3. In the case illustrated in Figure 7C, the future time (F) is the second choice; this is an action to ascertain whether the CPA will be sufficiently large. If F is changed, it is always increased (which gives longer vectors). It can be said that situations 7A to 7C represent an increasing level of complication.

As regards the transitions between the Digiplot features the following can be inferred from Table 4.

The frequencies in the row for TAR, which is one of the most important entires, correspond to variables which are the most difficult to determine by LOK and RAD, namely course and speed and CPA/TCPA. The fact that the frequencies of the use of DMO, DM1 and DM3 are fairly well balanced indicates that the navigator tends to provide himself with all the available numerical information. The same applies to the entries for these three features after DIG. The location TAR-TAR is empty, which means that mere repetitions of TAR do not occur. One reason for this may be that the navigator always wishes to determine more than one variable per target. Another possible reason is that the navigator needs to request a target's course and speed immediately after using the joystick in order to verify that the marker has in fact picked up the target.

The possibility of feeding in alarm CPA's was not used, probably because the frequency with which the Digiplot was inspected was so high that targets could not possibly have been missed.

There is a close relationship between TRU, REL and F. Normally, the navigator has the Digiplot system representing true motion and the main radar relative motion. In the relative-motion mode, lengthening F is a means of estimating CPA's. The same holds in the true-motion mode when the vector tips of own ship and the target meet. The future time was lengthened sixty times with the Digiplot in the true-motion mode (column F) and four times after the system had been switched from the true-motion mode to the relative-motion mode (entry REL-F). The future time was changed most frequently after the selection of DM3. Apparently the navigator wishes to obtain a visual representation of future situations when a particular CPA/TCPA is given.

7.2 Analysis of the decision process under direct threat of collision

Tables 3 and 4 and the available loggings reveal the following points of interest concerning the use of the trial manoeuvre facilities:

(i) The frequency of trial course changes closely corresponds to the number of trial manoeuvres actually carried out.

(ii) Mere repetition of a trial manoeuvre seldom occurs. There are several possible reasons for this. In the first place, the data presented may be sufficiently clear for the information to be processed in one trial. This will hold particularly when the trial manoeuvre roughly corresponds to the navigator's mental representation of the situation and his expectations about its development. Another possibility is that the safety margins are so large that one presentation is sufficient. One could argue that a trial manoeuvre will be repeated when the navigator wishes to make certain that a particular CPA will not be too small. However, if the navigator remains on the conservative side, i.e. when he applies wide margins of safety, such a procedure is improbable since a trial manoeuvre will then clearly be either inside or outside the margin of safety.

(iii) The number of changes in the delay time is considerably lower than the number of trial manoeuvres. The delay time can be set in the range 0 to 9 minutes; in most cases it was fixed at 0 or 3 minutes. This suggests that the navigator rarely uses the feature to predict events that would occur after a certain amount of time has elapsed but, rather, makes certain if a manoeuvre is safe at the particular moment. Thus, in many cases the trial manoeuvre seems to have the character of a negative choice, that is to say the navigator tests a manoeuvre without delay (DT = 0); the manoeuvre is chosen and carried out if the situation is sufficiently clear and safe.

One could argue that a delay time of 2 or 3 minutes would be more appropriate than DT = 0. In the latter case, the simulation makes no allowance for the fact that the navigator needs time to inspect the display of the accelerated situation at sea, make his decision and give the order to the helmsman, whereas the former case takes into account the time required for these actions. On the other hand the margins of safety appear to be such that it makes little difference whether the delay time is 0 or 3 minutes.

There are a few other reasons why the delay time is seldom changed. The control is rather inadequately positioned and several navigators did not know that they could make use of it. (In the current Digiplot models the position of this control has been improved. Figure 2 shows the current layout.) Others argued that the feature is of little use since its range is too small. In any case, the indications are that a navigator carries out a trial manoeuvre without knowledge of the delay time. In view of this, the delay time should preferably be programmed to return to the zero position automatically so that it can be used only if the navigator definitely wished to have a time delay in his trial manoeuvre.

(iv) The trial speed (own ship) is seldom changed; we assume this would be changed only when the situation leaves no other options. All four changes observed were due to the adjustment of the Digiplot to the actual speed of the ship.

(v) The entry TM-TC refers to the checking of an alternative trial manoeuvre. There is an asymetry between TC-TM (18) and TM-TC (9). On 50 % of the occasions a trial manoeuvre was not accepted and immediately followed another trial.

On eleven occasions during the trip interviews were conducted after certain trial manoeuvres and/or course changes had been carried out. Owing to difficulties in programming the Nova computer, not all the situations at sea could be played back on the slave monitor. However, the other means available for the reconstruction of the events were found to be sufficient. The navigators appeared not to be disturbed either by the presence of the interviewers or by the procedure. Their memories of the events that had taken place during the watches proved to be very accurate and the Polaroid pictures taken of the slave monitor were found to be helpful in the reconstructions.

In only three out of the elven cases did the navigator remark that he would have acted differently if the Digiplot had not been available. He would either have carried out the manoeuvre later or have decided to deviate farther from the course. Thus, in the absence of the Digiplot, the ship would have returned to its original course at a later time. In addition, we may assume that wider margins of safety would have been observed. From this one might conclude that the use of Digiplot would imply a certain erosion of safety margins. Such a conclusion, however, would be premature for, in the absence of predicting facilities and particularly in difficult situations, the navigator may well act with more care than is necessary and reasonable. One of the three cases demonstrated that this hypothesis is not purely academic. After carrying out a trial manoeuvre, the navigator concluded that the ship could comfortably return to the original course.

In the remaining cases the navigator stated that if the Digiplot had not been available he would have acted in the same way. However, the interviews suggest that this statement does not mean that the navigator refrains from making explicit use of the system.

For example, in one interview the navigator remarked that his decision was based on the chart, but that the Digiplot had made it easier to interpret the situation. Thus, the Digiplot did contribute to the final decision and the action. In another case the captain said he would have normally swung around the target, using the Digiplot picture. Furthermore, it seems strange that in several cases a significant contribution of the predicting facility should have been denied, whereas several trial manoeuvres had been carried out before the actual manoeuvre was made. The least one can say is that the Digiplot made the navigator feel less uncertain about his ideas and intentions. A further argument suggestive of a contribution of the Digiplot system to the decision-making process comes from a condiseration of the numbers of trial manoeuvres recorded. In each of two cases two trial manoeuvres were carried out, on another occasion three and on a fourth occasion four were recorded. It is very improbable that this feature was used without reason.

If we disregard those manoeuvres which were mere repetitions with a steady decrease in delay time, then it would seem obvious that the navigator uses the Digiplot as a means to select one manoeuvre from several possibilities he has in mind. Apparently, the predicting facility helped to clarify his mental visualisation of the feasible solutions, so that he could more easily weigh the options open to him. It may be supposed, therefore, that some of the manoeuvres made would not have been carried out without the Digiplot's assistance, and the navigator's remarks thus seem somewhat dubious. We even have an instance in which the navigator's denial starkly contrasted with his comment that the trial manoeuvres were carried out to ensure that there would be adequate clearance for all vessels on a particular course. Thus, in the navigator's mind, the actual manoeuvre would at least have been more risky if he had not used the predicting facility. In another notable case, the navigator was observed to have given orders from the Digiplot console after prolonged consultation of the screen and yet, during the structured interview, he stressed the insignificance of the system. Consequently, the data suggest that the navigator is sometimes aware of a significant contribution of the Digiplot to his decisions and actions, but that in many cases he denies the explicit use of the system.

Since the number of interviews was very limited, it is difficult to state an opinion about the possible erosion of margins of safety. As remarked earlier, there are three cases in which an (excessively) cautious manoeuvre would have been made in the absence of the Digiplot. Mostly more than one trial manoeuvre was carried out; this indicates that the navigator does not accept just any trial manoeuvre as a basis for his decision. Multiple trial manoeuvres are also an indication that the situation was difficult to appreciate on the basis of the information provided by the conventional equipment alone. On only one out of the eight occasions when a trial manoeuvre was actually translated into a course change did the actual manoeuvre deviate from the trial manoeuvre: a smaller course change than the one simulated in the trial manoeuvre appeared to be safe enough (opposite effect to erosion).

When the course was changed after a trial manoeuvre, the latter contained no delay time and the course was adopted immediately. Most trial manoeuvres were connected with a course change for navigational purposes, including collision risks; in two cases the course was changed for collision avoidance only.

8. Conclusions

In human-engineering research, successful use is often made of simulation techniques. However, for the investigation of the longterm effects of the use of sophisticated navigational equipment on both the erosion of safety margins and the risk of overconfidence of the navigator, simulation techniques are hardly suitable. Since reliable information on the safety margins used in practice is always needed to verify the results of simulations, such an investigation can only be based on a time-consuming analysis of the use of the systems under normal operating conditions.

In respect of the method of investigation used here and the data collection procedure, it can be concluded that both are fully acceptable in practice. The presence of an observer on the bridge does not, after a few hours, influence the behaviour of the navigator. The procedure used to obtain information about the navigator's decisionmaking process under direct threat of collision, and the role of Digiplot in this process, appeared to be acceptable and sufficiently comprehensive. On comparison with the objective information recorded, the navigators' memories of significant events at sea were found to be remarkably detailed and reliable.

With regard to the contributions made by Digiplot, we feel that no firm opinion about the use of the Digiplot during watchkeeping can be formed without a longer period of observation. No definite conclusions about the use of the Digiplot in situations with a direct threat of collision can be formulated either, as the number of significant events that occurred during the investigation was unfortunately too small. However, the following tentative conclusions can be drawn from the limited amount of data available, even though they should be considered with care and might be restricted to the particular ship and the navigators who took part in the study.

(i) The Digiplot is frequently used, but is not (to be) considered the main source of information. The use of the system is closely integrated with that of the other sources of information. In the procedure of information collection Digiplot does not terminate the cycle. The radar and Digiplot displays are frequently checked against the information obtained by visual inspection of the sea and vice versa.

(ii) The most frequently used features of the Digiplot are the readout of range and bearing, course and speed and the CPA/TCPA of targets. Except for range and bearing, these parameters can be inferred from data obtained by other means only by a time-consuming procedure.

(iii) There are various reasons for frequent checking of the Digiplot data against the radar. They partly originate from deficiencies in the equipment. However, one could argue that these imperfections stimulate the frequent consultation of other sources of information, thus minimizing the risk of the navigator basing his decisions on only one source of information.

(iv) A specific trial manoeuvre is seldom repeated. Since one manoeuvre appears to be sufficient for making a decision, the navigator is very likely to maintain wide safety margins.

(v) The possibility of carrying out trial manoeuvres with a long time delay is hardly utilized. In situations where either a course change for navigational reasons or a course-resuming manoeuvre has to be made, the navigator, instead of using the delay time feature to establish - in one series of trials - the first point in time at which he can start his manoeuvre, repeatedly uses the trial manoeuvre feature without a time delay.

(vi) The future time control is also used as a means to predict situations at sea when no significant alterations are expected.

(vii) The Digiplot would be more valuable if some target differentiation (type of craft, buoys, shallow water, etc.) were possible. The technical problems in obtaining a sufficient degree of differentiation appear to be insuperable at present.

(viii) The data suggest that the navigator is sometimes aware of a significant contribution of Digiplot to his decisions and actions, but that in a number of cases he denies the explicit contribution of the system to his decisions.

In view of the limited number of interviews and the absence of objective standards, it is difficult to draw fully justified conclusions regarding a possible erosion of safety margins. Without the aid of the Digiplot, a wider safety margin would sometimes have been used; this does not mean that the margin needs to be so wide since the information provided by the predicting facility may be sufficient for the navigator to conclude that it is safe to accept narrower margins.

The danger of overconfidence of a navigator using an automatic plotter certainly exists; it is imaginable that the uncontrolled introduction of automatic plotters might foster a false sense of security. Owners who choose to fit automatic plotters would be well advised to ensure that their navigators fully understand the limitations and imperfections of the equipment selected and know how to weigh and implement the information they provide. The accelerated display technique used in this investigation is one way of alerting the navigator in this respect. The play-backs of encounter situations clearly showed the surprised navigators the imperfections of the data displayed by the system; the accelerated presentation was found to contrast strongly with the navigators' perception of stability in real time on the bridge.

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