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Engineering and
Construction Bureau
Panama Canal
Commission
APO Miami FL 34011

Panama Canal Fog Navigation Study

System Requirements Statement

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March 1984
Final Report

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16. Abstract

Efforts to minimize the adverse impact of fog on Panama Canal operations have focused in the past on obtaining methods of predicting fog, of dispersing fog and of providing navigation during fog. This report describes the result of the most recent fog navigation system requirements study. The study is based on information gathered by an on-site visit, a review of past studies conducted by the Panama Canal Commission (PCC), and interviews with the Pilot force, engineering staff, and management personnel.

The canal's fog navigation problem areas are defined. The performance requirements of a fog navigation system for use by Pilots in the Gaillard Cut are given. Broad system requirements are crosstrack accuracy of 16 to 20 feet (2 standard deviations, 95 percent), along-track accuracy of 32 to 40 feet (2 standard deviations 95 percent), display resolution of 512 by 512 pixels and an update rate of one per second. All requirements can be met with state-of-the-art navigation equipment and display systems.

Technical details on all assumptions and the impact of these assumptions on the navigations system design are given.

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PREFACE

Fog has been a major and continuing obstacle to the realization of optimum and safe canal usage in all types of weather.

The Engineering Division of the Engineering and Construction Bureau of the Panama Canal Commission is engaged in defining the performance requirements and the overall design characteristics of a fog navigation system to satisfy this operational need. This effort is being coordinated with the Marine Bureau and also the Panama Canal Pilots Branch. The Engineering Division requested the assistance of the Department of Transportation, Transportation Systems Center, with the definition of performance requirements for a fog navigation system, the determination of candidate systems and the preparation of a test and documentation program plan.

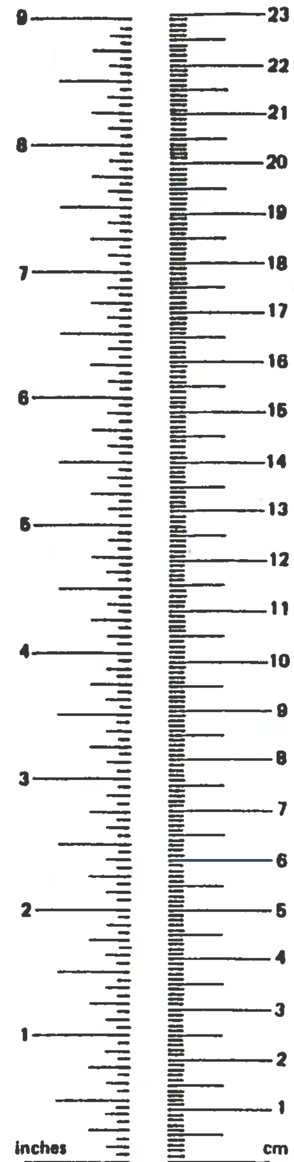
This report constitutes the results, in part, of that assistance.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

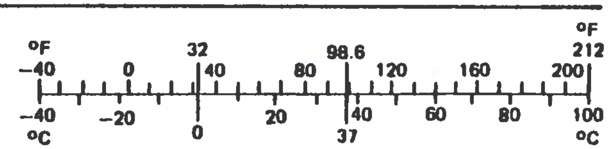
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in. = 2.54 cm (exactly). For other exact conversions and more detail tables see NBS Misc. Publ. 286. Units of Weight and Measures. Price $2.25 SD Catalog No. C13 10 286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



I. EXECUTIVE SUMMARY

Efforts to minimize the adverse impact of fog on Canal operations have focused in the past on obtaining methods of predicting fog, of dispersing fog and of providing navigation during fog. This project memorandum describes the result of the most recent fog navigation system requirements study. A concise summary of the requirements study results follows in the Project Summary.

The approach used in this study is described in Section 2.0. It included an on-site visit, a review of past studies conducted by the Panama Canal Commision (PCC), and interviews with the Pilot force, engineering staff, and management personnel.

As a result of these three activities the fog navigation problem areas were defined; these are described in Section 3.

The performance requirements of a fog navigation system for use by Pilots in the Gaillard Cut has been established in this study. The system requirements are listed in Section 4 and include crosstrack accuracy of 16 to 20 feet feet (2 standard deviations, 95 percent), along-track accuracy of 32 to 40 feet (2 standard deviations 95 percent), display resolution of 512 by 512 pixels and an update rate of one per second. All requirements can be met with state-of-the-art navigation equipment and display systems.

Technical details on all assumptions and the impact of these assumptions on the navigations system design are given in Appendix A.

II. PROJECT SUMMARY

Navigation in the Panama Canal is currently dependent upon fixed and floating navigation aids, such as lights, range markers, and buoys, to mark safe passages through the waterway. All these navigation aids are visual and hence can not be used during periods of restricted visibility.

Unfortunately, serious fog conditions exist over the Canal during the eight-month rainy season. The area primarily subject to heavy fog is the Gaillard Cut but the fog may extend to the Pedro Miguel Locks and Miraflores Lake. Heavy tropical downpours can also reduce visibility for short time periods.

The Panama Canal Marine Traffic Control (MTC) Center's present procedure for dealing with fog is to halt all traffic through the fog areas when so advised by the Control Pilot. This effectively reduces Canal capacity, resulting in the equivalent loss of two ship transits per day (1990 traffic forecast). There is also a safety problem since, in spite of the precautions taken ships occasionally get trapped in the Gaillard Cut by fog, creating the potential for a ship colliding with another ship or with the Canal bank.

Solving the reduced visibility navigation problem is one of the Panama Canal Commission's priority tasks. The Engineering Division of the Engineering and Construction Bureau, is presently engaged in defining the performance requirements and the overall design characteristics of a fog navigation system which would satisfy the Commission's operational need. This effort is being coordinated with the appropriate elements of the Marine Bureau and also with the Panama Canal Pilots Branch. The Engineering Division requested the assistance of the Department of Transportation, Transportation Systems Center (TSC) with the definition of performance requirements and recommendation of a solution.

A TSC team visited the Panama Canal to gain firsthand information on Canal operations, fog navigation problems and procedures. In addition, previous related studies and projects were studied as well as reports on similar problems on other waterways such as the Suez Canal and the St. Lawrence Seaway. The TSC team concluded that the overall reduced-visibility navigation problem at the Canal could best be met by a navigation system which would:

a) Provide Control Pilots with on-board navigation and guidance information necessary for all-weather operation in the Gaillard Cut.

b) Provide Control Pilots on-board guidance information on own-ship velocity, heading, and other vessel traffic, in order to reduce the accident rate.

c) Provide the MTC with near real-time vessel traffic information for positive management of the Canal traffic.

Furthermore, the system must be modular and easily expandable, so that it can be deployed as a fog navigation system and, at a later date, be readily expanded by adding sensors and computer modules, to provide other services such as lock entry guidance, collision avoidance and full vessel traffic management.

This project memorandum constitutes TSC's definition of the fog navigation system requirements. The requirements of the various system users are as follows:

<u>Control Pilot Requirements</u>

o Data should be displayed in a digital data block and on a moving-map type display showing, in their actual location and to scale as appropriate:

- Own-ship and Canal banks with details - own-ship to be always located at the bottom of the display screen.

- Bow and stern position of own-ship to ± 20 ft, 2 standard deviations.
- Own-ship velocity to + 0.1 mph, 2 standard deviations.
- Changes in own-ship's bow and stern position with a resolution of ± 3 ft.
- The point where turns should be initiated and the time-to-turn-point.
- Extended ship centerline (jackstaff) and ship's wake (to aid in determining ship motion).
- Rate-of-turn values: both the computed value for the particular vessel and the actual value.
- Canal centerline and sailing lines.
- Course to steer value.
- All other Canal traffic, including transiting vessels, tugboats, barges, pilot launches, etc.
- All nav-aids such as range markers and buoys.

In addition

- o The display must allow separate selection of horizontal and vertical display scales to provide more sensitivity in the horizontal direction, helpful in a ship-meeting situation.
- o The display scales must be selectable to allow looking at one reach or several reaches ahead of the ship.
- o The display content must be updated at least once per second.
- o All ships on display must be tagged, identifying name, velocity and other pertinent parameters.
- o The display should use color to make identification of various display elements easier.
- o The display must be readable in sunlight.
- o The display must be portable, and easily positioned on a ship's bridge or bridge wing.
- o A digital display for remote conning during lock entry will be available.

The system shall provide indications of hazardous situations such as excessive speed, potential collisions or the existance of a bank suction condition with visual and/or aural alarms.

If the system can not be made fail-safe, a back-up capability must be provided to prevent total loss of information while in reduced visibility conditions.

Equipment Requirements

- All carry-on equipment must be portable; no item shall weigh more than 25 lbs.
- All carry-on equipment must have its own power supply (battery) and be independent of ship's power.
- Ship-borne sets must be able to withstand accidental immersion (for short time periods) in fresh or salt water. The equipment must float to aid in recovery after an accidental drop.
- Ship-borne sets must be able to withstand accidental drop or contact with hard surfaces.
- All land-based equipment items must contain an uninterruptible power supply.
- The equipment must be designed to withstand the high temperature and humidity of the tropics. (except for any computer equipment located in an air conditioned area).
- All field equipment repair must be on a "remove and replace" basis.
- All repairs should be performed at a suitable PCC facility.

Marine Traffic Control Requirements

- All traffic information shall be available to the MTC controllers on suitable displays.
- The MTC displays shall be capable of displaying the same information as the shipboard displays, i.e., ship position, velocity, Canal banks, etc.
- The displays should allow selection of one reach, two or more reaches or an entire area.
- The display center (offset) shall be selectable via the display cursor which shall be positioned using a "trackball" or a "mouse".

- The system shall be capable of sounding visual and aural alerts.
- The system must be capable of an initial capacity of 50 targets, and be expandable to 100.
- All traffic information shall be recorded on tape for later playback to allow reconstruction of events.
- The system must provide direct communications between MTC and any Pilot for the purpose of providing assistance in terms of traffic advisories.
- The system shall incorporate sensors which can provide early warning of the onset of fog (if feasible).

PCC General Requirements

- The fog navigation system must be capable of safety-related functions such as providing precise velocity and heading information when a vessel is entering locks, and collision avoidance information.
- The system shall not require additional PCC personnel for its operation. The shipboard equipment shall be carryable on and off the vessels by the line handlers.
- The system must be modular and also provide for future expansion into a full vessel traffic management system.

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1. INTRODUCTION

The Panama Canal operates 24 hours per day, year round. Vessels transiting the Canal are under command of a Control Pilot who has sole responsibility for guiding the ship during the entire transit between the Atlantic and Pacific terminals. At present, the Pilot has only visual navigation aids available to him, such as range markers, buoys and terrain features. The Canal banks and navigation aids are illuminated to allow night transits. Under good visibility conditions, adequate navigation and guidance information is available to enable the Pilot, barring any human errors or equipment malfunctions, to safely transit the Canal.

However, some Canal areas are subject to heavy fog conditions. This is true primarily in the Gaillard Cut, but the fog can also extend to the Pedro Miguel Locks and the Miraflores Lake. Fog occurs during the rainy season which persists for about 8 months each year. Typically the fog can be expected between 2AM and 7AM on days when it occurs.

The present procedure is, at the advice of the Control Pilot, to halt all Canal traffic through the potential fog areas if it is judged that fog is likely to occur. Regardless of these precautions vessels still get caught in fog because of its unpredictability creating a potentially hazardous condition.

Heavy tropical downpours also can reduce visibility to the point where the Pilot can lose his visual cues, again creating a potentially hazardous situation.

The visibility-related Canal navigation problem has been studied in the past. No viable solution has been arrived at to-date, leaving the problem essentially unsolved.

The Panama Canal Commission (PCC) requested the DOT/TSC Navigation Center to investigate this problem. Under the terms of an Interagency Agreement, TSC was asked to define fog navigation requirements, recommend a solution, and outline a plan to evaluate and demonstrate the feasibility of the proposed solution.

This project memorandum documents the first of the three tasks: the definition of system requirements.

2. APPROACH

At the outset of the program, a visit was made to the Panama Canal by TSC staff to observe Canal operations firsthand . This provided an opportunity to hold discussions with Canal Pilots, the management staff and traffic control personnel. In addition, this visit ensured the operational authenticity required in the system requirements analysis effort.

To prevent duplication of effort, the results of previous studies and projects related to the Panama Canal navigation problem were examined, as well as similar work on other waterways such as the Suez Canal and the St. Lawrence Seaway.

A team composed of members from the Panama Canal Engineering Division and the TSC Navigation Center conducted the on-site studies, interviews and discussions.

2.1 ON-SITE INVESTIGATION

2.1.1 Canal Transits

The full length of the Canal was transited on a Panamax (maximum allowable size) vessel. Day and night transits also were made between the Pedro Miguel Locks and Gamboa (spanning the Gaillard Cut) aboard smaller vessels and a radar equipped tugboat.

During the transits, the activities of the Pilots were observed, particularly during the passage through the Gaillard Cut, and during lock entrances and exits. The Pilots were very cooperative, explaining the use of navigation aids such as range markers, and landmarks, their methods of determining points where turns were to be initiated and ship handling problems. Of particular interest were discussions about instances where Pilots were unexpectedly caught in fog, their methods of handling the situation, and the type of information they felt was required to safely transit the Cut under conditions of low visibility.

The information available from the ship radar was also examined with respect to its ability to distinguish the Canal bank, the level of detail it presented, and the degree to which it provided information on the ship position, velocity and attitude.

During the transits, details of the terrain on each side of the Canal were noted.

2.1.2 Discussions with PCC Engineering Staff

Considerable time was spent discussing with the PCC engineering staff past efforts directed toward solving the problem of fog in the Canal, and reviewing the results of those efforts. It appeared that many of these efforts were directed primarily toward dissipating the fog. One proposal suggested that ionized particles be dispersed in the fog. Another called for blowing the fog away with helicopters. There also were other suggestions such as burning material along the banks of the Cut, on the assumption that the resulting heat would dissipate the fog. The general conclusion after several of these approaches were tried was that they had too many technical and operational problems and consequently fog dissipation efforts were abandoned.

There were other approaches proposed. One suggestion involved the use of shore-based radars. The geometry of the Cut and the surrounding terrain required approximately 10 radar sites for full coverage. This plan was rejected due to the high cost of installing and manning the radar sites. Another approach which was studied but not accepted, required that portable radars, including auxiliary power units and displays, be placed on each ship by a crane.

A promising approach, tried recently, involved the use of a radar equipped tug as a "seeing eye dog" for each ship. The basic idea was to have the tug precede the ship and guide it through the cut. Enhancing this approach is the fact that frequently the Pilot on the tug would have greater visibility than the Pilot on the bridge of the vessel because the tug Pilot was in a clearer air layer and he could see the banks. This type of operation was not adopted due to the need for additional radar-equipped tugs and possible Pilot opposition, because it essentially transfers the command to the leading tug.

Other proposals presently before the PCC include use of two tugs per ship. The tugs would be attached to the ship fore and aft and physically move the ship through the canal. The tugs obtain their guidance information from a precision position measurement system. Another proposal involves the use of each ship's radar and radar transponders (RACONS) along the shore. The transponder code would be displayed on the ship's radar as coded radials which the Pilot would use to align the ship.

There also was an attempt to predict the onset of fog by measuring a large number of meteorological parameters which were thought to be related to the fog generation mechanism. This was not a successful approach since the predictions were not sufficiently accurate to allow their use in vessel scheduling.

2.1.3 Discussions with PCC Management Staff

A number of discussions were held with various members of the PCC management staff in order to gain their view of the fog navigation problem. Discussions regarding the economic aspects of the Canal's operations were of special interest because these would serve to define the cost limits of a viable solution.

In general, the management consensus was that an acceptable system should not require additional manpower, should require minimal equipment and occasion minimal operating and maintenance costs, and should be accepetable to all system users, especially the Pilots. In addition, management expressed a desire for a system that would contribute to the improvement of other aspects of Canal operations, such as reducing accidents which presently cost the PCC approximately $15M per year, and improving traffic management.

The recently concluded "Canal Improvements Study", performed by the PCC staff, provided many valuable inputs for the requirements determination, especially regarding operating costs, benefits of increased traffic, and potential safety benefits.

2.1.4 Discussions with Panama Canal Pilots

Discussions with Canal Pilots primarily took place aboard ships during Canal transits. Pilots also were interviewed during other meetings at the PCC facilities. A great deal of time was spent trying to ascertain the type of information they would require in order to transit the Gaillard Cut under reduced visibility conditions. Particular attention was paid to the attitude Pilots had toward such a system; i.e., the degree to which they felt it was necessary for them to maintain control, their perception of their role and the marine traffic management role and how they thought responsibilities should be allocated.

2.1.5 Discussion with Marine Traffic Control Personnel

The Marine Traffic Control (MTC) Center was visited and its operations examined. The review encompassed the methods of scheduling traffic, monitoring vessels during transit, and handling the fog problem as well as a survey of existing computer facilities and capabilities.

The information content of the MTC displays was reviewed, particularly the type of information which could be called up for display, and shortcomings of the present system were discussed with controllers and supervisors. Some of the drawbacks of the present system which were mentioned were inadequate computer capacity and lack of real-time traffic surveillance in harbors and during transit.

2.1.6 Discussions with the Board of Local Inspectors

The Board of Local Inspectors (BLI) is responsible for the investigation of all ship accidents. Its members are present or former senior Control Pilots and as such are fully cognizant of all phases of Canal operations. The discussion at BLI concerned the types of ship accidents, their frequency of occurence and their underlying causes(s).

2.2 REVIEW OF RELATED PROGRAMS

In addition to the Canal site visit, the results of other waterway study projects were reviewed. These included the following:

2.2.1 Vessel Traffic Management System for The Suez Canal

Vessel management along the Suez Canal system is accomplished through a hybrid system consisting of shore based radars and a LORAN-C chain installed just for this purpose. The system is designed only for vessel traffic monitoring. Ships Pilots do not have a situation display nor do they receive traffic information other than that obtained via communication with the control center. The system contractor, Airborne Instruments Lab, Deer Park N.Y. was visited and the details of the system installation and operations were discussed.

2.2.2 St. Lawrence Seaway Navigation Project

TSC conducted a demonstration program in the St. Lawrence Seaway designed to demonstrate the feasibility of using radio navigation systems to extend Seaway operations into the late fall and winter months. There appear to be many similarities between problems met by this program and those found at the Panama Canal. The project results, hardware implementation, problem areas and related documentation were reviewed and discussed with TSC staff who participated in the program.

2.2.3 CAORF Simulation Review

The Maritime Administration's Computer Aided Operations Research Facility (CAORF) at King's Point, N.Y. was used by the Coast Guard to evaluate the effect on a pilot's performance of various aids to navigation. The simulation involved piloting in narrow channels, a problem similar to that of the Panama Canal. The simulation results which are directly applicable to the Panama Canal were used in the development of the system requirements.

3. PROBLEM DEFINITION

During the conduct of this study, a major emphasis was placed on defining the weather and navigation related operational problems encountered in the Canal. In order to properly understand these problems a visit was made to the Canal during which both day and nighttime Canal transits were made on various ships. In addition, discussions were held with approximately 18 PCC Pilots, with the Marine Traffic Control (MTC) Center personnel, and with the Canal's meteorological office. Past studies relating to the Canal navigation problems were also reviewed. It was concluded that there are three (3) main, interrelated Canal problems which must be addressed in considerations of an improved system for reduced visibility navigation.

a) the lack of all-weather navigation capability, which has an adverse effect on capacity and safety of operations.

b) lack of guidance information aboard ships, which has an adverse effect on safety of operations under all conditions.

c) lack of a modernized Vessel Traffic Management (VTM) System, which adversely impacts the efficiency and safety of Canal operations.

The problems are discussed in further detail in the following sections.

3.1 LACK OF ALL-WEATHER NAVIGATION CAPABILITY.

At present, the only navigation aids available to PCC Pilots responsible for guiding ships through the Canal are visual aids, such as buoys and range markers. The Pilot relies on these aids as well as his comprehensive knowledge of Canal terrain, lighting and other visually discernible features, to guide the ship. The onset of fog, or the occurrence of very heavy rain, deprives him of this guidance information, resulting in a dangerous situation particularly if the ship is at that time navigating through the Gaillard Cut. There is at least one known instance of a ship grounding in Gatun Lake due to poor visibility caused by heavy rain. Almost every Control Pilot with whom discussions were held, had experienced being trapped by fog in the Gaillard Cut. It seems remarkable that there has never been an accident in the Cut severe enough to cause a major Canal shutdown.

When fog is present the Control Pilot decides if traffic through the Cut must be halted. This may be equivalent to reducing the number of ships transiting the Canal by one to two ships per day. When the traffic is high, near or at the maximum capacity of the Canal, this can result in lost revenues, increased ship operation costs and delayed schedules.

A requirement therefore exists for a navigation/guidance system which will allow scheduling of traffic and safe Canal operations regardless of the visibility conditions.

3.2 LACK OF ON-BOARD GUIDANCE INFORMATION

The Pilot requires knowledge of the motion and the heading of his ship at all times everywhere in the Canal system. This is especially true for his vessel's position and velocity relative to the locks, Canal sides, etc. He presently acquires this information from visual cues, and from a "feel" of the ship's motion which he has learned to sense through long experience. The adequacy of this type of guidance information is questionable and it is the type of information that is very difficult to translate into quantitative terms.

A high incidence of accidents reported in the Canal occur during the approach to the locks where precise knowledge of ship velocity and heading is critical and sometimes results in a collision between the ship and the "knuckle" (a concrete wall extending along the side of the lock), or collisions with the lock center-wall. Another hazard often encountered in the lock area, and more so in the Gaillard Cut, is "bank suction", which is the action affecting a ship moving too close to the walls or banks. The resulting lateral forces on the ship's stern can cause loss of control and in many cases a collision with the wall or bank. Similar problems could arise when two ships meet in the Cut.

Wind, current and the wake from preceding vessels can also cause undesirable motions which, if not compensated for early enough, can lead to accidents, particularly when entering the locks.

Therefore, there is a need to provide the Pilot with precise information on ship velocity, heading and position relative to the locks, the Canal banks, and other ships. This data if properly presented could serve to reduce accident levels.

3.3 LACK OF A MODERNIZED VTM SYSTEM

The existing MTC VTM system consists primarily of a minicomputer-based data management system. Vessel position in the Canal is determined from Pilot communications, shore reports, and from a television traffic monitoring system which, although limited in coverage at this time, will be extended to cover the full length of the Canal. The present computer system with alphanumeric outputs allows ready access to traffic data. There are no real-time ship position monitoring displays in the control center other than the video system. Furthermore, the present MTC minicomputers (NOVA 840) are operating at capacity, thereby limiting any further automation of the MTC functions. Thus, traffic scheduling, and similar activities are for the most part manual, labor intensive operations, and the computer is being used primarily for data storage and distribution.

The lack of a real time vessel traffic management capability places the MTC Center primarily in a monitoring role. The burden is on the Pilots to communicate with each other using walkie-talkies to coordinate the required ship movements. This lack of positive vessel traffic management probably contributes to the accident rate. In addition, at night or when weather reduces visibility, MTC capability to monitor traffic via its video system is proportionally reduced.

Traffic management also requires early warning of the onset of fog which would allow the MTC to alert ships in transit. Attempts thus far to predict the occurrence of fog have been unsuccessful. Today, the only pertinent information available at the MTC are weather condition reports generated from observations by Pilots in the Canal.

A requirement therefore exists for a VTM system to automate routine MTC functions and so provide quick adaptation of vessel scheduling to meet changing conditions, better monitoring of vessel position and motion in real time, improved traffic flow, reduction of accidents and, through the use of automated weather monitoring data, improved ability to adjust traffic flow with the onset of bad weather.

4. SYSTEM REQUIREMENTS

4.1 GENERAL SYSTEM REQUIREMENTS

The Gaillard Cut fog navigation system study has resulted in a list of general system requirements as well as specific navigation and guidance requirements.

The system should be sized to handle the maximum throughput capacity of fifty ships per day as well as all dredging and drilling barges, tugboats and pilot launches.

The basic design of the system should be modular to permit expansion into additional reaches if the need for extended coverage is warranted.

The elements of the system which are shore based should be serviceable by water, immune to electrical power variations, require no increase in the present PCC staffing level, have a high value of reliability and be compatible with a tropical environment.

The shipborne equipment should have the following characteristics: light weight, require no increase in the present number of line handlers or Pilots on a vessel, be independent of vessel power systems, be easy to operate, and have a display which would give the Control Pilot all the cues during fog navigation that are available to him visually during daylight transits.

In addition, the fog navigation system should furnish the Pilot with ground track velocity information as his vessel approaches the locks.

4.2 NAVIGATION AND GUIDANCE REQUIREMENTS

Observations and discussions with PCC Pilots brought out the following requirements for navigating a vessel in the fog:

All visual cues available to a Pilot during a daylight transit must be given to the Control Pilot during the fog environment including the following: vessel (bow and stern) position and velocity relative to the physical elements and layout of the Gaillard Cut, center range and sailing line markers, geographic outline of the nine reaches and eight turns in the cut, all aids to navigation such as red and green bouys, location of other vessels, barges, and tugs in the immediate vicinity of the transitting vessel, a jackstaff or flagstaff position and relative motion, a vessel track or wake, and the ability to look at one reach, or several reaches, at one time. A data box inserted in the display will present digital data in support of the graphical presentation.

There are displays which can present these visual cues to the Pilot while transiting the Cut in a fog environment. The important question is: how accurately will the sensor part of the system measure position and velocity? To put the aforementioned qualitative cues into a quantitative regime several assumptions were made. The rationale for these assumptions and the impact of these assumptions on the system design are presented in Appendix A.

The display resolution should be 512 by 512 pixels. The accuracy of vessel position on the display relative to the channel centerline will be subject only to random errors; all bias errors will be removed. The range of the random error in the crosstrack direction should be 16 to 20 feet, 2 standard deviations, 95 percent. The range of the random error in the along-track direction should be 32 to 40 feet, 2 standard deviations, 95 percent.

The availability of the navigation system to provide guidance information to the Pilot will be no less than 95 percent.

Spacial coverage will be 100 percent of the Gaillard Cut and the entering and departing reaches: Pedro Miquel Approach and Chagres Crossing.

The fix rate will be set at a value which will give the Pilot a fresh view of the vessel on the display every second. The fix dimension will be a two-dimensional position fix.

The system capacity will be fifty vessels a day plus all tugs, barges, dredges and pilot launches - less than 100 vessels a day total. The instantaneous capacity at any one time will be twenty-five vessels, expandable to forty-three vessels.

4.3 SAFETY REQUIREMENT

The performance measures that provide a suitable representation of navigation safety are the mean and standard deviation of the crosstrack position of a ship's center of gravity. The two areas where the greatest demand is placed on Pilot performance are in turns and approaches to the locks. The latter is not a "fog navigation" problem, but the Pilot would like to know his closing velocity - velocity over the ground - to a lock wall, to an accuracy of a tenth of a mile per hour over a range of one mile from the lock to the lock itself. This information should be available to the Control Pilot while he is on the wing bridge of the vessel. In a turning maneuver the graphic and digital display with a one per second update rate as specified in Section 4.1 should provide the Pilot with all the cues needed for safe transit. Additional turn-markings can be added to the display, if these are determined to be beneficial, during the implementation demonstration.

4.4 TRAFFIC MANAGEMENT SYSTEM REQUIREMENTS

The requirements for traffic management include ship identification, position, velocity, heading and the estimated time of arrival at each center-lane or sailing line intersection. The only additional requirement to the aforementioned navigation, guidance and safety requirements is the need for vessel identification.

4.5 VESSEL EQUIPMENT CONSTRAINTS

The vessel component including the carrying case, display, power supply, and antenna must be light weight (less than 25 lbs) and compact for easy deployment on the vessel bridge or wings. The display must have good resolution in bright sunlight and must have intensity adjustments. The equipment will be deployed and recovered by the line handlers and transported to and from the vessel in their launches. It is not envisioned that the display will be moved once it is placed on the bridge, but Pilot requests for repositioning should be easily accomodatable.

APPENDIX A. DERIVATION OF SYSTEM REQUIREMENTS

The quantitative values developed as part of this study are system goals instead of absolute values. The values have yet to be compared with present hardware capabilities and cost. The numbers are realistic, and are within the state-of-the-art for navigation equipment and display systems. Changes may be made in the values if continuing study indicates changes that would bring about economic benefits.

A.1 FOG NAVIGATION SYSTEM PARAMETERS - DEFINITIONS

All candidate fog navigation systems are described in terms of system performance parameters which determine the utilization and limitations of the individual navigation systems. These parameters are as follows: signal charateristics, accuracy, availability, coverage, reliability, fix rate, fix dimension, capacity and ambiguity.

A.1.1 Signal Characteristics

Descriptions used to characterize the signal in space, are principally signal power levels, frequencies, signal formats, data rates, and any other data sufficient to completely define the means by which a user derives navigation information. The only signal characteristic defined to-date in this memorandum is the need for a one per second update rate for the Pilot display. The only signal constraint identified thus far is the need for the system to be immune to the electrical power variations experienced along the banks of Gaillard Cut.

A.1.2 Accuracy

In navigation, the accuracy of a measured position of a vessel at a given time is the degree of conformance of that position with the true position of the vessel at that time. Since accuracy is a statistical measure of performance, all statements of accuracy requirements will include a statement of the uncertainty in position. When specifying linear accuracy in terms of orthogonal axes, e.g., crosstrack and along-track, the 95 percent confidence level will be used. Accuracy in this memorandum is defined as predictable accuracy: the accuracy of a position with respect to the geographic or geodetic coordinates of the earth.

A.1.3 Availability

The availability of a fog navigation system is defined as the percentage of time that the services of the system are usable by the Pilot. Availability of a system in the Panama Canal is a function of both the physical characteristics of the tropical environment and the technical capabilities of servicing the sensor system by water. Formally, availability is the ratio of the mean-time-between failures (MTBF) to the sum of the MTBF and the mean-time-to repair (MTTR).

A.1.4 Coverage

The coverage to be provided by the fog navigation system in the Panama Canal is the surface area in the Gaillard Cut and the two adjacent reaches; the Pedro Miquel Approach and the Chagres Crossing. Coverage will not be influenced by seasonal or temporal conditions.

A.1.5 Reliability

The reliability of the fog navigation system is a function of the frequency with which failures occur within the system. Because of the requirement in the Panama Canal to service the sensor system by water, redundancy will be used to keep the system performing its function within the defined performance limits. Formally, reliability is one minus the probability of failure.

A.1.6 Fix Rate

The fix rate is defined as the number of independent position fixes available from the system per unit of time. The fix rate for the fog navigation system must support an update rate for the display system of one per second.

A.1.7 Fix Dimension

The fog navigation system must provide a two-dimensional position fix.

A.1.8 System Capacity

The system must accomodate fifty transiting vessels, sixteen tugs, all dredges, drillers and pilot launches. Simultaneous accommodation will probably not exceed twenty-five vessels: one transiting vessel per reach, one tug per vessel, and seven work or launch vessels. However, expansion to accommodate 43 vessels simultaneously is easily accomplished with a modular system.

A.1.9 Ambiguity

Ambiguity exists when the navigation system identifies two or more possible positions for the vessel, with the same set of measurements, with no indication of which is the most nearly correct position. The potential for system ambiguities will be identified and provisions made to resolve them.

A.2 MATHEMATICAL DEFINITIONS

In the requirements analysis the following assumptions have been made.

A.2.1 No Bias Errors

All bias errors will be removed, leaving only random errors to be analyzed. In mathematical terms the mean position error is zero.

A.2.2 Normal Distribution

The random errors are assumed to be normally distributed. This assumption is required to permit a mathematical statement of overall accuracy relationships to be developed.

A.2.3 Independence

The errors associated with lines of position are assumed to be independent. This assumption implies that a change in the error of one line of position has no effect upon the other.

A.2.4 Linearity

The lines of position are assumed to be straight lines over a small area of interest in the neighborhood of the position fix. In the analysis of navigation systems this assumption is usually found to be true. It is valid so long as the standard deviation is small - less than one hundredth of the measurement range - with respect to the radius of curvature of the line of position.

A.3 REQUIREMENTS ANALYSIS SCENARIO

Requirements analysis can be performed using either simulation techniques, a measurement program of present operations or an analysis of representative reaches and turns in the Cut. The first two methods are justified if the resulting choice for a system is between an inexpensive or expensive system. At this point in the fog navigation study neither a simulation or measurement program is needed.

A.3.1 Vessel Activity

There are no plans to allow vessels to meet in the Gaillard Cut in a fog environment. However, for the purpose of estimating critical parameters, this study assumes that two vessels meet in a reach. To ameliorate the action, this study will restrict the meetings to the straight sections of the Cut.

A.3.2 Geographic Assumptions

The geographic characteristics of the nine reaches are listed in Table A.1. NOTE: The nine reaches include the entering and exiting reaches. Figure A-1 and A-2 illustrate the impact of the geographic length of the displayed map on the vessel diameter as a function of the display resolution. Figure A.1 illustrates that very little navigation and guidance information can be gained from a total view of the Canal. NOTE: One can always distort the horizontal scale so that one picture element (pixel) in the horizontal direction is equivalent in distance to ten pixels in the vertical direction. For the initial assumption one pixel on both axis will represent the same distance. The scenario chosen for analysis is the Bas Obispo Reach (length 1.63 nm) with a northbound ship and a southbound ship entering their respective ends of the reach and scheduled to meet approximately mid-reach. Table A-2 lists the pixel dimensions for a 512 by 512 matrix and a 256 by 256 matrix for each reach.

The second geographic assumption is a turning scenario. The turn selected for analysis will be the largest course change between reaches in the Gaillard Cut. Table A-3 lists all the course changes in the Gaillard Cut. The largest change is 30 degrees from Bas Obispo Reach to Chagres Crossing.

In summary the geographic assumption for the analysis is the Bas Obispo Reach followed by a turn into Chagres Crossing.

A.3.3 Vessel Characteristics

As stated in Section A.3.1 there are no plans to allow vessels to meet in a fog environment in Gaillard Cut. In the present time period with good

TABLE A-1. COURSES AND DISTANCES, NORTHBOUND TRANSIT

COURSES	DISTANCE (NM)	TRUE°	MAG°
*PEDRO MIGUEL APPROACH	0.23	312	310
PARAISO REACH	0.66	295.5	293.5
CUCARACHA REACH	1.07	307.5	305.5
CULEBRA REACH	1.30	325.5	323.5
EMPIRE REACH	0.82	303	301
CUNETTE CURVE	0.38	321	319
LAS CASCADAS REACH	0.91	340	338
BAS OBISPO REACH	1.63	331	329
*CHAGRES CROSSING	0.82	301	299

MAGNETIC VARIATION -2° EAST

*THESE TWO COURSES ARE THE ENTRANCE AND EXIT COURSES FOR GAILLARD CUT.

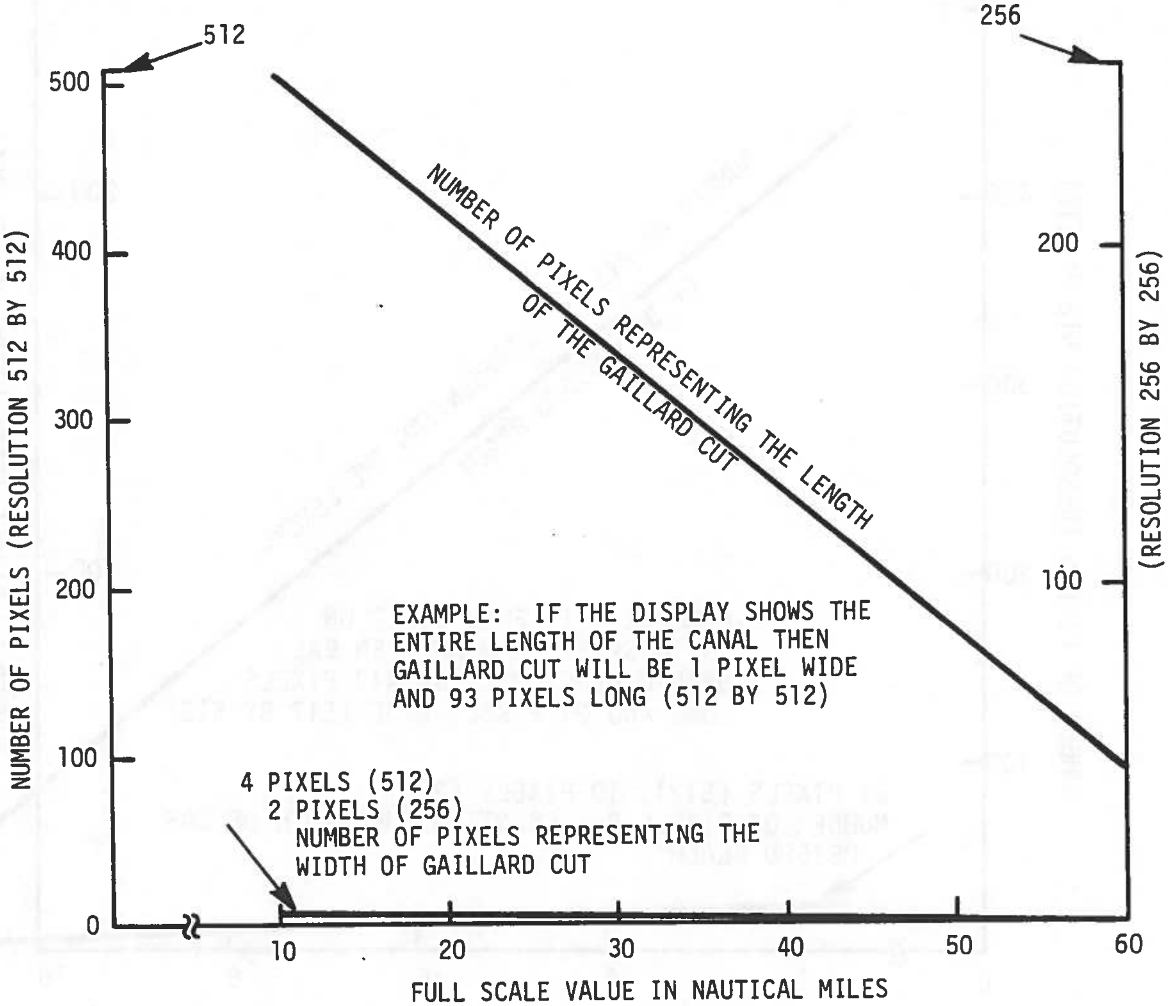

FIGURE A-1. DISPLAY SCALE 60 TO 10 NAUTICAL MILES

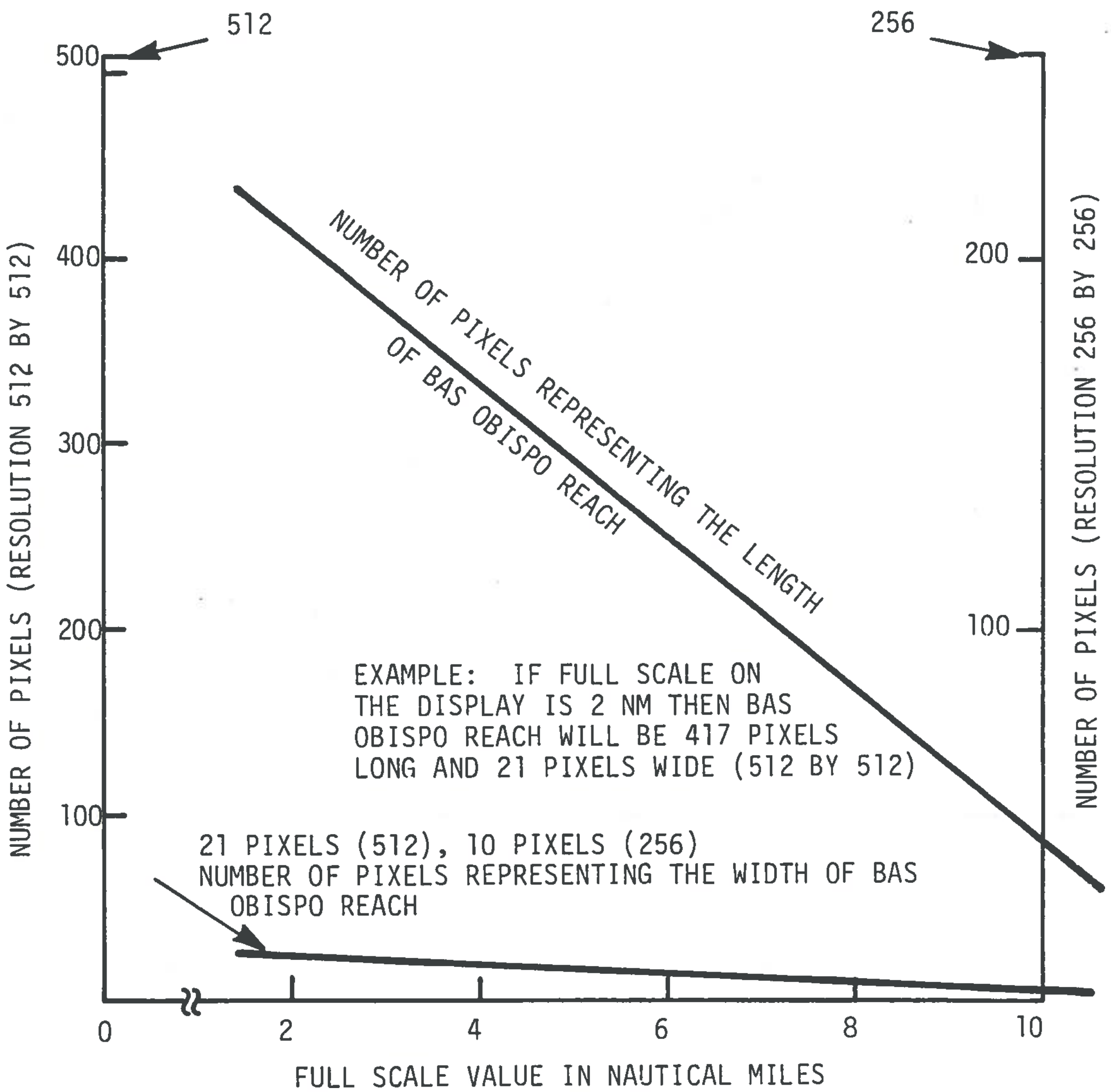

FIGURE A-2. DISPLAY SCALE 10 TO 2 NAUTICAL MILES

TABLE A-2. PIXEL DIMENSION FOR FULL COURSE DISPLAY

COURSES	DISTANCE		LENGTH OF A PIXEL (FEET)	
	NM	FEET	(512)*	(256)**
BAS OBISPO REACH	1.63	9877.8	19.3	38.6
CULEBBA REACH	1.30	7878.0	15.4	30.8
CUCARACHA REACH	1.07	6484.2	12.7	25.4
LAS CASCADAS REACH	0.91	5514.6	10.8	21.6
EMPIRE REACH	0.82	4969.2	9.7	19.4
CHAGRES CROSSING	0.82	4969.2	9.7	19.4
PARAISO REACH	0.66	3999.6	7.8	15.6
CUNETTE CURVE	0.38	2302.8	4.5	9.0
PEDRO MIGUEL APPROACH	0.23	1393.8	2.7	5.4

*512 by 512 PICTURE ELEMENTS (PIXELS)

**256 by 256 PICTURE ELEMENTS (PIXELS)

TABLE A-3. COURSES, HEADINGS AND CHANGES IN HEADING

NORTH COURSES	MAG.°	TRUE°	ΔTRUE°
*PEDRO MIGUEL APPROACH	310	312	
PARAISO REACH	293.5	295.5	16.5
CUCARACHA REACH	305.5	307.5	12.0
CULEBRA REACH	323.5	325.5	18.0
EMPIRE REACH	301	303	22.5
CUNETTE CURVE	319	321	18.0
LAS CASCADAS REACH	338	340	19.0
BAS OBISPO REACH	329	331	9.0
*CHAGRES CROSSING	299	301	30.0

MAGNETIC VARIATION -2° EAST

*THESE TWO COURSES ARE THE ENTRANCE AND EXIT COURSES FOR GAILLARD CUT visibility there are restrictions on the combined width of vessels allowed to meet in the Cut. In general the requirement states that the combined beam of both vessels must be less than 180 feet and the lengths of each ship be 600 feet or less; there are other restrictions on meeting in the Cut based on types of cargo and types of vessels. For the purpose of this study these additional restrictions have no impact on the analysis. Figure A-3 illustrates the maximum heading error for an assumed error in bow and stern positioning accuracy as a function of ship length. The longer the vessel the less the heading error for a fixed positioning error. A vessel the length of a tugboat has the potential for large heading errors, however its maneuverability will permit quick correction of this error. A 600 foot long vessel is mid-range in potential for heading error and maneuverability. This observation coupled with the present procedure of allowing vessels of this length - assuming the combined beam restriction is met - to meet in good visibility, make a vessel of this length the correct choice for analysis. There is a small probability that two such vessels could become trapped in an unexpected fog condition while transiting the Cut and meet; so the design of a fog navigation system must include this scenario.

In summary the vessel dimensions assumed for this analysis are 600 foot length and 90 foot beam for each of two vessels.

Another vessel characteristic that needs defining is vessel speed in the Cut. Presently in good visibility vessels move through the Cut at 6 to 8 knots (7 to 9 mph), with reductions in speed for tactical maneuvering. A well designed fog navigation system would allow the Pilot to maintain presently accepted speeds. Physical characteritics of the Cut limit the upper speed to 6 to 8 knots and the fog navigation system will not remove these limits.

A.3.4 Pilot Performance Characteristics

The perceptual and recognition process of Pilot performance can not be simply measured. His performance is very much related to his reactions to

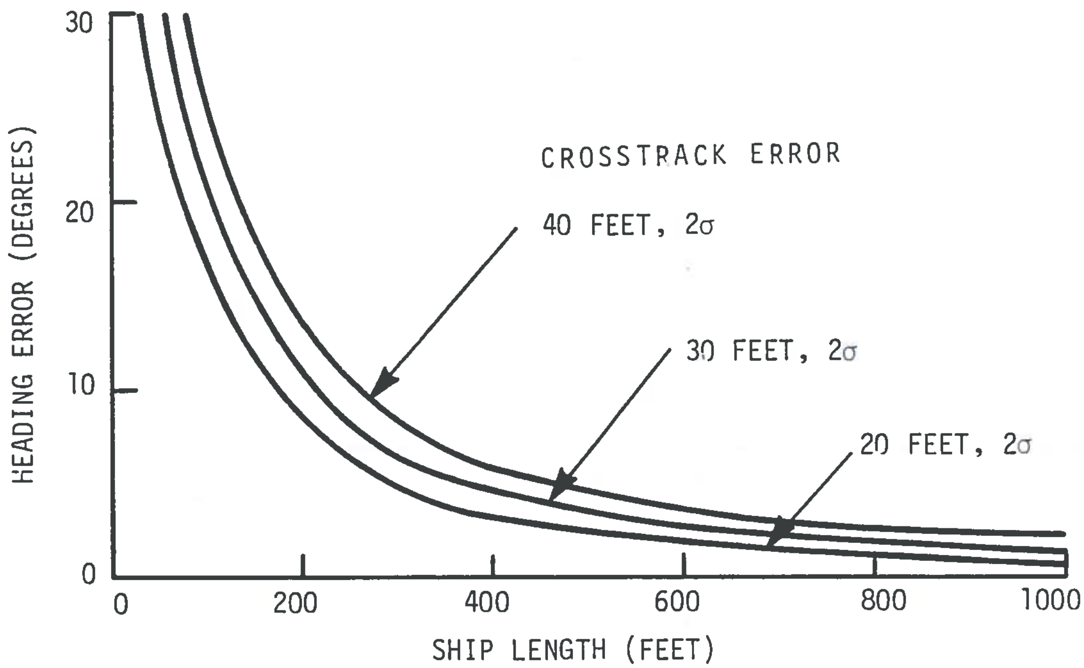

FIGURE A-3. HEADING ERROR AS A FUNCTION OF SHIP LENGTH perturbational forces (turns, currents, winds, traffic, bottom and bank effects, and ship maneuverability) that do or do not permit the Pilot both to maintain dead-reckoned knowledge of his position and to make fresh estimates of that position.

In developing the requirement, it was assumed that crosstrack error is the key parameter. The technique used to determine the value of this error was developed by the USCG for determining navigation requirements for the St. Marys River in Michigan's Upper Peninsula, and in other narrow waterways. The half channel width for the Gaillard Cut is 250 feet. From this is subtracted the "half-vessel-width" for the largest vessel- (105 feet). What remains is how far the centerline of the vessel can stray from the center of the channel without part of the vessel extending outside of the channel. This defines the total allowable error as 200 feet, two standard deviations, 95 percent. For the meeting maneuver, the ships "half-vessel-width" is 45 feet. The vessels allowed to meet in Gaillard Cut must have a combined beam width of less than 180 feet. The procedure used for vessels to meet is to move right from the centerline to the north (south) bound sailing line. Each vessel moves 90 feet to the right. Thus there will be a separation of 90 feet. Subtracting half of this from the half channel width results in the allowable error for a meeting maneuver for two vessels whose combined beam is 180 feet. The allowable error is 160 feet, two standard deviations, 95 percent. For lack of a simple way to apportion this performance between a navigation system input and the Pilots ability to make the vessel respond to the visual input, a range of crosstrack values of 16 to 20 feet, two standard deviations were chosen as the accuracy of the navigation system.

As pointed out earlier in this Appendix the requirements will have to pass the scrutiny of hardware capabilities and will be evaluated during the measurement program.

Figure A-4, illustrates the relationship between crosstrack error, range

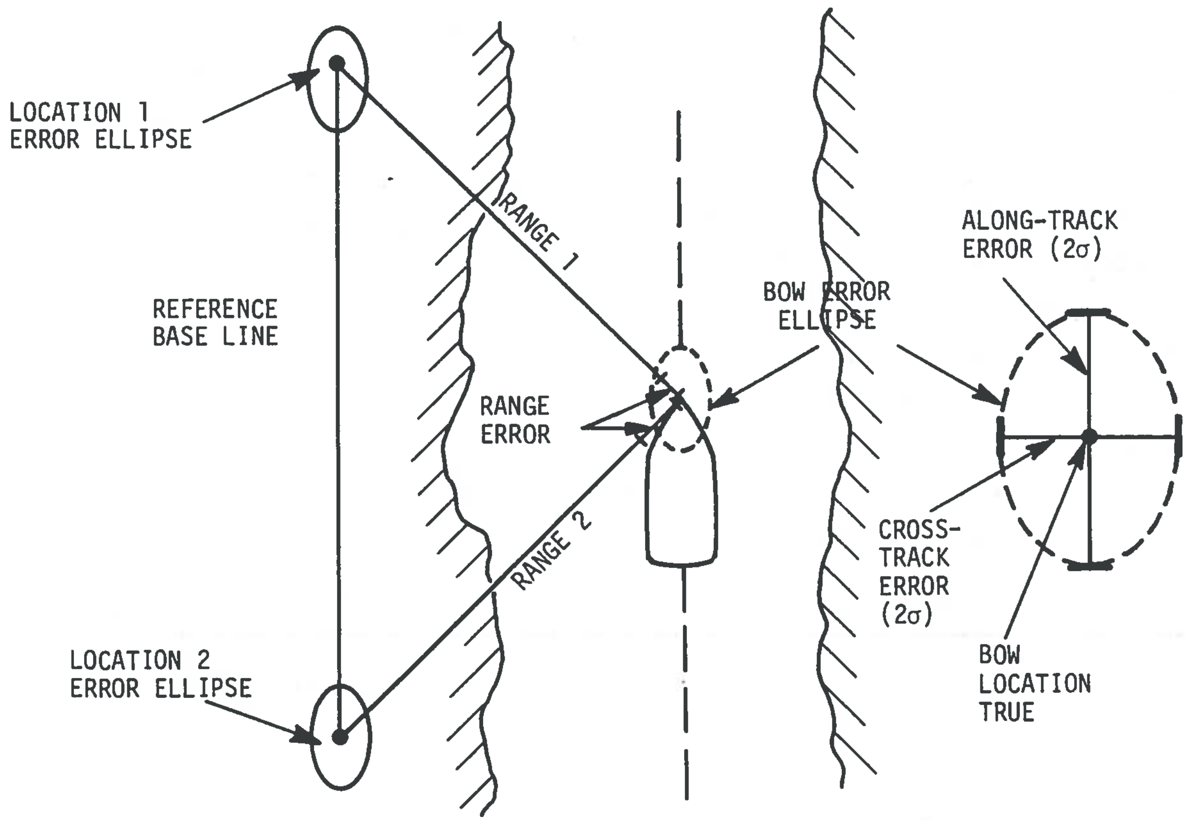

FIGURE A-4. RELATIONSHIP BETWEEN ERROR SOURCES error and location error. To demonstrate the technique of combining random errors, an assumption will be made that all random errors are aligned with the crosstrack and along-track axes, and that one system is perpendicular to the center line and the other is aligned with the center line. The range of the crosstrack error in the display is limited to 16 to 20 feet, 2 standard deviation, 95 percent. For the purpose of this example the range of the along-track error is also limited to 16 to 20 feet. NOTE: In the following section, the along-track error will be shown to be 32 to 40 feet, however for this example the lesser value will be used.

A careful position location survey (second order) will have an accuracy error of 9 feet, 2 standard deviations, 95 percent. Therefore, the error budget chosen will accommodate a precision ranging system with an error in range measurement of 14 feet, 2 standard deviations, 95 percent. This type of accuracy is within the state of the art.

The along-track accuracy requirement is a function of the course change in degrees and the allowable crosstrack error. Figure A-5 illustrates this relationship. For the largest course change - 30 degrees between Bas Obispo and Chagres Crossing - and a crosstrack accuracy of 16 to 20 feet, the required along track accuracy is 32 to 40 feet, 2 standard deviations, 95 percent.

In summary, the crosstrack accuracy requirement is 16 to 20 feet, 2 standard deviations, 95 percent; the along-track accuracy requirement is 32 to 40 feet, 2 standard deviations, 95 percent.

A.3.5 Pilot Display Characteristics

The Pilot will need a navigation system display to provide the visual cues he needs to guide his vessel through the Gallard Cut in fog.

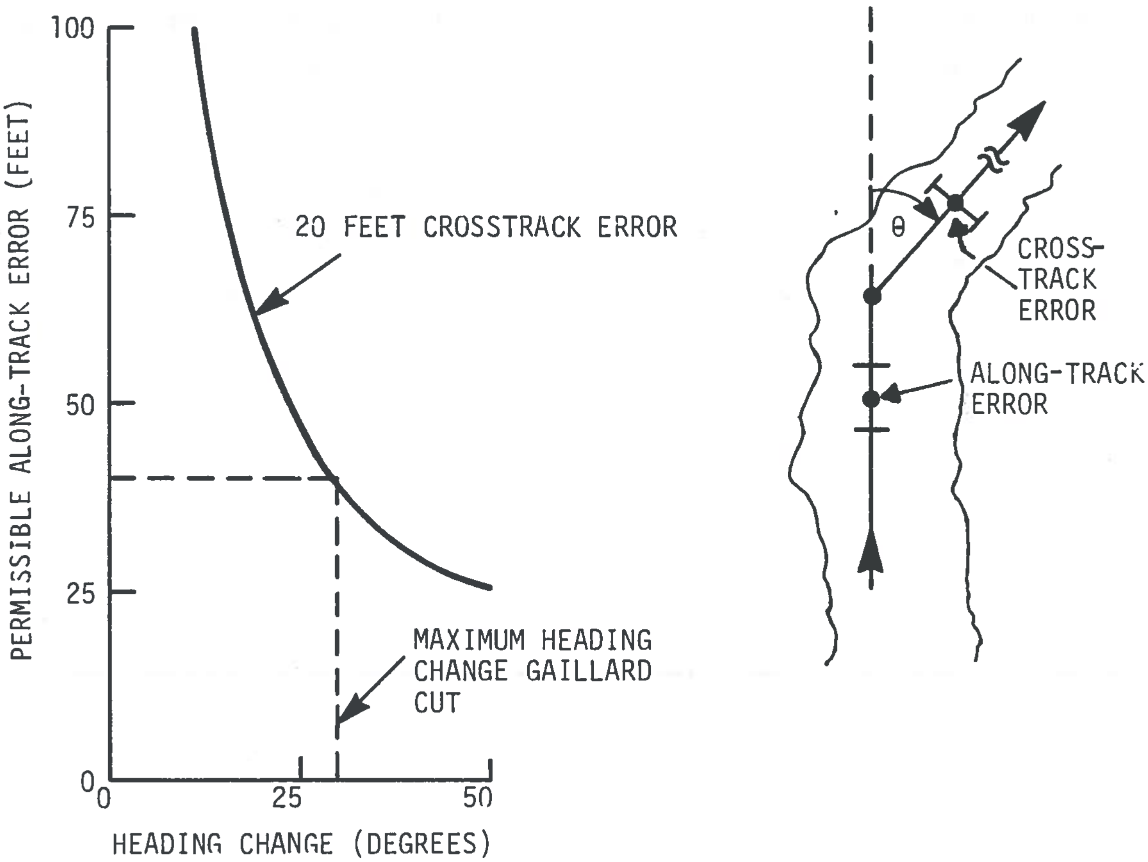

FIGURE A-5. ALONG-TRACK ERROR

These include the following:

a. Position of the bow and stern of the vessel
b. Location of the banks
c. Centerline range marking and sailing line markers
d. Aids to navigation, both fixed and floating buoys
e. Jackstaff or flagstaff location
f. Positions of other transiting vessels
g. Locations of work vessels and launches
h. Other terrain features identified as navigation aids.
i. Data block for digital data

Figure A-6 illustrates the probability of a Pilot sensing vessel motion on the display as a function of display resolution, update rate and vessel velocity. In good visibility, a Pilot looking at the bank - right angles to the direction of motion - will detect motion 100 percent of the time, assuming the vessel is moving. A Pilot using the display has an increase in his "comfort factor" when the display has an update rate and resolution which allows a 50 to 100 percent probability of detecting motion. For this analysis, an 8 knot (9.2 mph) vessel speed will be assumed.

To make the display dynamic, the Pilot will get a fresh view every second. The probability of detecting motion is 70 percent. When the Pilot is looking at the entire range of Bas Obispo reach his vessel will be 31 pixels long and 5 pixels wide in a display with a resolution of 512 by 512 pixels.

The use of color in the display would add another safety dimension to the program, in that it would be easier to correlate the display features with terrain features and navigation aids.

A-4 SUMMARY OF ASSUMPTIONS

CRITERIA	RATIONALE
600 FOOT VESSEL	1. Allowed to meet another vessel in the Gaillard Cut in good visibility if total combined beam width of both vessels is 180 feet or less.

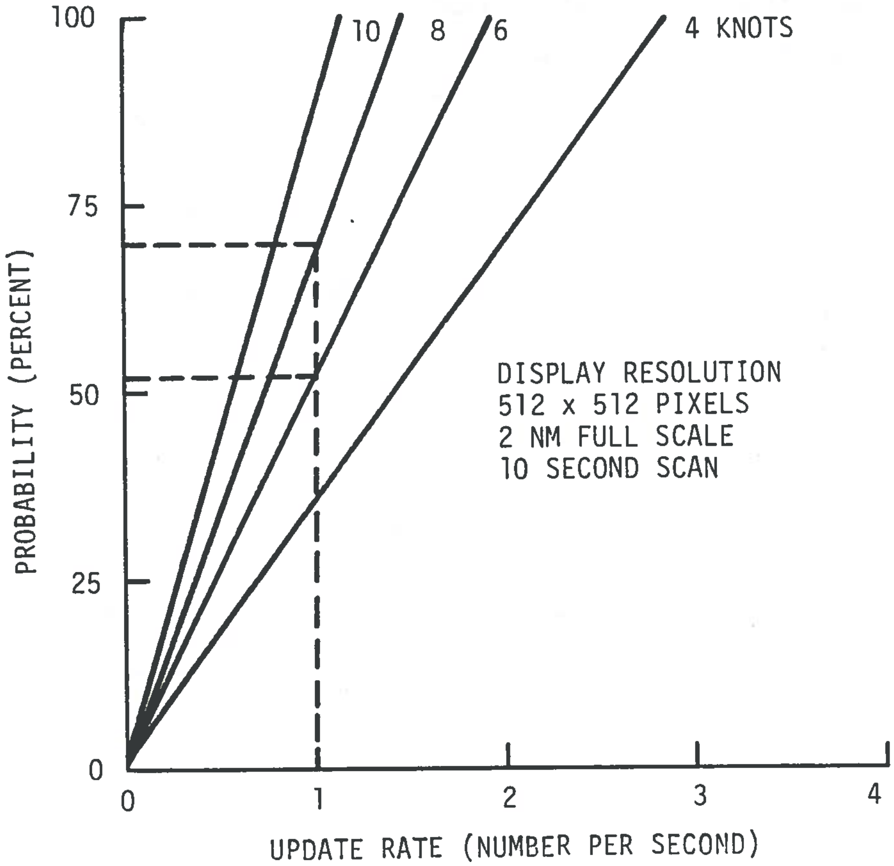

FIGURE A-6. PROBABILITY OF A PILOT DETECTING VESSEL MOVEMENT

CRITERIA	RATIONALE
	2. The longer the vessel the less the crosstrack error will contribute to the heading error. 3. Shorter vessels have more maneuverability.
BAS OBISPO REACH	1. 1.63 nautical miles or 9877.8 feet; this reach is the longest in the Cut. 2. This is the longest view on the display needed for meeting maneuvers. The Pilot may wish to view additional reaches for advanced information on ship traffic.
30 DEGREE COURSE CHANGE. BAS OBISPO REACH TO CHAGRES CROSSING	1. Largest course change between reaches in the Cut. Northbound, the the course changes from 331° 01' to 301° 02'.
DISPLAY RESOLUTION 512 BY 512 PIXELS	1. If the full length of BAS OBISPO reach is shown on the display, then one pixel equals 19.3 feet. 2. 8 knots equals 13.5 feet per second.
ONE SECOND UPDATE RATE	1. At a vessel speed of 8 knots, the displayed vessel position will move seven times in ten seconds. 2. When the display is at full scale (BAS OBISPO REACH) the vessel will be in motion on the display 70% of the time.

CRITERIA	RATIONALE
CROSSTRACK ERROR 16 TO 20 FEET, 2 STANDARD DEVIATIONS, 95 PERCENT.	1. A USCG designed analysis for operational requirements for vessels in narrow channels was used to determine these values. 2. Full scale on the BAS OBISPO REACH will show the edge of the vessel at least one pixel away from the center range (95 percent) 3. Two vessels abeam on sailing lines with the display on full scale (BAS OBISPO REACH) will be separated by at least three pixels (95 percent). 4. A vessel with maximum undetected heading error will take 45 seconds to intrude on the center range, 1.5 minutes to intrude on the opposite sailing line passing range, and 2.25 minutes to reach the prism edge (95 percent). Figure A-7.
ALONG TRACK ERROR 32 TO 40 FEET, 2 STANDARD DEVIATIONS, 95 PERCENT.	1. An along-track error larger than 32 to 40 feet will result in a crosstrack error greater than 16 to 20 feet after completing a 30 degree course change. 2. Smaller course changes can have larger along-track errors without exceeding the crosstrack error limit upon completing a turn.

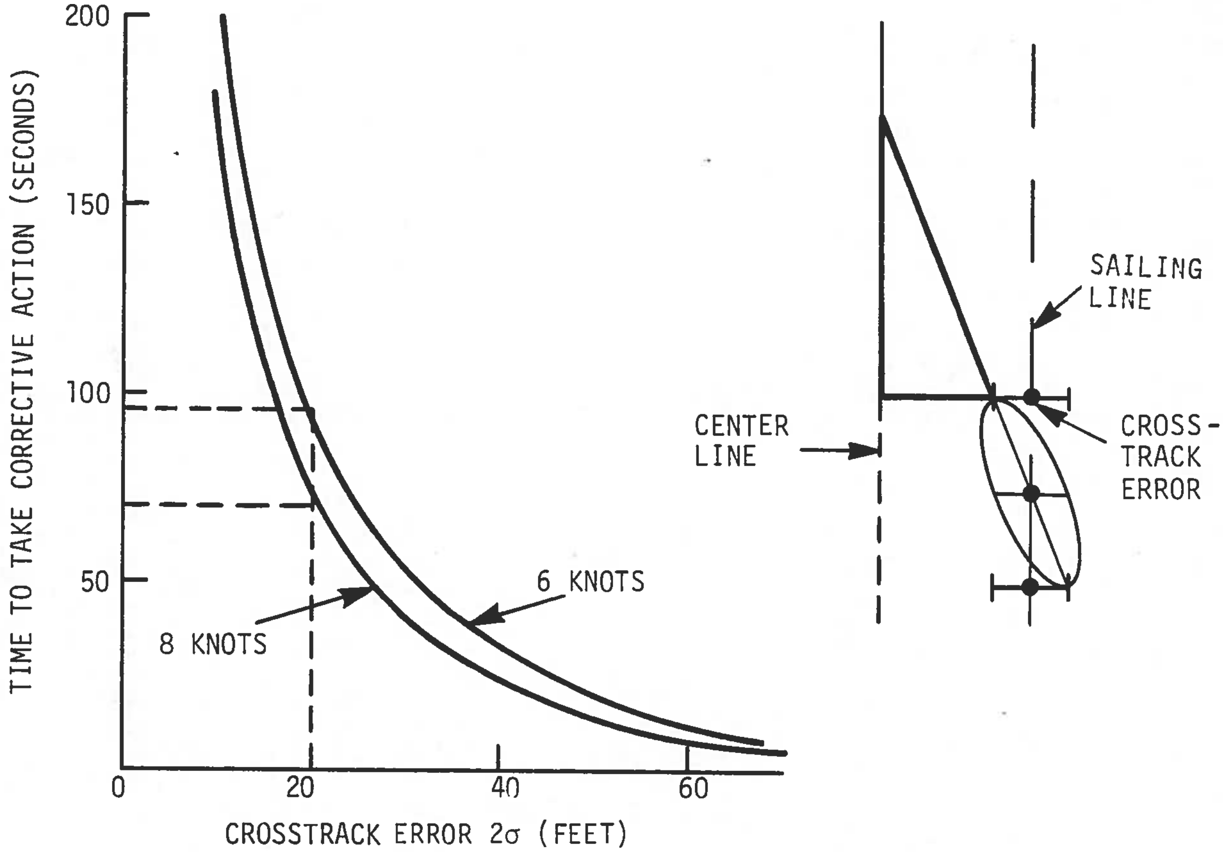

FIGURE A-7. CENTER LINE INTRUSION

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