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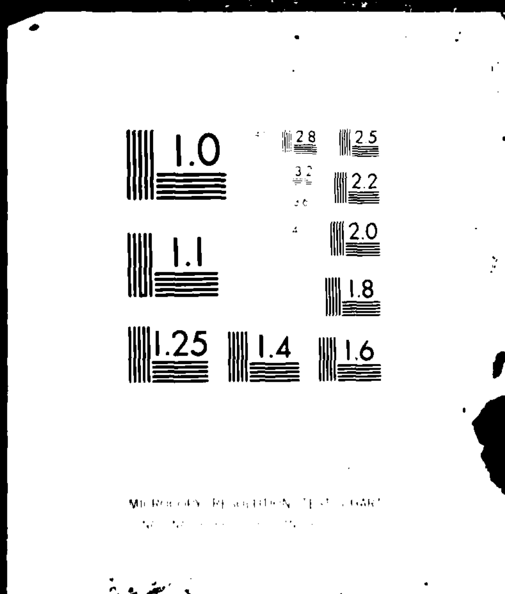

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AIDS TO NAVIGATION PRINCIPAL FINDINGS REPORT: RANGE LIGHT CHARACTERISTICS AND THEIR EFFECT ON PILOTING PERFORMANCE

Eclectech Associates, Inc.
North Stonington Professional Center
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December 1981

Interim Report

Prepared for

U.S. Department of Transportation
United States Coast Guard
Office of Research and Development
Washington, D.C. 20593

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16. Abstract

The experiment described here is one of a series done for the U.S. Coast Guard to quantify the relationship between variables related to aids to navigation and piloting performance in narrow channels and, potentially, safety in such channels. This is one of several experiments restricted to visual piloting and was performed on a simulator built for the U.S. Coast Guard at Eclectech Associates in North Stonington, Connecticut. The variable conditions evaluated were: (1) sensitivity ranges (high lateral sensitivity at $K \approx 4.5$ or low lateral sensitivity at $K \approx 0.5$), (2) designated track (with the objective to stay either on the centerline or on the right quarterline), and (3) angle of turn (15-degree or 35-degree noncutoff turn). The constant conditions were a 500-foot channel with two 1.3 nm straight legs joined by a bend. Each straight leg has a range light marking the centerline of the legs and these were the only aids available. The scenarios were run at night with wind and current varying through the transit. The ship was a 30,000 dwt tanker with the bridge 75 feet forward from the center of gravity, and pilots were instructed to keep transit speed at 6 knots. The findings of the experiment are presented as the means and standard deviations of crosstrack position of transits under each condition. These are interpreted in terms of their implications for the design of channel markings.

17. Key Words	18. Distribution Statement
aids to navigation, piloting range configuration, range sensitivity bridge simulation trackkeeping, maneuvering, channel boundary, pilot performance, crosstrack movement, alongtrack position, channel width	Document is available to the public through the National Technical Information Service, Springfield, VA 22161

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PREFACE

The experiment described here is a component of the United States Coast Guard's Performance of Aids to Navigation Systems project. The project is meant to collect the data necessary to lead to guidelines for the design of AN Systems. The project includes (or will include) a survey of U.S. ports to summarize existing conditions; a survey of relevant variables to be considered; a major simulator experiment in visual piloting done at Maritime Administration's Computer Aided Operations Research Facility (CAORF) in New York; four visual piloting (SRAN) and three radio aids piloting (RA) experiments performed at a simulator developed for the project at Eclectech Associates, Inc., in North Stonington, Connecticut; and an at-sea data collection to provide validation of the USCG/EA simulator and the experimental results. The final step will be the preparation of the overall findings for the development of design guidelines.

The experiment described here is the last of four visual piloting experiments performed on the USCG/EA simulator. Range lights were the only aids in this experiment. The experiment evaluated the effects of sensitivity of the range (to the pilot, the rate at which the range opened as the ship moved off the center) and its effect on several piloting tasks. The capability of the USCG/EA simulator to simulate range lights was evaluated for the first time. The following is a summary of conclusions supported by the experiment.

- A sensitive range is extremely effective for finding and maintaining the axis of that range, even in the presence of crosswind and crosscurrent.
- A low-sensitivity range is less effective than a high-sensitivity range for finding and maintaining the axis of that range. It can even be less effective than a parsimonious buoy arrangement for that purpose.
- Even a high-sensitivity range is not effective for finding or maintaining a track that is not on the axis of the range. This weakness has implications for traffic conditions.
- Ranges are useful for turns only under the most favorable conditions: for example, a high-sensitivity range and low angle of turn.
- The USCG/EA simulator is useful for the simulation of range lights over a wide set of values of horizontal and vertical visual angles.

ACKNOWLEDGEMENTS

The authors would like to express their appreciation to CAPT J.T. Montonye of the United States Coast Guard for his continued personal participation in the project. We would also like to thank CDR J.F. Roeber and LT J. Anthony for their contributions. We are grateful to Mr. K. Schroeder for his continuing help and support.

The authors would like to thank Captain D.G. Leonard, President of Northeast Marine Pilots, Inc., for his cooperation. We would like to thank Captain A. Duffy for serving as presimulation subject and consultant and to thank the other members of the association for serving as experimental subjects. We are grateful to all the pilots who were involved for their comments on the experiment and on the simulation.

EXECUTIVE SUMMARY

OVERVIEW

Range lights are a highly specialized aid, useful for finding and maintaining the axis of the range. However, for other purposes, piloting performance is susceptible to perturbing factors in the situation.

INTRODUCTION

The purpose of this experiment was to evaluate the effectiveness of range lights as the only aid to navigation for a variety of piloting tasks. These included finding and maintaining a track, maneuvering through the turn, and trackkeeping off the axis of the range.

The variables were selected to increase the generality of the findings and are identified below:

(1) Lateral sensitivity of the range. The pilots define this as the speed with which the range lights open as the ship moves off the centerline. It can be operationally defined in terms of the parameters of the situation as:

$$K = WR/D\,(H - h)$$

where:

K = lateral sensitivity
W = channel width (feet)
R = distance between lights
D = distance from front light to observer
H = height of rear light (feet)
h = height of front light (feet)

The researchers suggest another measure of sensitivity is crosstrack position sensitivity:

$$X_Q = \frac{(\theta_Q/\Delta)\,(W)}{K}$$

where:

X_Q = crosstrack displacement in feet when horizontal visual angle is θ_Q
θ_Q = horizontal visual angle of separation which 65 percent of the subjects judge to be still vertically aligned (min arc)
= vertical visual angle of separation (min arc)
W = channel width (feet)
K = lateral sensitivity

The conditions were:

High Sensitivity	Low Sensitivity
K = 3.5 to 10.0 X_Q = 1.8 to 6.3 feet	K = 0.5 to 0.8 X_Q = 20.0 to 40.0 feet

(2) Angle of the turn. Either 15 degrees or 35 degrees.

(3) Intended track. Either on the centerline or the quarterline.

The constant conditions for this experiment were:

(1) Ship type: 30,000 dwt tanker at a transit speed of 6 knots.

(2) Channel: A 500-foot wide channel with two 1.3 nm straight legs and a turn.

(3) Scenario: Consisted of a maneuver to the designated track with a following wind and current, a turn, and a return to the designated track with a crosswind and crosscurrent.

(4) Visiblity: Unlimited.

(5) Aids to navigation: Two ranges marking the centerline of each straight leg. No buoys or radar were available.

FINDINGS OF THE EXPERIMENT

<u>Finding and Maintaining a Track on the Range Axis in Various Crosscurrent Conditions</u>

Range sensitivity determines its effectiveness to pilots for finding and maintaining the track in a crosscurrent condition if the strategy is to remain on the centerline. The high sensitive range allows the pilot to identify and compensate for the effects of current while the low sensitivity range does not. The following general conclusion is supported:

> **A high sensitivity range is effective for finding and maintaining a track on the range axis under a variety of perturbing conditions.**

<u>Finding and Maintaining a Track Off the Axis of the Range on the Quarterline of the Channel</u>

The pilots were able to make a small maneuver onto the quarterline with a following wind and current. Piloting performance, however, was poor finding the quarterline after the turn and with the crosswind and crosscurrent even with high sensitivity ranges. The following general conclusion is supported:

High sensitivity ranges are effectively used off the range axis in only the most favorable circumstances. By extension, ranges in two-way traffic situations probably encourage approaching ships to maintain the channel centerline except for brief excursions off the centerline to pass.

Turns With Range Lights as the Only Aid

Performance was inadequate (the ship hull often exceeded the channel edge) in making a 35-degree turn from a high to a high sensitivity range. It was worse when making a 35-degree turn from a low to a low sensitivity range. It was equally poor in turning from a high to a low sensitivity range where pilots began the turn with good crosstrack information from leg 1.

It was possible to turn adequately from range to range only with a 15-degree turn with high sensitivity ranges. The following conclusions are supported:

> Ranges are useful for turning only under the most favorable circumstances. These include very wide channels and low angle turns that do not exceed 15 degrees and do not require the ship to move far off the axes of the ranges during the turning maneuver.

The pilots did turn from range to range, albeit with a very wide distribution of tracks. From this it is possible to conclude that turns aided only by ranges might be adequate if the channel is very wide or if the turn area is widened by dredging.

IMPLICATIONS FOR THE DESIGN OF AID TO NAVIGATION SYSTEMS

The factors to be considered in marking a channel with ranges are:

- Expected visibility
- Sensitivity of the range
- Traffic
- Current
- Width of turn region
- Angle of turn

The detection distance of the range lights must be as long as the distance from the start of the channel to the rear light for ranges to be effective. If transits are made when the visibility is less than this, buoys and/or radio aids must be used to mark the channel. When ice makes buoy use impossible, ranges with their vulnerability to visibility may be the only aid available and operations will necessarily be limited by the available visibility. (This assumes visual piloting only.)

Piloting performance is dependent on the sensitivity of the range. If the range cannot be designed to provide adequate performance for the width of the channel, buoys are the obvious alternative for visual aids, based on previous experiments which evaluated piloting with buoys.

When it is critical that a ship stay on a designated track despite crosscurrent (i.e., a large ship, hazardous cargo), a highly sensitive range is more effective than buoys.

If there is a large area in which to turn, because the channel is very wide, or because the turn is widened, high sensitivity ranges are possible alternatives to buoys.

If the channel is limited in width and a turn of greater than 15 degrees is required, then buoys must be used to achieve adequate performance in the turn.

If the angle of the turn is very low, that is, 15-degrees or less, high sensitivity ranges are an alternative to buoys in the turn. Even for these turns, performance with the turns marked with buoys will be superior to those marked only with ranges.

Ranges generally do not support good piloting performance off the axis of the range. It may be expected that in two-way traffic situations, ranges will encourage traffic to maintain tracks near the range axis except during a passing maneuver. This behavior may cause the range lights to be obscured by one or the other of the traffic ships. The result of such an occurrence was not studied in this experiment.

VALIDITY OF THE USE OF THE SHIPHANDLING SIMULATION FOR RANGE LIGHT EXPERIMENTATION

Prior to the conduct of the range light experiments, perception tests were conducted on the simulator to establish whether or not the perception of vertical lights would be equivalent to that previously tested in both laboratory and field tests. The simulator results showed that the subjects' performance was statistically equivalent to the previous results for vertical visual angles of separation of 25 to 10 minutes of arc. These findings support the following conclusion:

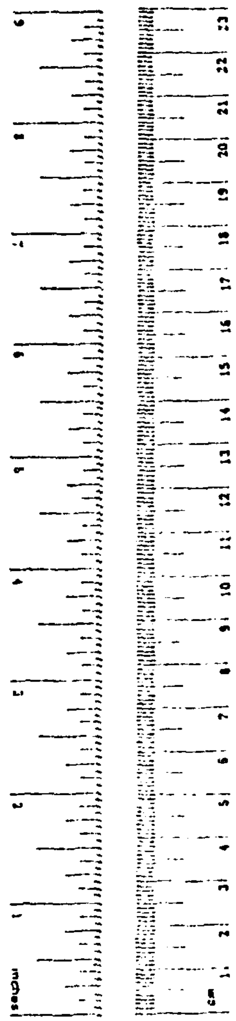
> **Piloting performance using range lights may be evaluated on the USCG shiphandling simulator if the vertical visual angle separating the lights is greater than 25 minutes of arc. Perception of the vertical alignment of such range lights will be equivalent to behavior at sea.**

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

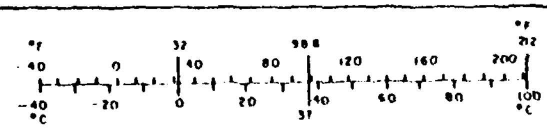
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	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 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights 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	35	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



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Section 1

INTRODUCTION

1.1 OVERVIEW OF THE AIDS TO NAVIGATION PROJECT

The United States Coast Guard is responsible for safety in U.S. harbors and channels and, therefore, for the aids to navigation (AN) necessary to ensure that safety. In fulfillment of this responsibility, the Coast Guard is sponsoring a simulator-based program of research into the performance of aids to navigation systems. Their interests include visual aids to navigation, radar, and radio aids. The final objectives of the project are the use of experimental data to derive design criteria for the placement of aids to navigation and to specify radio aids to navigation systems for narrow channels with turns. Completed components of the project are available as separate reports. The first of these was an analysis of the variables expected to affect visual piloting.[1] To enhance the applicability of the findings to real-world harbors, major U.S. ports were surveyed from charts, cataloging the conditions that exist.[2] Four experiments on visual piloting with floating aids have been completed. These are the "CAORF,"[3] "Channel Width,"[4] "Ship Variables",[5] and "One-Side Channel Markings"[6] experiments. The planning of the present experiment is referred to as

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[1]W.R. Bertsche and R.C. Cook. "Analysis of Visual Navigational Variables and Interactions." U.S. Coast Guard, Washington, D.C., October 1979.

[2]W.R. Bertsche and R.T. Mercer. "Aids to Navigation Configurations and the Physical Characteristics of Waterways in 32 Major U.S. Ports." U.S. Coast Guard, Washington, D.C., October 1979.

[3]M.W. Smith and W.R. Bertsche. "Aids to Navigation Report on the CAORF Experiment. The Performance of Visual Aids to Navigation as Evaluated by Simulation." U.S. Coast Guard, Washington, D.C., August 1980.

[4]M.W. Smith and W.R. Bertsche. "Aids to Navigation Principal Findings Report on the Channel Width Experiment: The Effects of Channel Width and Related Variables on Piloting Performance." U.S. Coast Guard, Washington, D.C., January 1981.

[5]W.R. Bertsche, D.A. Atkins, and M.W. Smith. "Aids to Navigation Principal Findings Report on the Ship Variables Experiment: The Effect of Ship Characteristics and Related Variables on Piloting Performance." U.S. Coast Guard, Washington, D.C., April 1981.

[6]K.L. Marino, M.W. Smith, and W.R. Bertsche. "Aids to Navigation Principal Findings Report: The Effect of One-Side Channel Marking and Related Conditions on Piloting Performance." U.S. Coast Guard, Washington, D.C., July 1981.

the "Range Light Presimulation Report."[7] Several related studies on radio aid piloting are also complete.[8,9,10]

The first simulator experiment on floating aids to navigation was conducted at CAORF, the Maritime Administration's Computer Aided Operations Research Facility in New York. Later ones, including the one to be described here, were conducted at a simulator built for this U.S. Coast Guard project by Eclectech Associates in North Stonington, Connecticut. Both are bridge simulators, which provide the bridge, the ship hydrodynamics, the environmental effects, and the visual scene necessary for this series of experiments. A comparison of the results obtained on the two is discussed in the Channel Width and Ship Variables reports.

The performance of aids to navigation, and of pilots using aids to navigation, is the result of a complex process under the control of many variables. The 15 variables of interest in the project are listed in Table 1. There are more variables than can be included in a single experiment. Instead, a systems approach which evaluates a part of the process at a time is necessary. The subsets of the relevant variables selected for the first visual experiments are indicated in the table. The emphasis in the first experiments was on varying the conditions that control the amount of visual information buoys provided to the pilot. The visual conditions provided were combined with a complex scenario that required performance in both trackkeeping and maneuvering, with and without perturbations. The general finding of the experiments was a relationship between the maneuvering and/or perturbation requirements of the scenario and the reliance on visual information: when maneuvering was difficult, the pilot's performance was more dependent on the buoy configuration.

1.2 EXPERIMENTAL CONDITIONS FOR THE RANGE LIGHT EXPERIMENT

The purpose of this experiment was to evaluate the effectiveness of range lights as the only aid to navigation for a variety of piloting tasks. These included: (1) trackkeeping on the range, (2) maneuvering through the turn, and (3) trackkeeping off the range. Trackkeeping

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[7] M.W. Smith. "Aids to Navigation Presimulation Report: Range Light Charactertistics and Their Effect on Performance." U.S. Coast Guard, Washington, D.C., July 1981.

[8] R.B. Cooper and K.L. Marino. "Simulator Evaluation of Electronic Radio Aids to Navigation Displays - The Miniexperiment." U.S. Coast Guard, Washington, D.C., September 1980.

[9] R.B. Cooper, K.L. Marino, and W.R. Bertsche. "Simulation Evaluation of Electronic Radio Aids to Navigation Displays, The RA-1 Experiment." U.S. Coast Guard, Washington, D.C. 1981.

[10] R.B. Cooper, K.L. Marino, and W.R. Bertsche. "Simulation Evaluation of Electronic Radio Aids to Navigation Displays, The RA-2 Experiment." U.S. Coast Guard, Washington, D.C., April 1981.

and maneuvering are constantly used in piloting, however, there is not a clear distinction between them. When trackkeeping, pilots move the ship toward an immediate destination. Here they need only know the position of destination and the direction of the ship in relation to it. They do not need precise knowledge of the channel edges or crosstrack position in relation to them. When maneuvering, pilots move the ship in relation to relatively close points such as the outline of a turn, the edges of a channel, or a traffic ship. Here they need more information than for trackkeeping because they must continually reevaluate position to make frequent estimates of ship position and velocity (direction and speed) in relation to close points. For a turn, the maneuver is relatively severe so channel boundaries must be identifiable. To pass a traffic ship, pilots must consider both the ship and the channel edges so this information must be available.

Prior to conducting the range light experiment, static tests were run on the simulator to determine if pilot perception of the vertical separation of the lights were equivalent to empirical equations derived from previous studies. Appendix A discusses the static tests and shows pilot performance was statistically equivalent to empirical performance.

TABLE 1. NAVIGATION PROCESS VARIABLES

VARIABLE	EXPERIMENT WHICH EVALUATED THE VARIABLE
Ship	
Perspective view	Ship Variables
Speed	Ship Variables
Maneuverability	Ship Variables
Channel dimensions	
Banks	None
Width	Channel Width
Turn angle	CAORF, Range Light
Turn radius (configuration)	CAORF, Range Light
Environmental factors	
Current/wind	CAORF, Channel Width, Ship Variables, One Side, Range Light
Day/night	CAORF
Visibility/detection distance	CAORF, One Side
Traffic ships	CAORF
AN placement	
Spacing	CAORF, Channel Width, Ship Variables, One Side, Range Light
Straight channel marking	CAORF, Channel Width, Ship Variables, One Side, Range Light
Flash period	None
Turnmarking	CAORF, Ship Variables, One Side

The variables for this experiment were:

- Sensitivity of ranges. High lateral sensitivity ($K \approx 4.5$) or low lateral sensitivity ($K \approx 0.5$) ranges. See Appendix B for a discussion of the design parameters for these ranges.
- Intended track. Either on the centerline or on the right quarterline.
- Angle of turn. 15-degree or 35-degree noncutoff turn.

The experimental conditions and comparisons are shown by Table 2 and outlined by Table 3. The scenarios are diagrammed in Appendix C. The hypotheses associated with the selection of these variables were:

1. Effect of Range Sensitivity. Scenario 1 will be used as a standard to compare the other scenarios. Each straight leg is marked by the same high sensitivity ($K \approx 4.5$) range placed to mark the centerline. The pilot was asked to trackkeep on the range in both segments with and without crosswind and crosscurrent. Additionally, he had to maneuver through a 35-degree turn and find the centerline with no additional aids. Performance under these conditions will be compared with performance in scenario 2 which differs only in the low sensitivity ($K \approx 0.5$) of the ranges in each leg. It is expected that performance will be better in scenario 1. Performance can be compared for both trackkeeping and maneuvering portions.

Scenario 6 is marked by two different range sensitivities. Leg 1 has the high sensitivity range of scenario 1, and leg 2 has the low sensitivity range of scenario 2. This scenario will investigate the possibility that the superior crosstrack information provided by the high sensitivity range in the first leg as the ship approaches the turn will allow for a better turn onto the low sensitivity range than that made in scenario 2. Scenario 6 can also be compared to scenario 1. It is expected that performance will be best in scenario 1, followed by scenario 6, with scenario 2 resulting in poorest performance.

2. Effect of Intended Track. Scenario 1 will be compared with scenario 4 which differs only in instruction to the pilot. In scenario 4 the pilot is asked to trackkeep at the center of the right-hand quarter using the range lights. Scenario 4 is dedicated to an evaluation

TABLE 2. EXPERIMENTAL CONDITIONS

Scenario*	Degree of Turn	Range Sensitivity Leg 1	Range Sensitivity Leg 2	Intended Track
1	35 degree	High ($K \approx 4.5$)	High ($K \approx 4.5$)	Centerline
2	35 degree	Low ($K \approx 0.5$)	Low ($K \approx 0.5$)	Centerline
4	35 degree	High ($K \approx 4.5$)	High ($K \approx 4.5$)	Quarterine
5	15 degree	High ($K \approx 4.5$)	High ($K \approx 4.5$)	Centerline
6	35 degree	High ($K \approx 4.5$)	Low ($K \approx 0.5$)	Centerline

*Note: Scenario 3 eliminated from experiment.

TABLE 3. AVAILABLE COMPARISONS BY SCENARIO

VARIABLE	SCENARIOS
EFFECT OF RANGE SENSITIVITY	
High sensitivity in legs 1 and 2 versus low sensitivity in legs 1 and 2	1 versus 2
High sensitivity in legs 1 and 2 versus high sensitivity in leg 1 and low sensitivity in leg 2	1 versus 6
Low sensitivity in legs 1 and 2 versus high sensitivity in leg 1 and low sensitivity in leg 2	2 versus 6
EFFECT OF INTENDED TRACK	
Centerline track versus quarterline track with high sensitivity ranges in legs 1 and 2	1 versus 4
EFFECT OF TURN ANGLE	
High sensitivity ranges in legs 1 and 2 with a 35-degree turn versus high sensitivity ranges in legs 1 and 2 with 15-degree turn	1 versus 5

of performance off the range. It is expected pilots will have difficulty finding and maintaining the quarterline so performance will be better in scenario 1 when the pilot is trackkeeping on the range.

3. Effect of Turn Angle. Scenario 1 will be compared with scenario 5 which differs only in the angle of turn. Scenario 5 will have a 15-degree turn. If a general finding of the experiment is that ranges are inadequate for turning, the more gradual turn may find a limit to this inadequacy: the ranges may be adequate for more shallow turns.

The wind and current effects were planned for the 35-degree turns as illustrated in Figure 1. This means for the 15-degree turn the wind and current in leg 2 are closer to following and provide a less difficult piloting problem. The 15-degree turn is, therefore, easier because it is a less abrupt turn and because there is less crosswind and crosscurrent. The difference is appropriate for this experiment since it compares turning from range to range with a difficult and with an easy turn.

This is the first time a 15-degree turn has been included in an experiment conducted on the USCG/EA simulator. The 15-degree turns at CAORF[11] were developed differently: the wind and current were changed at the turn so that leg 2 always had the same crosswind and crosscurrent effects. The 15-degree turn here is easier than at CAORF.

[11]M.W. Smith and W.R. Bertsche, op. cit., August 1980.

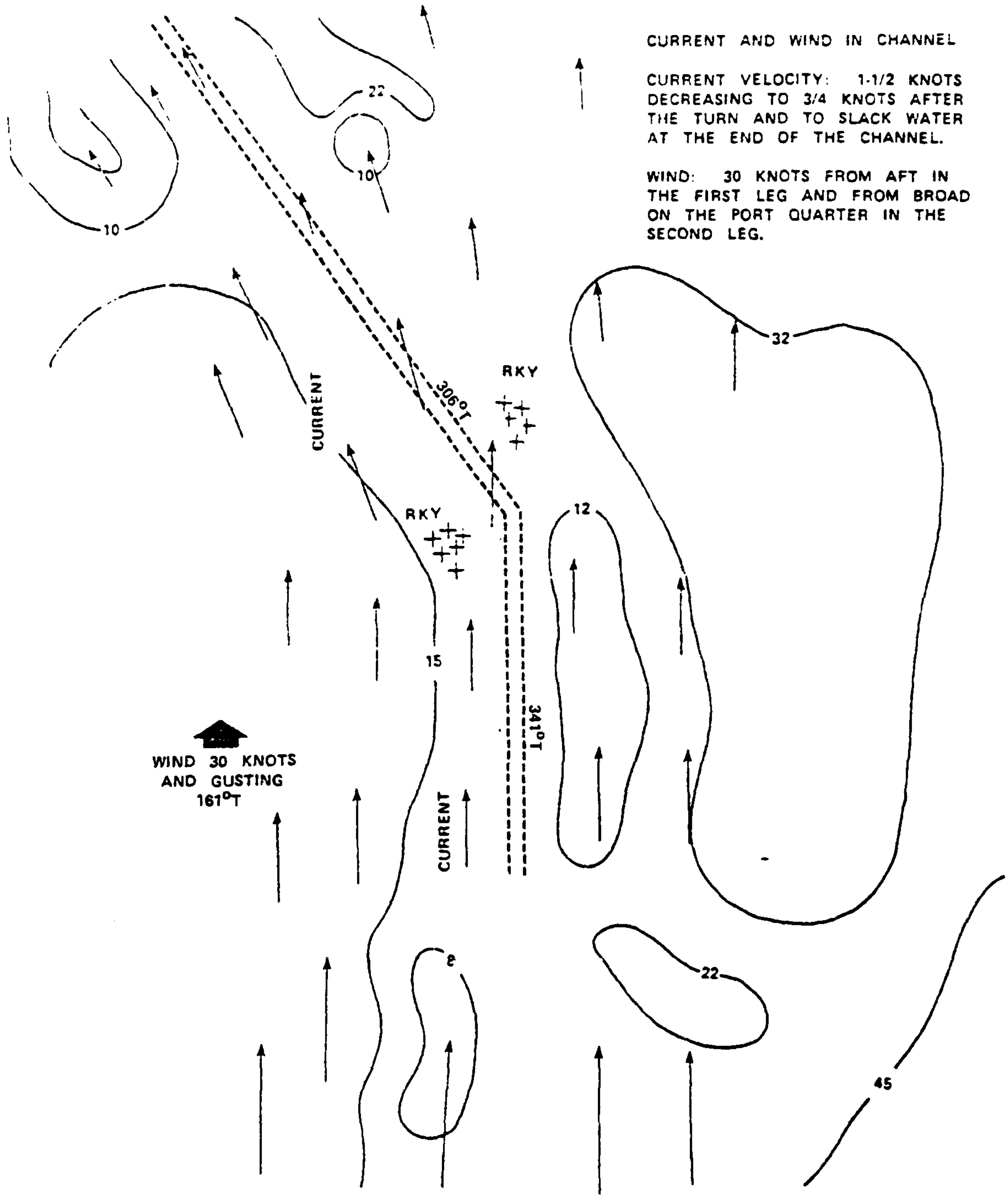

Figure 1. Current and Wind in Channel

1.3 CONDITIONS CONSTANT TO ALL SCENARIOS

The experimental comparisons of interest are made in a context of appropriate constant conditions. The comparisons among the experimental conditions are specific to the constant conditions and might not show the same differences if the constant conditions were changed. Therefore, it is necessary to use the same care in the selection of the constant conditions as in the selection of the experimental conditions. The constant conditions chosen here are similar to those that appeared as constant or varied in previous experiments. This similarity maximizes comparability between experiments. The selected conditions are summarized in Table 4.

1. The Channel Dimensions. The scenarios contain two channel legs that are connected by a turn. The channel is 500 feet wide and was chosen after the Channel Width experiment[12] demonstrated that this width, rather than the wider width to which it was compared, requires greater reliance on the channel marking. One foot of clearance under the ship was necessary to obtain the planned maneuverability.

2. Environmental Conditions and Visual Scene. The scenarios are run at night with unlimited visibility to allow optimal performance with range lights. The current and wind follow patterns similar to that used in the Channel Width and identical to that in the Ship Variables experiment.[13] The wind is following in the first leg and broad on the port quarter after the turn, with some variation in direction. The wind speed is 30 knots with some variation. The current, too, is following in the first leg and broad on the port quarter after the turn. It decreases in velocity from 1-1/4 knots at the beginning of the scenario to 3/4 knots after the turn to zero at the end of the run.

3. Ship Characteristics. The ship is a 30,000 dwt tanker with a split-house configuration and a viewing point located 75 feet forward from the ship's center of gravity. It has a 595-foot length overall, an 84-foot beam, a 45-foot height of eye, and a 34-foot draft. To be consistent with the previous experiments,[14,15] the ship transiting speed is 6 knots.

4. The Bridge Conditions. The pilot has available the following:

- A helmsman to receive his orders.
- A gyrocompass, a rudder angle indicator, and an rpm indicator.
- An engine order telegraph (with the opportunity to increase speed in the turn).

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[12]M.W. Smith and W.P. Bertsche, op. cit., January 1981.

[13]W.R. Bertsche, D.A. Atkins, and M.W. Smith, op. cit.

[14]Ibid.

[15]K.L. Marino, M.W. Smith, and W.R. Bertsche, op. cit.

TABLE 4. CONSTANT CONDITIONS

1. Channel Dimensions: • 500-foot width • 35-foot depth • Noncutoff turn configuration
2. Environmental Conditions: • Unlimited visibility • Nighttime • Current and wind varying over scenario
3. Ship Characteristics • 30,000 dwt tanker • 45-foot height of eye • Midship wheelhouse • Transit speed at 6 knots
4. Bridge Conditions: • Helmsman • Engine order telegraph • Gyrocompass, rudder angle indicator, rpm indicator • Chart
5. Visual Scene: • Outline of ship's bow with short jackstaff • Black sea and sky; no demarcation • Nonflashing green range lights
6. Performance Requirements: • Move to designated track following current • Align ship to turn • Make turn • Stabilize ship after turn with decreasing crosscurrent • Maintain channel designated track with decreasing crosscurrrent • Charts of the channel with the course and range locations. • A diagram of the current conditions. • No radar. (This is an experiment in visual piloting.)

5. The Visual Scene. The outline of the bow was visible with a shortened jackstaff so ranges are not obstructed. Past experiments demonstrated the usefulness of the bow and jackstaff for piloting so their inclusion makes performance comparable to that in earlier buoy experiments. The ranges appeared as nonflashing green lights which showed up against a black sea and black sky.

6. The Performance Requirements. The piloting tasks the pilot is instructed to perform are illustrated in Figure 2. The ship was initialized 1.3 nm below the turn and 92 feet to the right of the centerline. At that point there was a following current which decreased from 1.5 knots and a following wind of 30 knots and gusting. The pilot

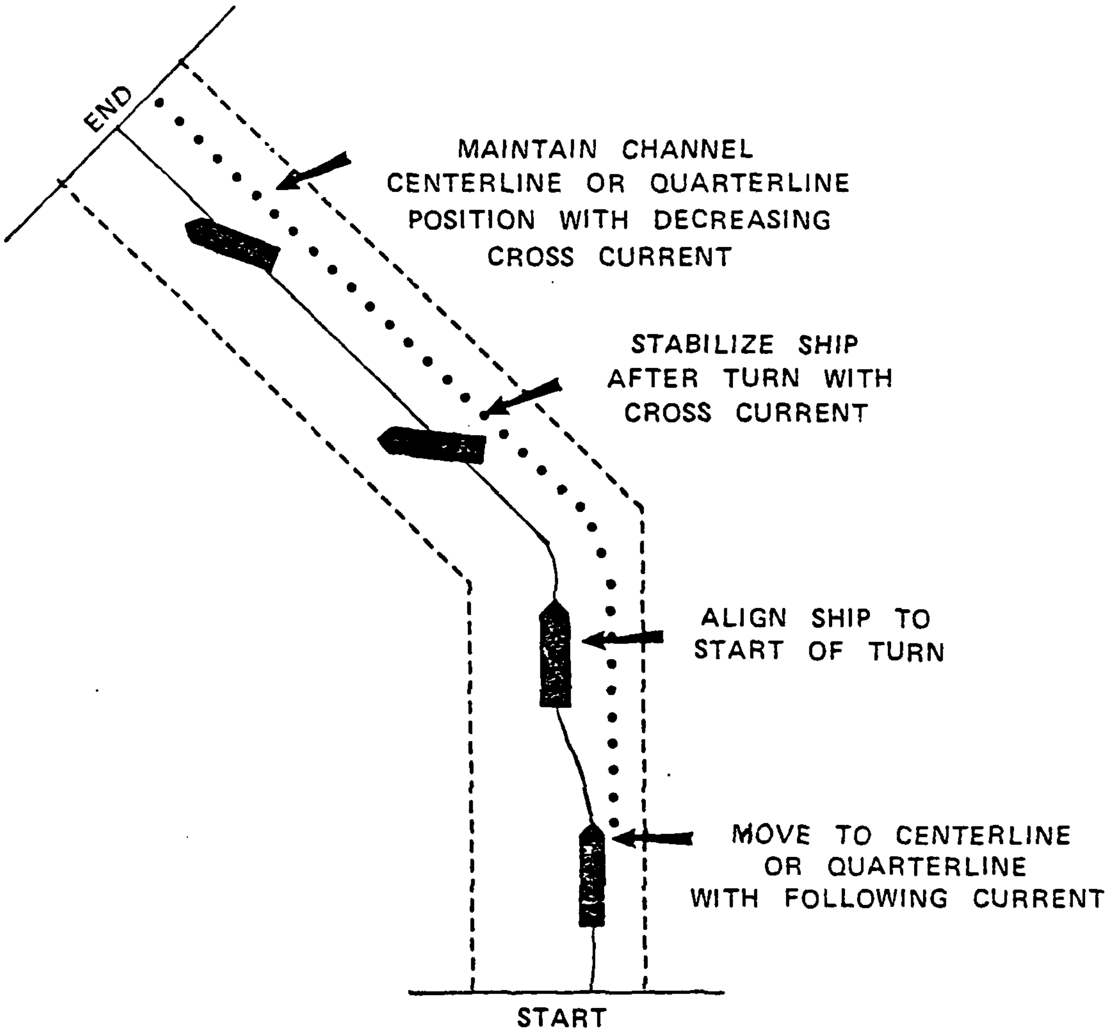


Figure 2. Performance Requirements

was instructed to take the ship to the designated trackline. He could leave that trackline when ready to negotiate the turn by his own strategy. He was asked to return to the designated track in the next leg as soon as possible. As he entered the new leg, the wind and current were broad on his port quarter. Given the current velocity of 3/4 knots and his speed through the water of 6-1/2 knots, he needed a drift angle of 3 degrees to maintain the course of the channel. As he attempted to return to the designated trackline, the current velocity, and the necessary drift angle decreased. The wind remained the same in direction and average intensity throughout the run. The instructions to the pilot and the postsimulation questionnaire appear as Appendix D. The wind and current effects are described more specifically in Appendix E.

1.4 DATA COLLECTION AND ANALYSIS

1.4.1 Data Collection

A variety of performance measures were collected for use in evaluating the scenario conditions. These include:

1. The ship's crosstrack position as a function of alongtrack position. (The graph of this relationship is referred to as a track plot.) A variety of related dependent variables are also recorded. When the ship crosses the data lines diagrammed in Figure 3 or when the pilot makes the responses described below, the computer records the following measures:

- Time of event.
- Ship's center of gravity position.
- Ship's bridge position.
- Ship's velocity relative to the ground.
- Ship's true heading.
- Rate of turn.
- Rudder angle.
- Course made good.
- RPM of propeller.

2. The subject's course, rudder, and engine orders are recorded with alongtrack position and a variety of other dependent measures.

3. A postsimulation questionnaire allows the subject to comment subjectively on the conditions of each scenario and on his strategies. This questionnaire appeared in the presimulation report cited earlier and formed the basis for the preliminary observations.[16]

[16]Eclectech Associates. "Preliminary Observations of the Range Light Experiment." August 1981.

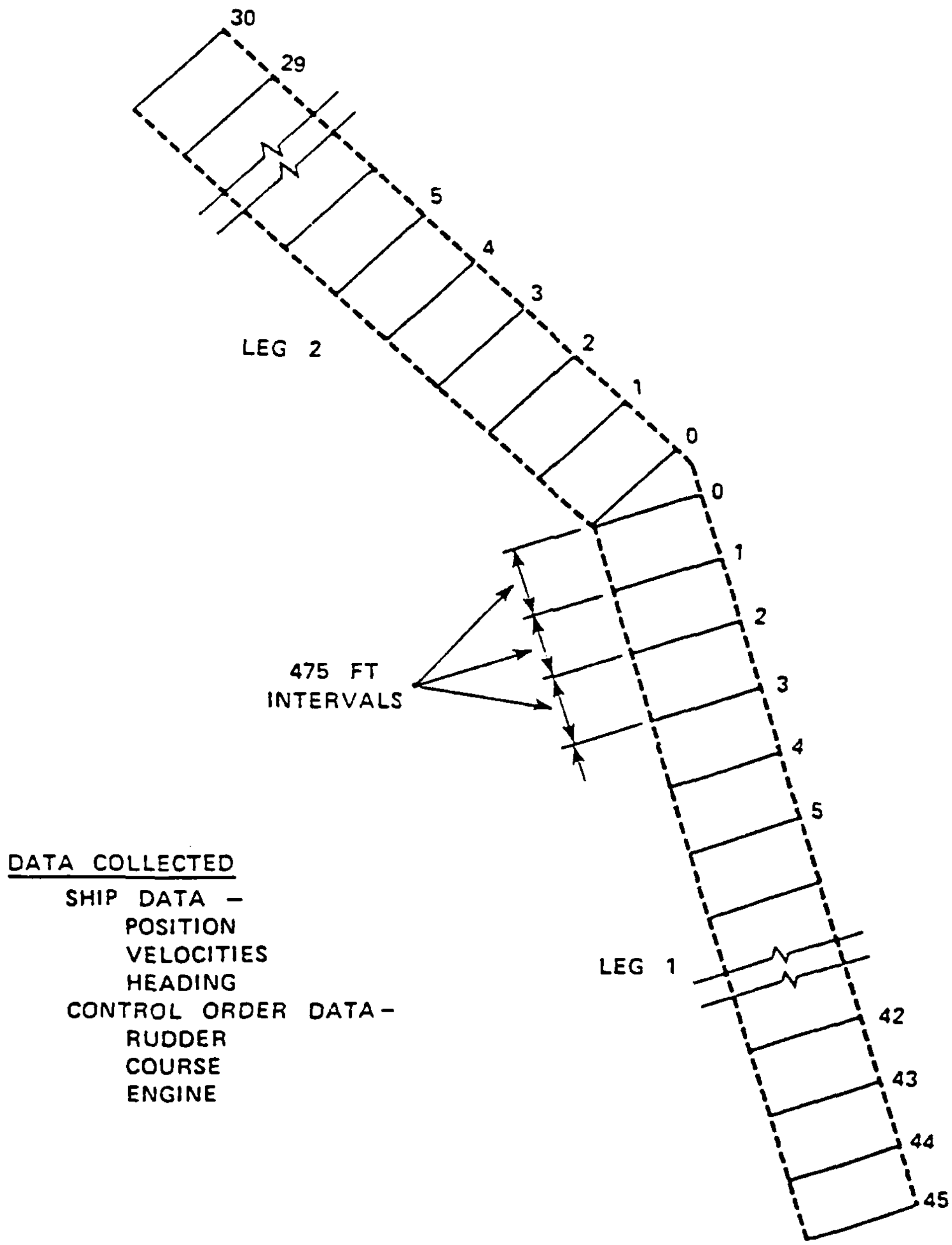


Figure 3. Data Collection Lines

1.4.2 Descriptive Analysis of the Data

The principal descriptive analysis is a compilation of data on the position of the ship's center of gravity. The basic measure of the ship's crosstrack position is treated as illustrated in Figure 4. The mean and standard deviation are calculated at each data line for the set of conditions to be described. The first set of axes shows the means; the second, the standard deviation. On the last axes is a "combined plot" which shows the band formed by the mean and two standard deviations to either side of it against the boundaries of the channel. The band encloses 95 percent of expected transits under the experimental conditions sampled. The placement (mean) and width (standard deviation) of this band within the boundaries of the channel are together a quantitative description of the set of transits under these conditions, and, therefore, of the performance of the range arrangements.

The trackkeeping portions of the scenario are the easiest to interpret. It is assumed that, because of instructions, the pilots are attempting to keep the ship on the designated track. The distance of the mean off either the centerline or the quarterline and the spread measured by the standard deviations are indications of the performance of the range configuration for the conditions sampled. Therefore, the best range configuration is one that puts the mean of the distribution on the designated track and minimizes the standard deviation. Performance in the maneuvering portions is more difficult to interpret. The distribution of crosstrack portions contains the variations in pilots' strategies as well as the performance of the ranges in guiding them in those strategies. An adequate range configuration should keep the combined plot well inside the channel.

There is an assumption in this discussion that the precision in piloting performance afforded by buoy configuration is related to the safety of that channel: a safely marked channel is one that results in a distribution of transits that is well within the channel boundaries for both trackkeeping and maneuvering. It should be reemphasized that these measures are derived from an experiment and not a real-world situation. They are measures of performance under the experimental conditions (the experimental design and the simulation) used. For application to real-world channels, they must be considered relative measures of the performance of range configurations of channel conditions. The interpretation of these performance measures as probability of grounding, for example, would be incorrect pending validation of such interpretation in the real world.

1.4.3 The Inferential Tests

The experiment cannot be analyzed with any single inferential procedure for the following reasons.

1. Each comparison is logically a separate experiment.

2. To adequately describe the data (the crosstrack position of the ship's center of gravity) requires both the mean and the standard

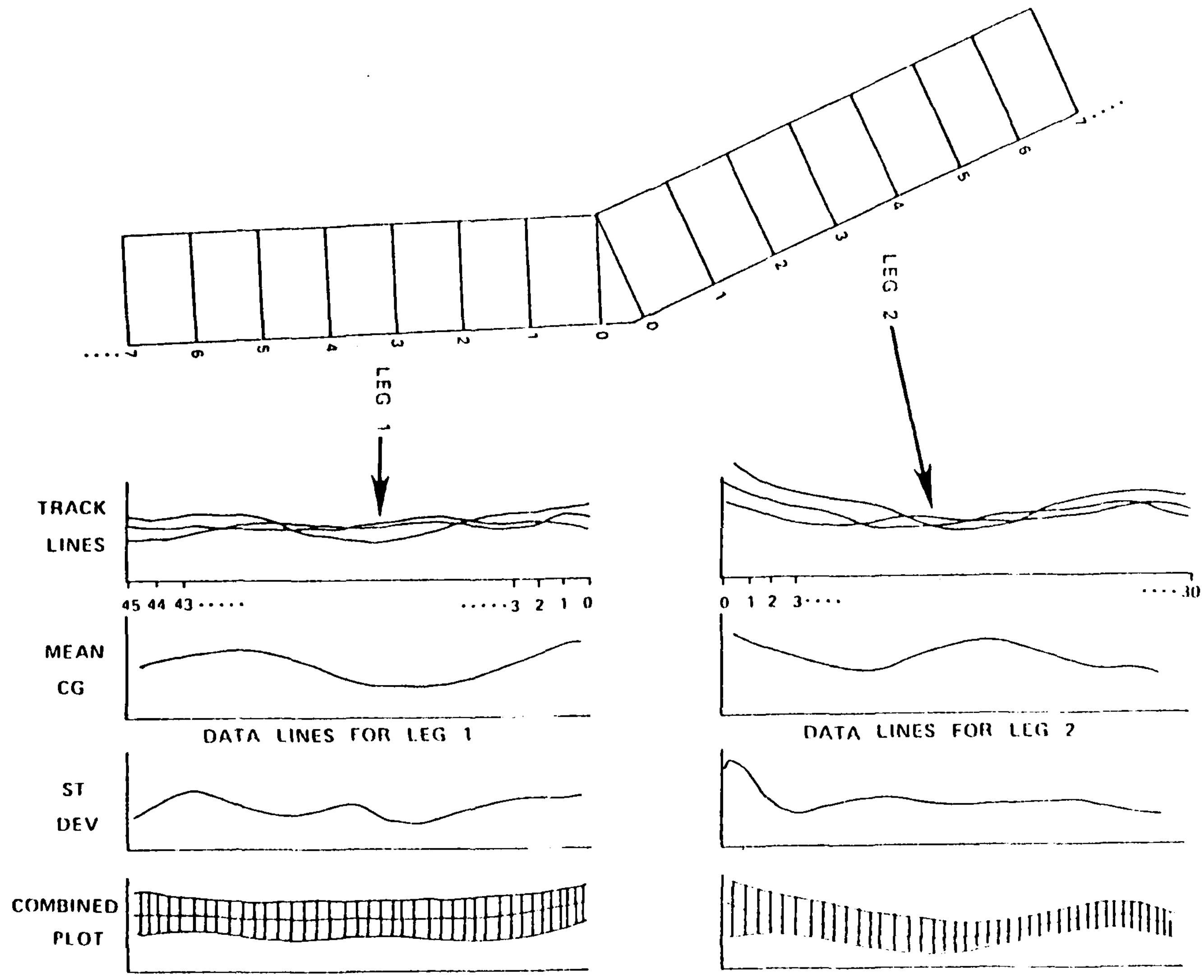


Figure 4. Descriptive Analysis of Ship's Center of Gravity Data

deviation (or variance), and these must be calculated at each data line over the scenario.

Instead, for each separate comparison the mean and standard deviations for each component scenario will be selected at critical data lines and tested for the significance of their differences by the following procedures which are described in McNemar.[17] When means from two conditions are to be compared, a t-test will be used. The standard deviations of the conditions will be compared in pairs dictated by the logic of the comparisons. They will be compared as variances, using variance ratios, or an F-test.

[17]Quinn, McNemar. Psychological Statistics, Fourth Edition. John Wiley and Sons, Inc., New York, 1969.

Section 2

PERFORMANCE AS A FUNCTION OF RANGE SENSITIVITY

2.1 OVERVIEW

Various range light sensitivities were compared to evaluate their effect on piloting performance. These were:

- High sensitivity ranges marking both legs
- Low sensitivity ranges marking both legs
- A high sensitivity range marking leg 1 and a low sensitivity range marking leg 2

Results of the experiment show a high sensitivity range is an effective aid to navigation for trackkeeping, that is, for finding and maintaining the marked track in the channel. However, for turning maneuvers of 35 degrees or larger, range configurations marking only straight legs are not adequate aids to navigation regardless of sensitivity. Pilots had difficulty turning and lining up on the range in the second leg.

Piloting performance was consistently worse with low sensitivity ranges. Pilots, however, generally did not perceive this and believed they performed better with the low sensitivity ranges. The low sensitivity range masked ownship's true crosstrack position since the horizontal separation of the lights was not detectable until the ship was 40 to 60 feet off the centerline.

Piloting performance was not improved in the turn by arranging a high sensitivity range for leg 1 and a low sensitivity range for leg 2.

2.2 EFFECT OF HIGH SENSITIVITY RANGES ON PILOT PERFORMANCE

Scenario 1, shown by Figure 5, has two high sensitivity ranges marking the channel. These ranges enable the pilot to detect small horizontal separation of lights which represent the crosstrack movement of the ship of as little as 2 to 6 feet off the range. Scenario 1 has the standard 35-degree turn which has been used in all USCG/EA simulator experiments. Since this scenario has variables common to the other scenarios, it will be the baseline to which the other scenarios will be compared.

Piloting performance for scenario 1 is plotted by Figure 6. The plots are shown as continuous linear plots with the bend at data line 0. The first plot depicts the mean track, the second plot depicts the standard deviations in the crosstrack direction, and the third plot combines the mean ± 2 standard deviations. This envelope encloses 95 percent of the expected transits under the experimental conditions sampled. Data are plotted for every data line where data lines are 475 feet or 5/64 nm apart.

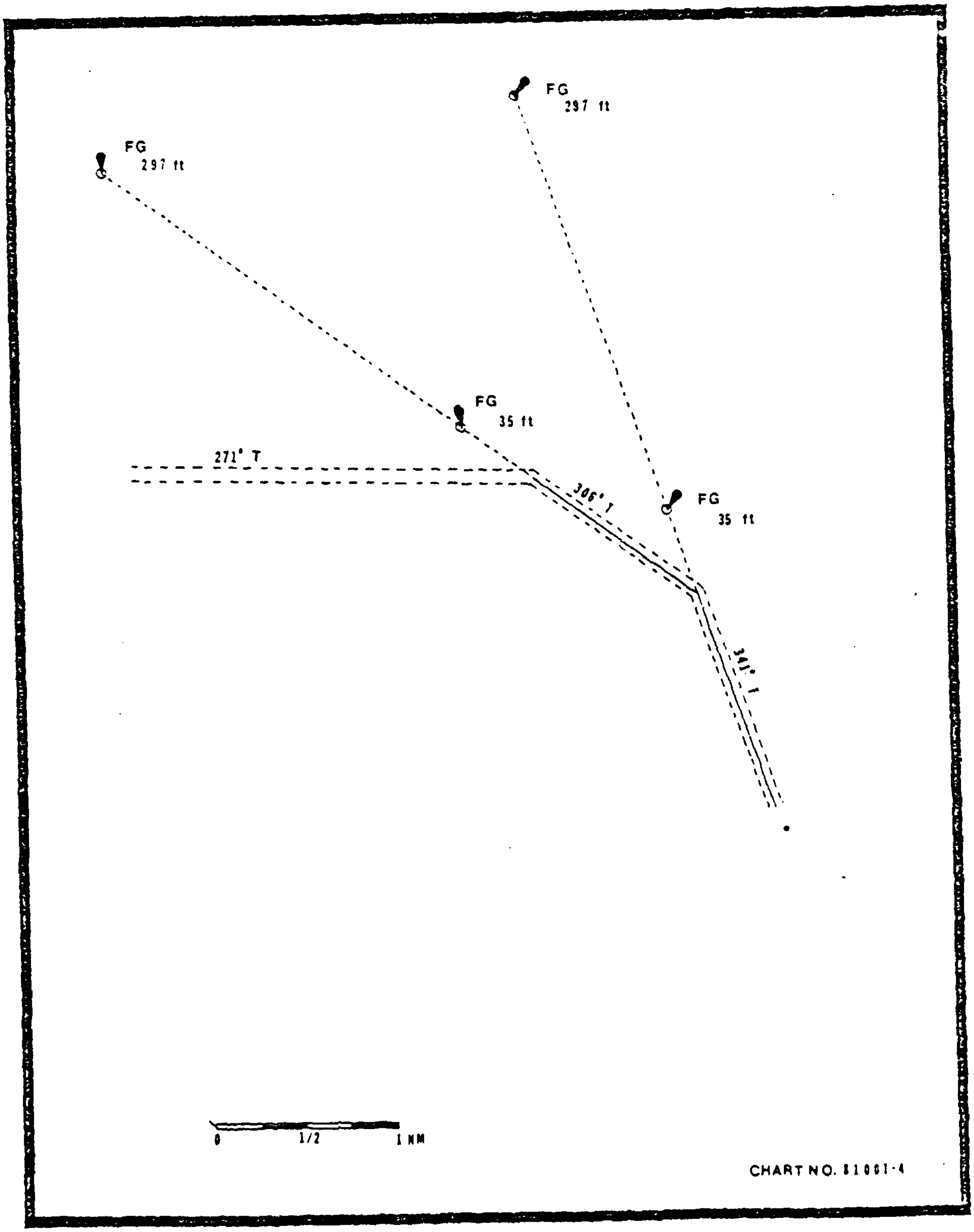


Figure 5. Scenario 1: Two High Sensitivity Ranges

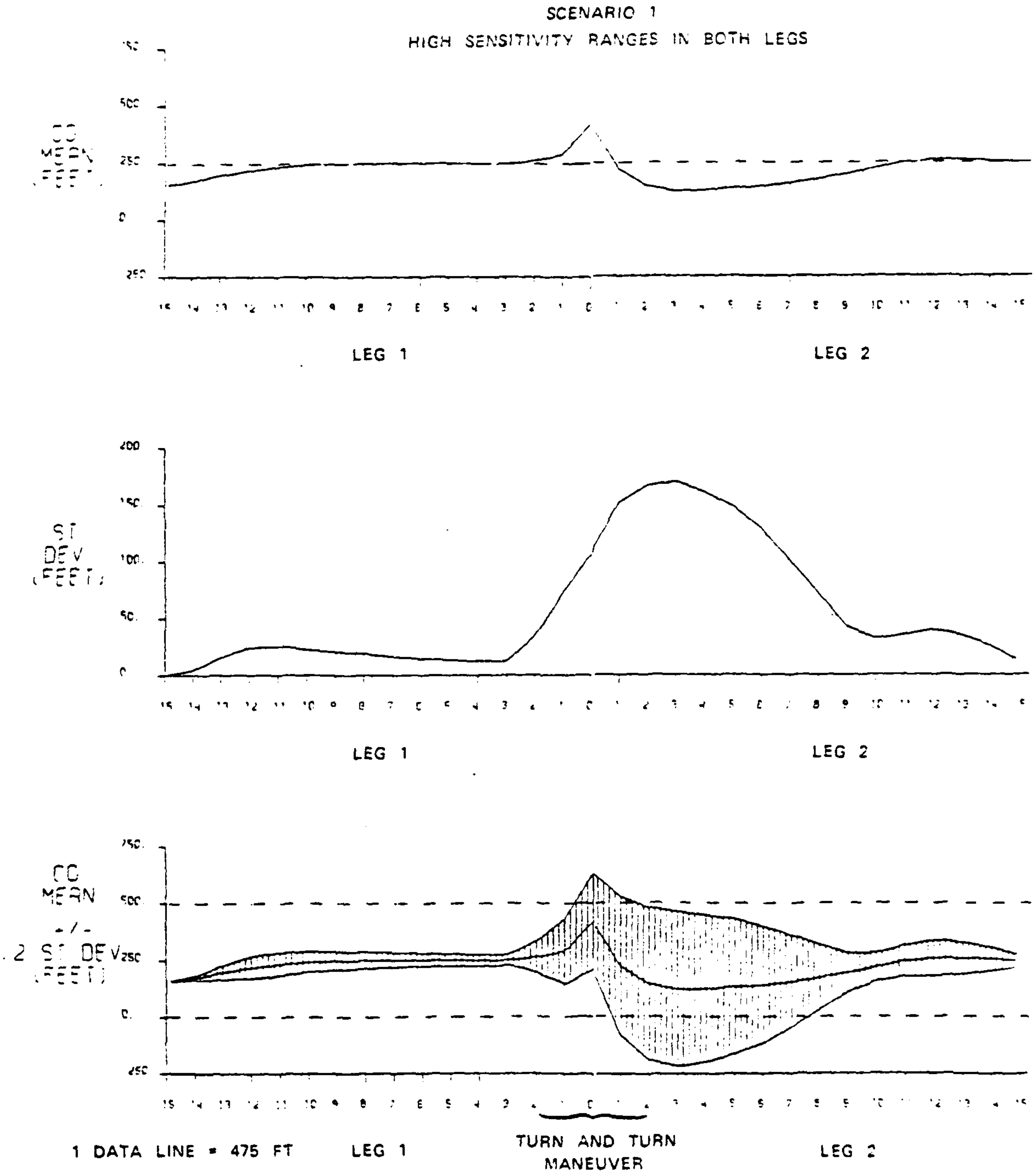


Figure 6. Combined Plots of Piloting Performance for High Sensitivity Ranges - Scenario 1

Figure 6 shows in leg 1 with a following wind and current, pilots had no difficulty maneuvering onto the range axis so trackkeeping was excellent. This is illustrated by the mean track located on the centerline from data lines 10 to 3 and the standard deviation which was no larger than 20 feet.

It appears for turns of 35 degrees or larger, range light configurations marking only the channel axes are not adequate aids to navigation regardless of sensitivity. Figure 7 shows unsatisfactory turn performance since the mean track comes close to the corner with some tracks actually cutting the corner. The bottom "combined mean and standard deviation plot" of Figure 6 shows the turn was initiated as early as data line 3 (indicated by the increasing standard deviation) and recovery from the turn continued through data line 9. Turn initiations beginning at data line 3 or 1425 feet before the turn were too early and resulted in the mean track swinging to the left at the turn apex. Due to either overcorrection for being to the left of the range or wind effects, the ship tracks were set sharply to the right following the turn.

Piloting techniques for making the turn varied. Several pilots used the clock as a cue to prepare for the turn, then tried to visually determine when the range was 35 degrees off the ship's course before initiating the turn. Another strategy was to watch the rate of closure of the range lights in leg 2. If the rate of closure was fast, the pilot gave a hard rudder order and when the rate of closure was slow, the rudder was eased over. Another strategy was a trial and error method which compared this run to others previously made since turns were either too early or too late.

Pilot performance in leg 2 was unsatisfactory because it took 4275 feet or 0.7 nm to recover from the turn and establish a track on the range axis. The maximum overshoot of the mean occurred at data line 3 and was 131 feet to the right of the centerline with a standard deviation of 170 feet. After this point, the tracks gradually merged toward the centerline.

Although the pilots agreed the range marking leg 2 was adequate for finding the centerline, several stated they had difficulty staying on the range due to the set and constant movement of the high sensitivity range. This concern for lining up on the range is reflected in their performance. Most pilots stated their technique for steadying up in leg 2 was to crab in the channel with the bow on the left side of the range and come up on the channel at an angle to allow for set. Several pilots attempted to come in on the high side, then steer heavily back on the centerline holding leeway throughout the transit. These tracks were very close to the right boundary.

Since the high sensitivity ranges provide the most accurate information possible with range lights, their performance can be compared to a scenario from an earlier experiment[18] that was marked by

[18] K.L. Marino, M.W. Smith, and W.R. Bertsche, op. cit.

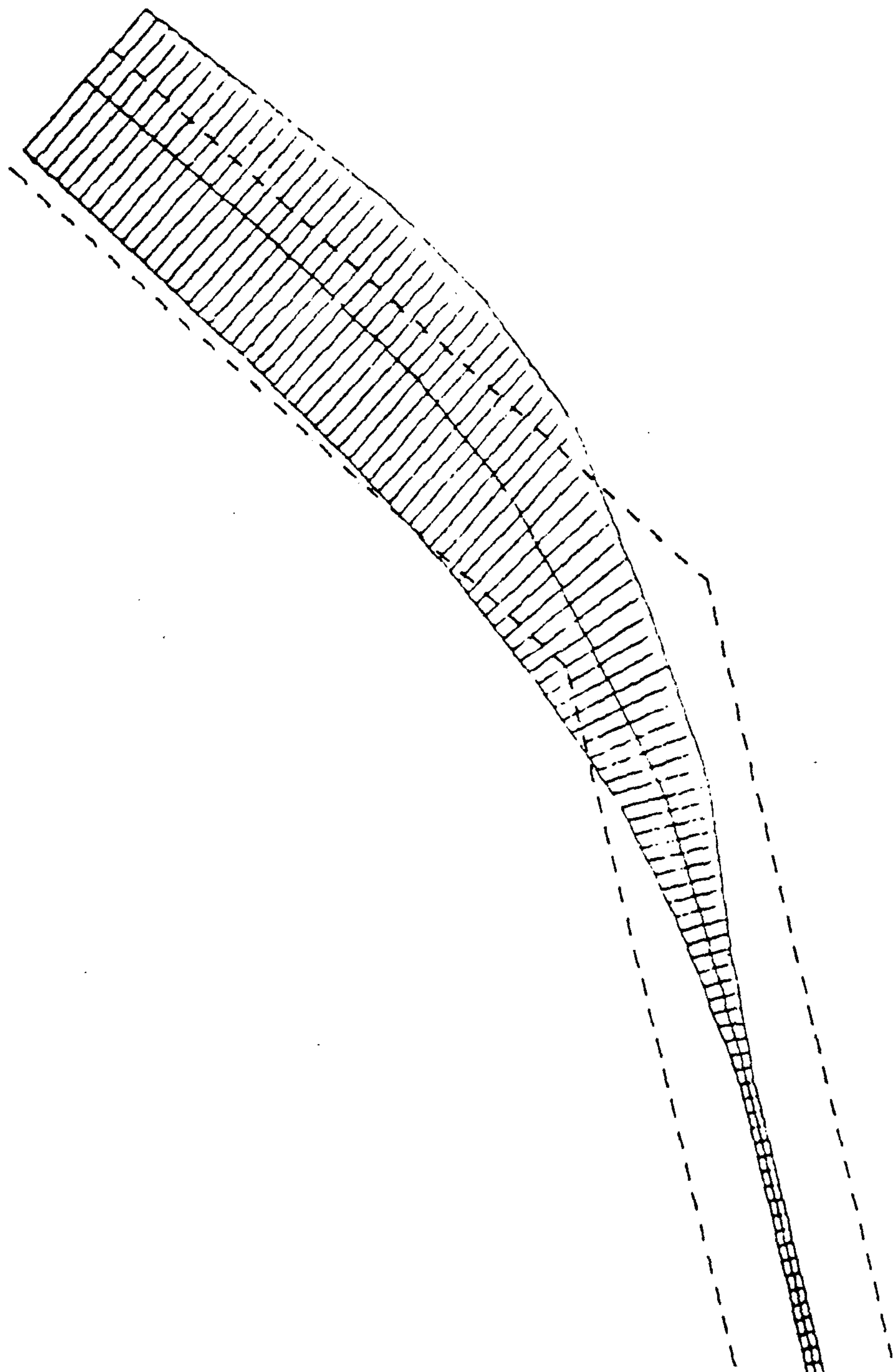


Figure 7. Turn Performance of Scenario 1

long-spaced gated buoys which also provided high density information. Figure 8 shows pilot performance which each aid arrangement, and Table 5 identifies performance differences by indicating maximum crosstrack position data. As can be seen by these, a highly sensitive range is a more effective aid for trackkeeping on an exact track than is a gated buoy configuration. The maximum crosstrack mean and standard deviation of the trackkeeping portions of leg 1 and leg 2 are smaller or equal to that of gated buoys. In the turn region, however, turn buoys yield superior performance.

Several conclusions can be drawn from pilot performance when using high sensitivity ranges. First, a highly sensitive range is an effective aid to navigation for trackkeeping; that is, finding and maintaining the marked track in the channel. Secondly, for turns 35 degrees or larger, range configurations marking only straight legs are not adequate aids. Thirdly, it is possible for pilots to turn range-to-range, however, they cannot do this and stay inside narrow channel boundaries.

2.3 EFFECT OF LOW SENSITIVITY RANGES ON PILOTING PERFORMANCE

Scenario 2, shown by Figure 9, has two low sensitivity ranges marking the channel. The ranges are not very sensitive; the pilot can at best detect crosstrack movement of ship of 23 to 62 feet off the range. Other than range sensitivity, scenario 2 is identical to scenario 1.

Piloting performance for scenario 2 is unsatisfactory as shown in Figures 10 and 11 and is compared to scenario 1 in these figures. The pilot's mean track does not reach the centerline in leg 1 or leg 2. With low sensitivity ranges pilots could only perceive large crosstrack changes in the movement of the ship in relation to the range so they could not accurately determine the ship's position. This is reflected by a continually large standard deviation which does not diminish when wind and current effects are reduced. The plots in Figure 10 show that through half the run (from leg 1 data line 2 through leg 2 data line 11), tracks went out of channel boundaries on both sides, and where tracks stayed in the channel, they were highly dispersed and not near the centerline. This plot shows low sensitivity ranges are not adequate for trackkeeping in a narrow 500-foot channel.

A statistical comparison of low sensitivity ranges (scenario 2) to high sensitivity ranges (scenaro 1) in both mean crosstrack location and standard deviation is shown in Figure 11. These data indicate there are significant differences between the range configurations throughout the transit. These will be discussed by region.

Region 1 shows the simple trackkeeping segment of the run where pilots only needed to find the centerline and steer onto the range with no maneuvering required in a following wind and current situation. At data line 15 the run begins with a 92-foot offset from the centerline. Pilot performance was signficantly superior with the high sensitivity range because from data lines 10 through 3, or for 0.5 nm, the mean track was within 4 feet of the centerline. When the pilots used the low

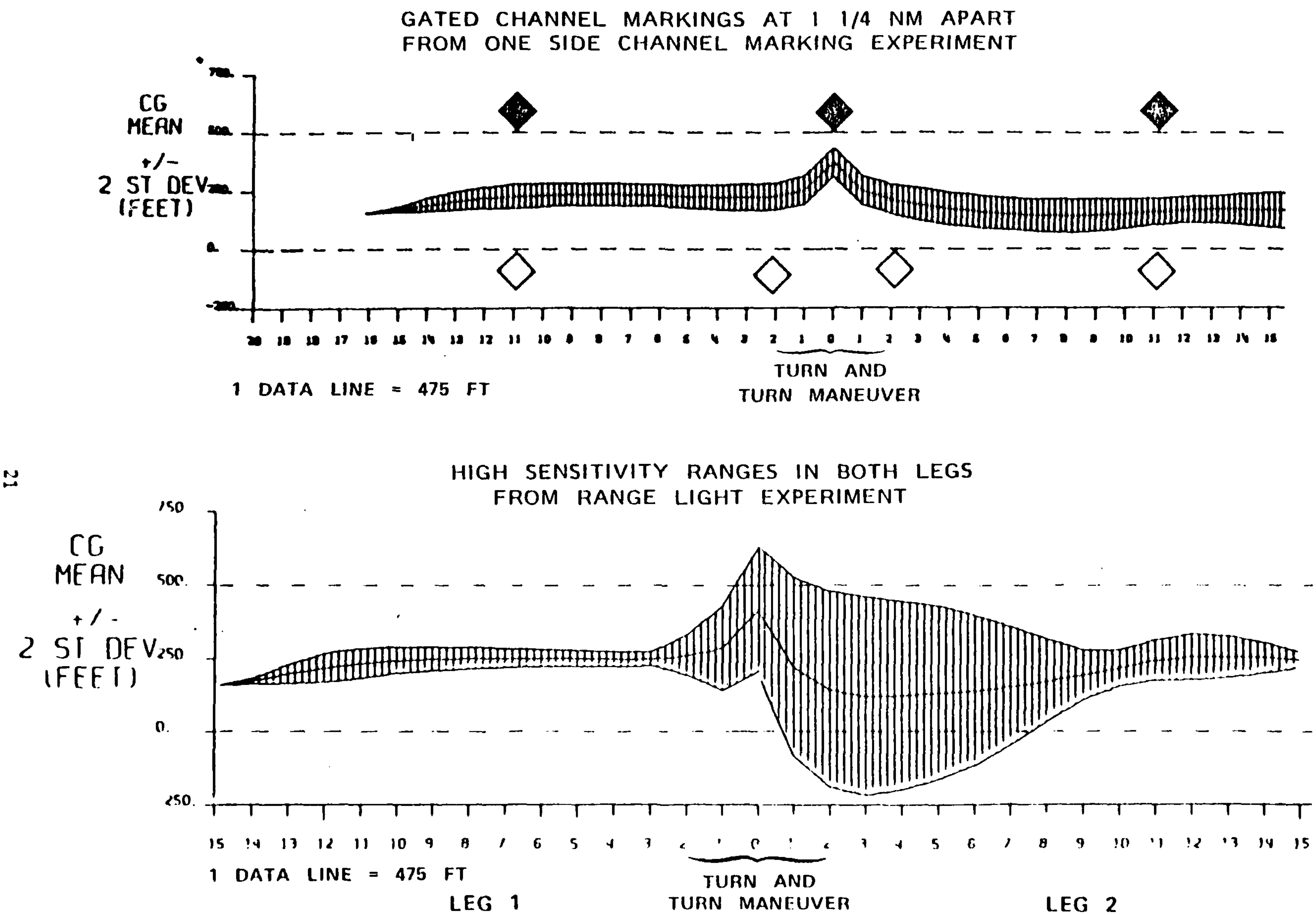


Figure 8. Combined Plots of Piloting Performance for High Sensitivity Ranges Versus Long Spaced Gated Buoys

TABLE 5. COMPARISON OF PERFORMANCE WITH BEST INFORMATION BUOY CONFIGURATION VERSUS BEST INFORMATION RANGE LIGHT CONFIGURATION

MAXIMUM MEAN CROSSTRACK POSITION IN FEET		
Location	Gated Buoys	High Sensitivity Ranges
Leg 1 trackkeeping between data lines 10 to 3	24R	4R
Turn maneuver region between data lines 3 to 3	77R	131R
Turn recovery region between data lines 3 to 10	104R	128R
Leg 2 trackkeeping between data lines 10 to 15	87R	5R
MAXIMUM CROSSTRACK STANDARD DEVIATION IN FEET		
Location	Gated Buoys	High Sensitivity Ranges
Leg 1 trackkeeping between data lines 10 to 3	27	21
Turn maneuver region between data lines 3 to 3	35	170
Turn recovery region between data lines 3 to 10	36	160
Leg 2 trackkeeping between data lines 10 to 15	38	39
R = right of centerline		

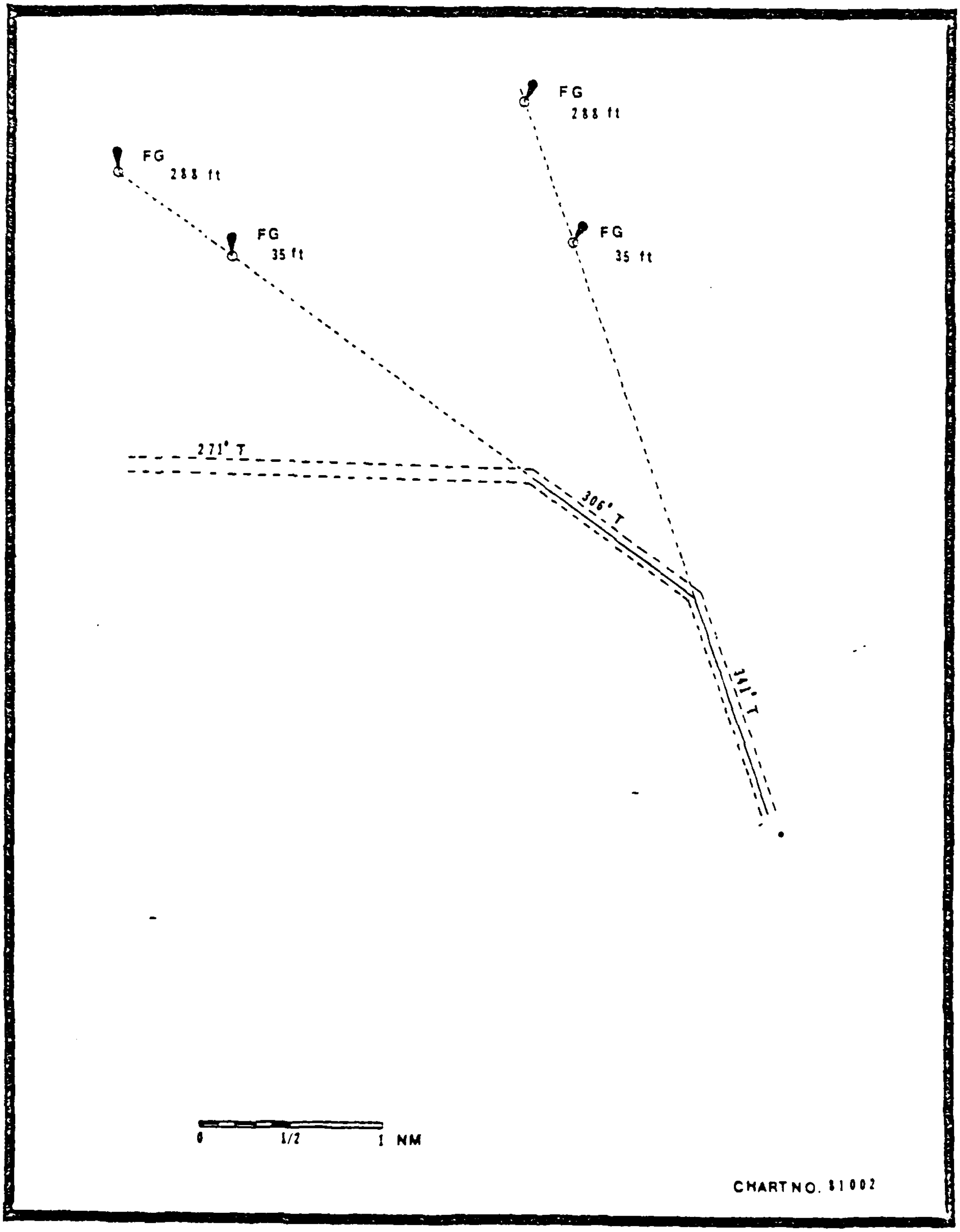


Figure 9. Scenario 2: Two Low Sensitivity Ranges

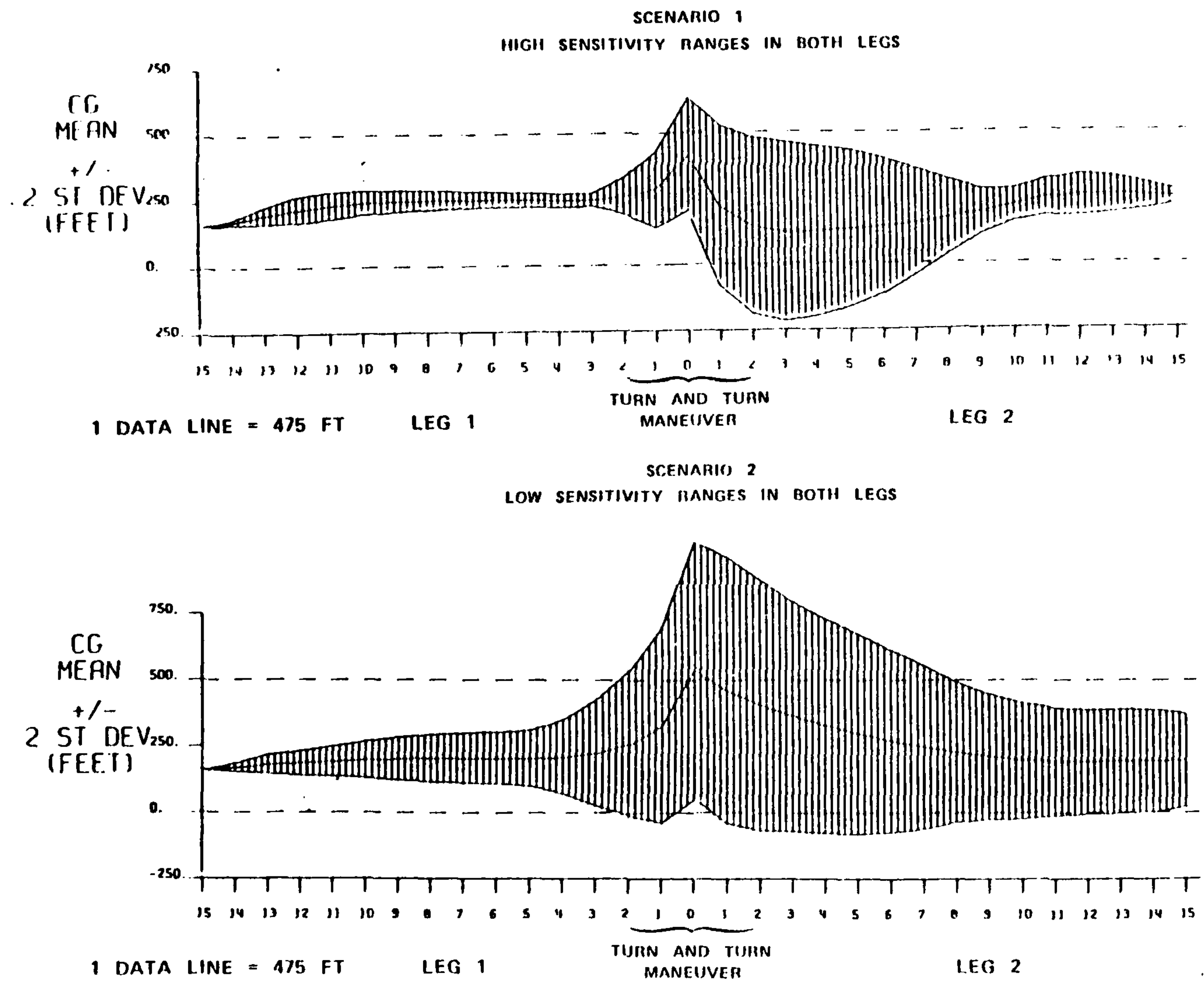


Figure 10. Combined Plots of Piloting Performance with High Sensitivity Ranges Versus Low Sensitivity Ranges

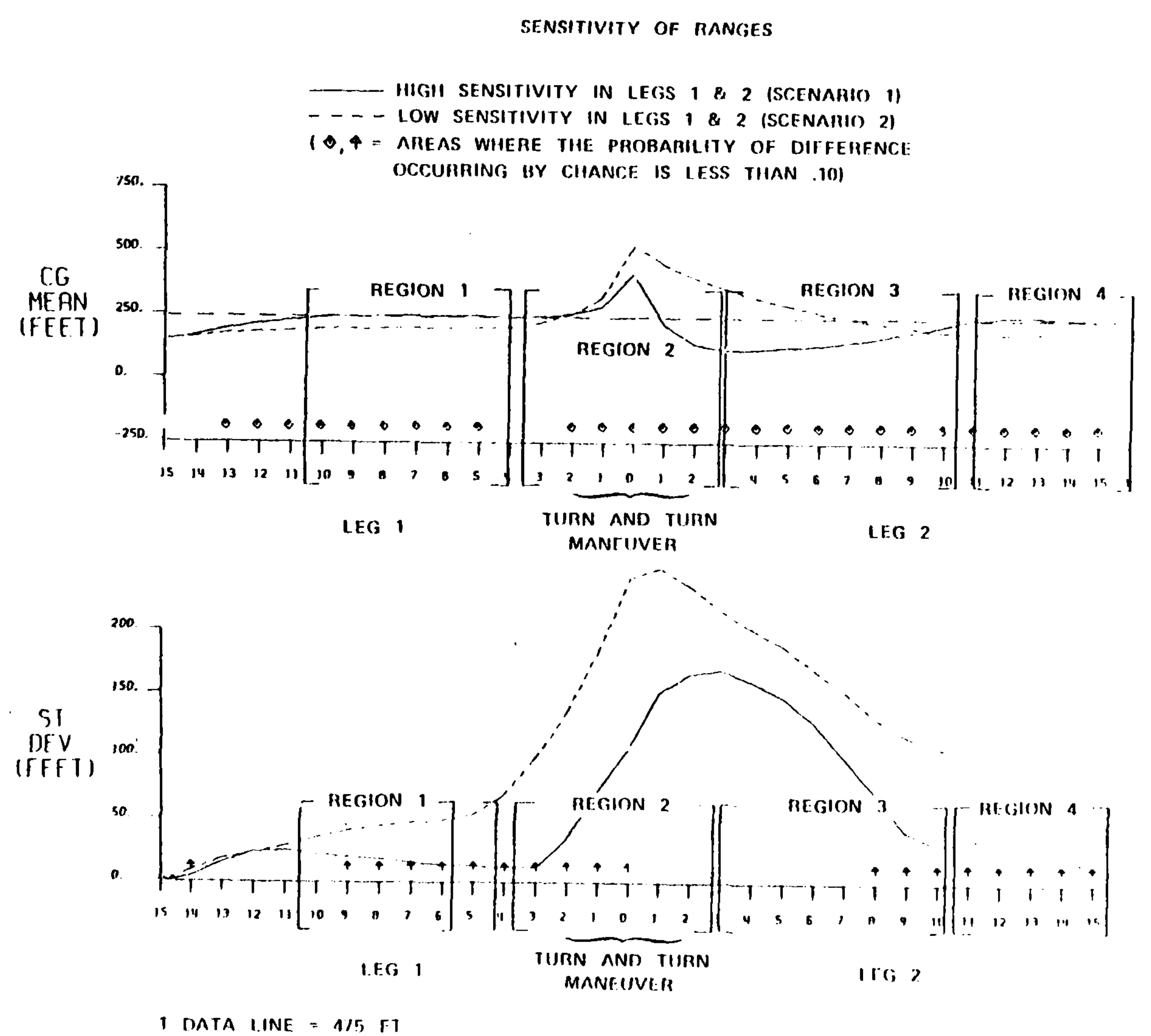


Figure 11. Crosstrack Mean and Standard Deviation of Piloting Performance for Sensitivity of Ranges: High Sensitivity Versus Low Sensitivity

sensitivity range, they also believed they steadied up on the range in this area; however, the mean track was approximately 50 feet to the right of the centerline. Table 5 shows the maximum crosstrack mean and standard deviation for each region. For region 1 the low sensitivity range performance data is more than double that of the high sensitivity data indicating the superior accuracy obtainable with the high sensitivity range. Performance in region 1, however, is acceptable for both range configurations indicating that in a perfect environment where there is no wind and current perturbation, it is possible to use a low sensitivity range to trackkeep in a 500-foot wide channel.

Region 2 of Figure 11 shows the turn maneuver for each range configuration and Figure 12 shows an enlarged plot of the position of combined plot through the turn. Performance and piloting technique are different with each range sensitivity. In the turn, performance is unsatisfactory with both range configurations; however, it was significantly worse with the lower sensitivity range. Here the mean track cut the inside corner and the standard deviation was over 200 feet wide. Table 6 describes the turn maneuver performance for each range configuration with data line 3 in each leg representing the average point where the pilot began turn initiation and where the ship should be returned to the centerline. Table 7 compares the maximum mean crosstrack position and maximum standard deviation in this region. The 208-foot offset of the mean and the 250-foot variance show the noise effect of the low sensitivity range where the ship's distance off the range was masked so pilots were unable to correctly ascertain ship's position.

The low sensitivity of this range configuration becomes further apparent when pilots compared their strategies when using high or low sensitivity ranges. As the pilots transited up leg 1 and watched the second range become closer to 35 degrees off the bow, they concentrated less on the first range and more on the second range. The rate of closure of the second range told the pilot when and how to begin turning. If the range of closure was fast, the pilot gave hard rudder to make the turn quickly and when the range of closure was slow, the rudder was eased over. The higher the range sensitivity, the faster the range closed. Therefore, several pilots believed that with the higher sensitivity range, there was greater certainty as to when to begin the turn. Rudder was put on later, usually hard over and taken off quickly. With the low sensitivity range, the rate of closure was slower so less rudder was applied sooner and taken off later. This explains the mean track being positioned to the left of the channel. The wide standard deviation is a result of uncertainty of when to begin the turn and where the ship was located in the channel.

Region 3 of Figure 11 shows the turn recovery area. Overall the mean track in this region is better with low sensitivity because the maximum mean crosstrack position is at 75 feet to the left as compared to 125 feet to the right for high sensitivity. However, the maximum standard deviation is higher at 202 feet with low sensitivity ranges compared to 160 feet with high sensitivity ranges. This wide standard deviation shown in Figure 10 falls outside channel boundaries for a substantial

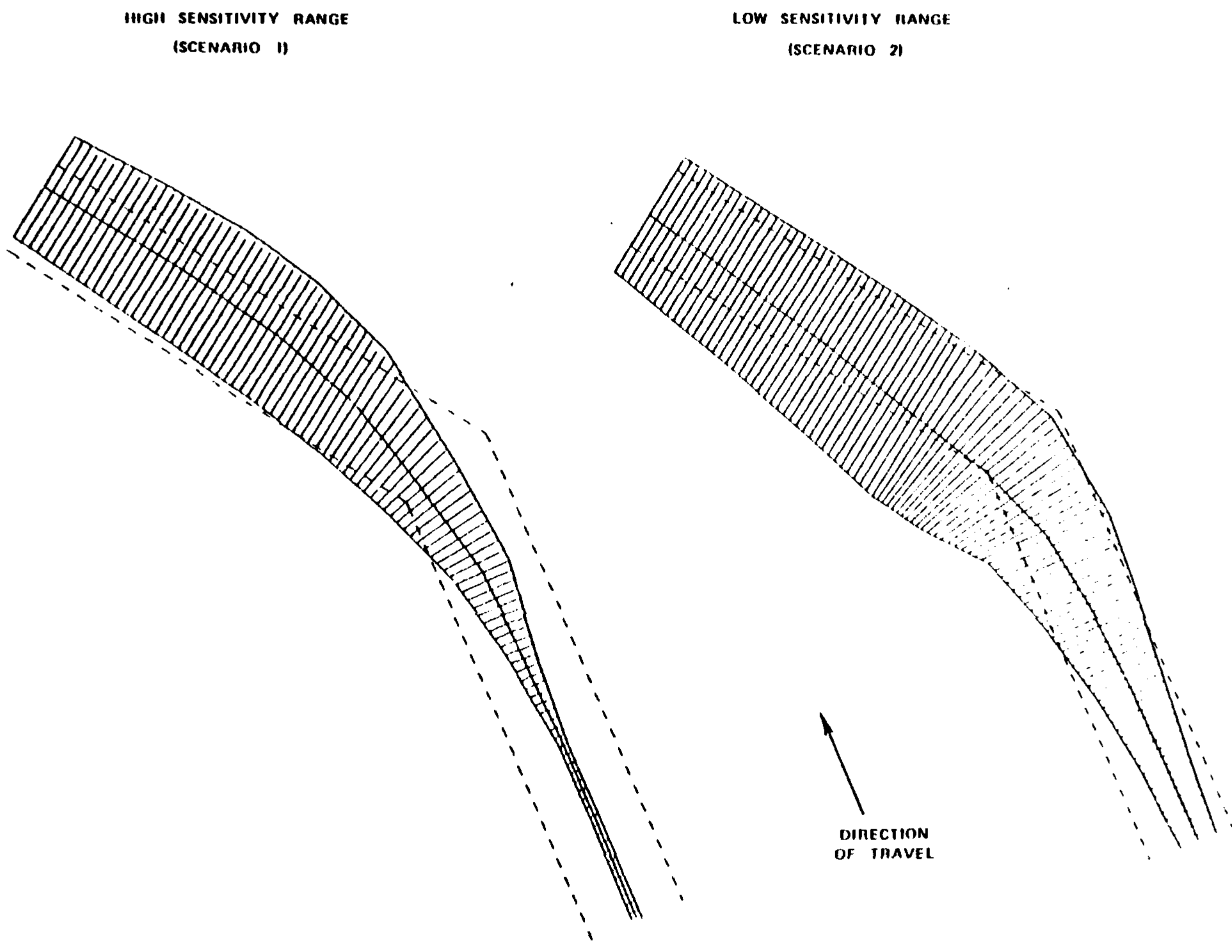


Figure 12. Turn Plots for High and Low Sensitivity Ranges

TABLE 6. TURN MANEUVER ANALYSIS

MEAN (FEET FROM CENTERLINE)		
Location	High Sensitivity Scenario 1	Low Sensitivity Scenario 2
Leg 1 - data line 3	0	26R
Leg 2 - data line 3	132R	110L
STANDARD DEVIATION (FEET FROM CENTERLINE)		
Location	High Sensitivity Scenario 1	Low Sensitivity Scenario 2
Leg 1 - data line 3	11	99
Leg 2 - data line 3	170	217

R = right of centerline
L = left of centerline

TABLE 7. CROSSTRACK PERFORMANCE DATA FOR HIGH VERSUS LOW SENSITIVITY RANGES

MAXIMUM MEAN CROSSTRACK POSITION		
Region	High Sensitivity Scenario 1	Low Sensitivity Scenario 2
1	4R	47R
2	131R	208L
3	128R	75L
4	5R	61L
MAXIMUM CROSSTRACK STANDARD DEVIATION		
Region	High Sensitivity Scenario 1	Low Sensitivity Scenario 2
1	21	70
2	170	251
3	160	202
4	39	100

R = right of centerline
L = left of centerline

distance of 6175 feet (1.02 nm) for low sensitivity ranges as compared to 3325 feet (0.55 nm) for the high sensitivity range.

Region 4 of leg 2 has reduced wind and current, thereby allowing the pilots an opportunity to simply trackkeep on the second range without performing maneuvers. Here it can be seen the high sensitivity range results in excellent performance with small standard deviation and a mean on the centerline. With the low sensitivity range, pilots never returned the ship to the centerline and tracks remained widely dispersed indicating pilots could not accuractly assess ship position.

It can be concluded that the sensitivity of the range determines its effectiveness for finding and maintaining the track. Therefore, a highly sensitive range is more effective than a lower sensitivity range because discrete ship movement is identifiable. Low sensitivity ranges which cannot identify ship movement until it is between 23 to 62 feet off the range are not adequate aids for trackkeeping in a 500-foot channel. A lower sensitivity range might be used to mark a wide channel if it can accommodate nonuniformity of tracks and a dispersion of up to 500 feet to either side of the range axis.

2.4 EFFECT OF COMBINING HIGH AND LOW SENSITIVITY RANGES ON PILOT PERFORMANCE

Scenario 6 shown in Figure 13 has a high sensitivity range marking leg 1 and a low sensitivity range marking leg 2. The range design for each leg is identical to scenarios 1 and 2, respectively. This scenario was included to investigate the possibility that the superior crosstrack information provided by the high sensitivity range in the first leg as the ship approaches the turn will allow for a better turn onto the low sensitivity range than that made in scenario 2. This scenario will, therefore, be compared to both scenarios 1 and 2.

Pilot performance for the three scenarios is shown by Figure 14. Performance resulting from the scenario 6 range arrangement show the high sensitivity range marking leg 1 yields the same superior trackkeeping as that in scenario 1 from data lines 15 through 5. However, as the ship approaches the turn, the standard deviation increases as pilots shift concentration to the second range to prepare for the turn. Turn performance is unsatisfactory since ship tracks cut the corner. Performance in leg 2 appears to be as poor as that in scenario 2.

Statistical comparison of these scenarios in both mean crosstrack location and standard deviation is shown in Figures 15 and 16. Figure 15 compares performance with high sensitivity ranges in both legs to that of high sensitivity marking only the first leg, and Figure 16 compares the performance with two low sensitivity ranges to that of one high and one low sensitivity range marking the same channel.

Pilot performance is similar when comparing trackkeeping segments of each leg marked by like range configurations. Therefore, in leg 1 between data lines 10 to 4, there are no significant differences between tracks from scenarios 1 and 6 since both are marked by a high

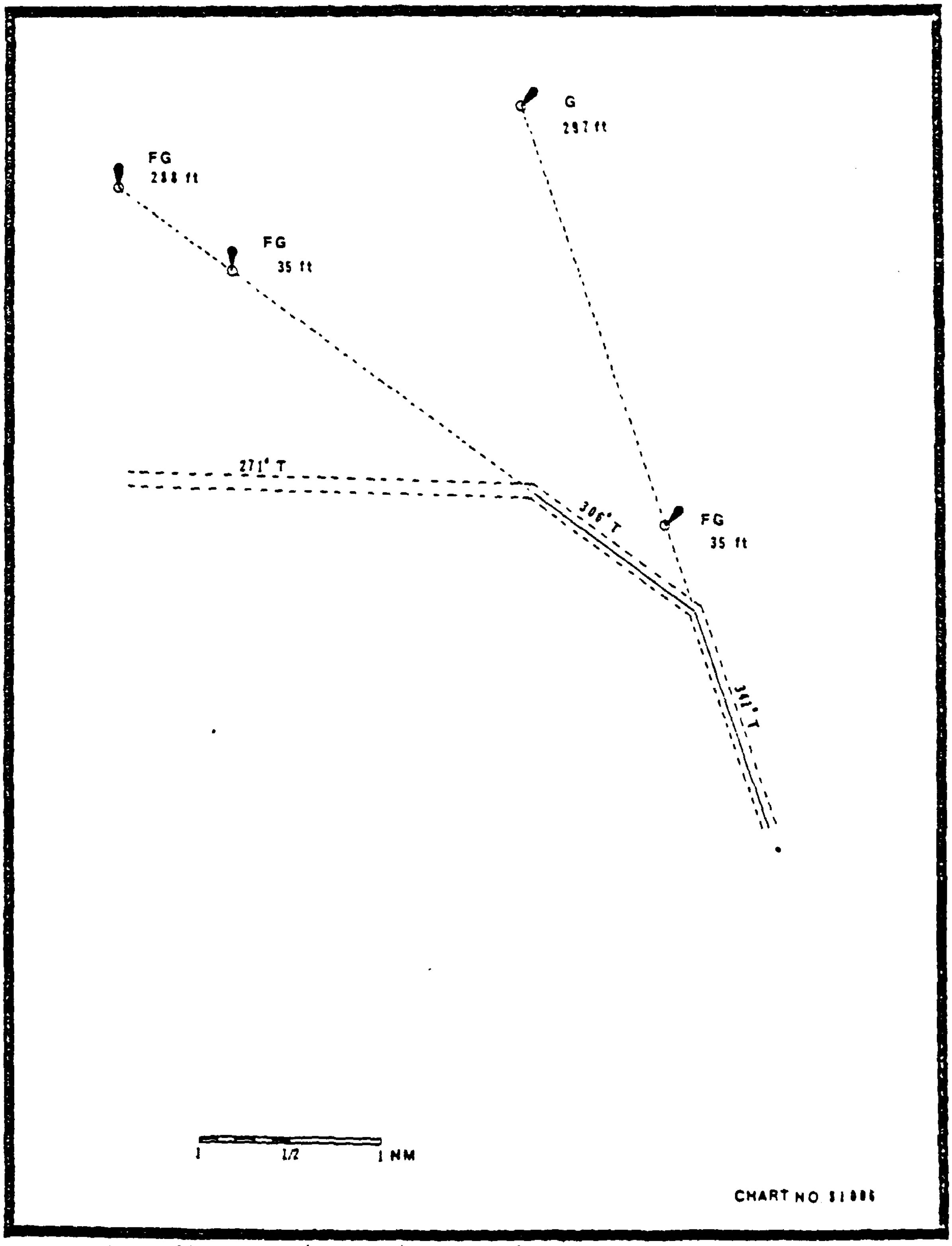


Figure 13. Scenario 6: High Sensitivity Range Marking Leg 1 and Low Sensitivity Range Marking Leg 2

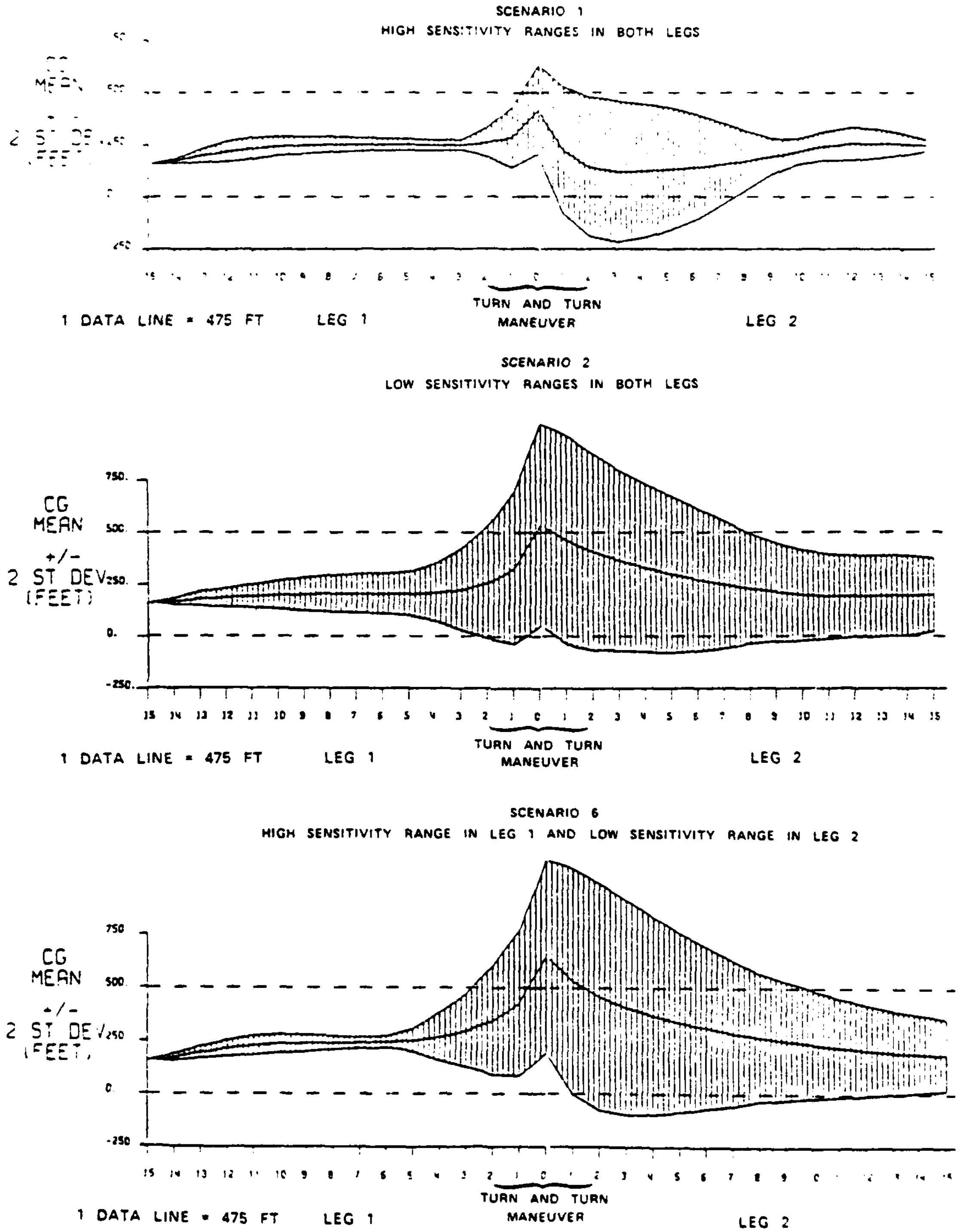


Figure 14. Combined Plots of Piloting Performance with High, Low, and Mixed Sensitivity Ranges

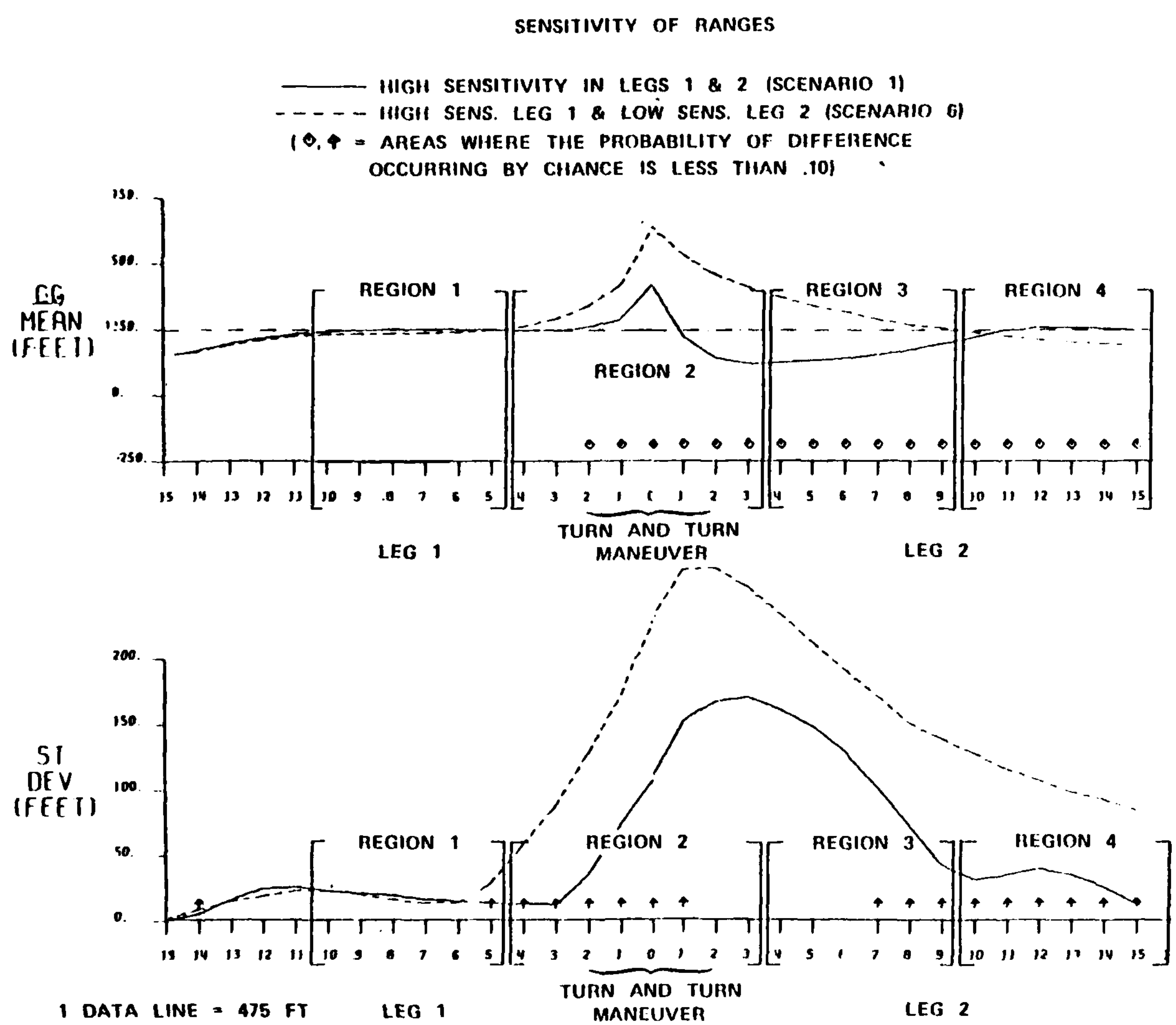


Figure 15. Crosstrack Mean and Standard Deviation of Piloting Performance for Sensitivity of Ranges: High Sensitivity Versus Mixed Sensitivity

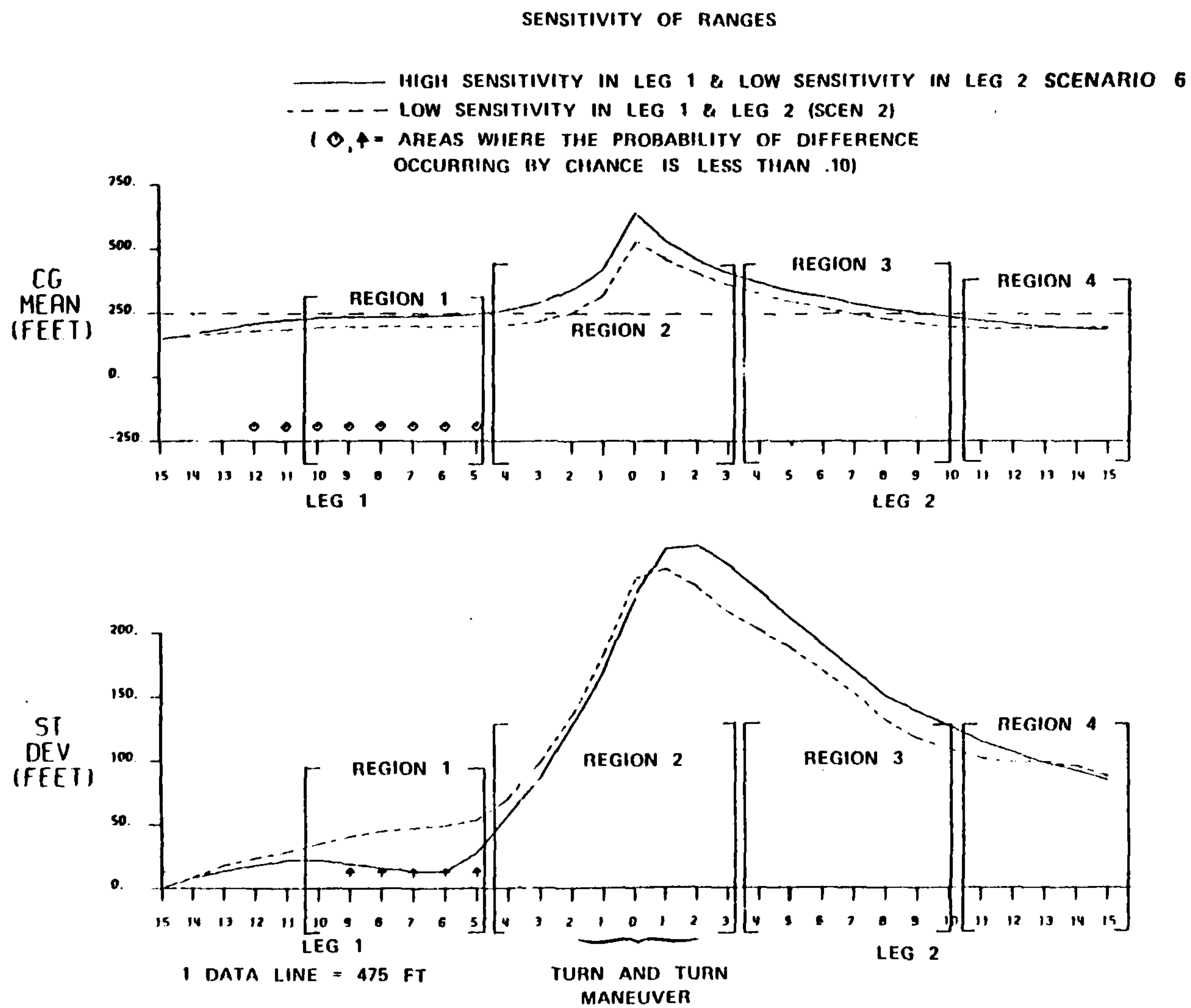


Figure 16. Crosstrack Mean and Standard Deviation of Piloting Performance for Sensitivity of Ranges High Sensitivity Versus Mixed Sensitivity

sensitivity range. Also, there are no significant differences between performance in scenarios 2 and 6 in leg 2, since both are marked by a low sensitivity range. Table 8 shows the maximum crosstrack mean and standard deviation values for these scenarios. The only relevant difference in performance lies in the preparation and recovery for the turn.

By comparing the tracks shown by Figure 15 and the turn plots of Figure 17, it can be seen that the crosstrack information provided by the high sensitivity range in the first leg does not improve turn performance. The mean track of scenario 6 is poorer than scenario 2 since it cuts the corner and remains close to the left channel boundary for 2850 feet. The standard deviation was slightly less when making the turn but was about 25 feet greater through most of leg 2. The higher sensitivity range in leg 1 does not provide additional turnmaking information, because it is the outline of the turn, not the centerline that is important.

The poor performance in the turn shows that when maneuvering, the pilots placed more emphasis on the range marking leg 2 so the high sensitivity range in leg 1 does not improve performance in the turn. Also, it appears that if a lower sensitivity range follows one which had higher sensitivity, pilots continue to navigate as if the second range were of a higher sensitivity. This is verified by the fact that in scenario 6, pilots believed the current did not affect the ship the same as in the other scenario (with high sensitivity ranges in leg 2). It appears the pilot's estimate of the ship's position and of the current were degraded by the low sensitivity ranges, thereby causing a high dispersion of tracks.

2.5 CONCLUSIONS REGARDING RANGE SENSITIVITY

Range sensitivity determines its effectiveness for finding and maintaining a track in the middle of the channel. A high sensitivity range is more effective than a low sensitivity range because it allowed the pilot to identify and compensate for the effects of current. The high sensitivity range is adequate for trackkeeping on the range axis in this 500-foot channel. The low sensitivity range is not adequate for this scenario; however, it could be used to mark a wider channel if the channel can accommodate a wide distribution of tracks.

Although it is possible for pilots to turn range to range, they cannot do this and stay inside channel boundaries of a 500-foot channel. Therefore, for turns of 35 degrees or larger, range light configurations marking only the channel centerline are not adequate aids to navigation regardless of sensitivity.

TABLE 8. CROSSTRACK PERFORMANCE DATA FOR VARIOUS RANGE SENSITIVITIES

Region	High Sensitivity Scenario 1	Low Sensitivity Scenario 2	High and Low Sensitivity Scenario 6	Comments
Maximum Mean Crosstrack Position				
1	4R	47R*	10R	Scenarios 1 and 6 No difference
2	131R*	208L*	279L*	Turn area Only area of difference
3	128R	75L*	117L	Turn recovery Only area of difference
4	5R*	61R	61R	Scenarios 2 and 6 No difference
Maximum Crosstrack Standard Deviation				
Region	High Sensitivity Scenario 1	Low Sensitivity Scenario 2	High and Low Sensitivity Scenario 6	Comments
1	21	70*	28	Scenarios 1 and 6 No difference
2	170*	251	268	Scenarios 2 and 6 No difference
3	160*	202	232	Scenarios 2 and 6 No difference
4	39*	100	115	Scenarios 2 and 6 No difference

*Area of significant difference
R = right of centerline
L = left of centerline

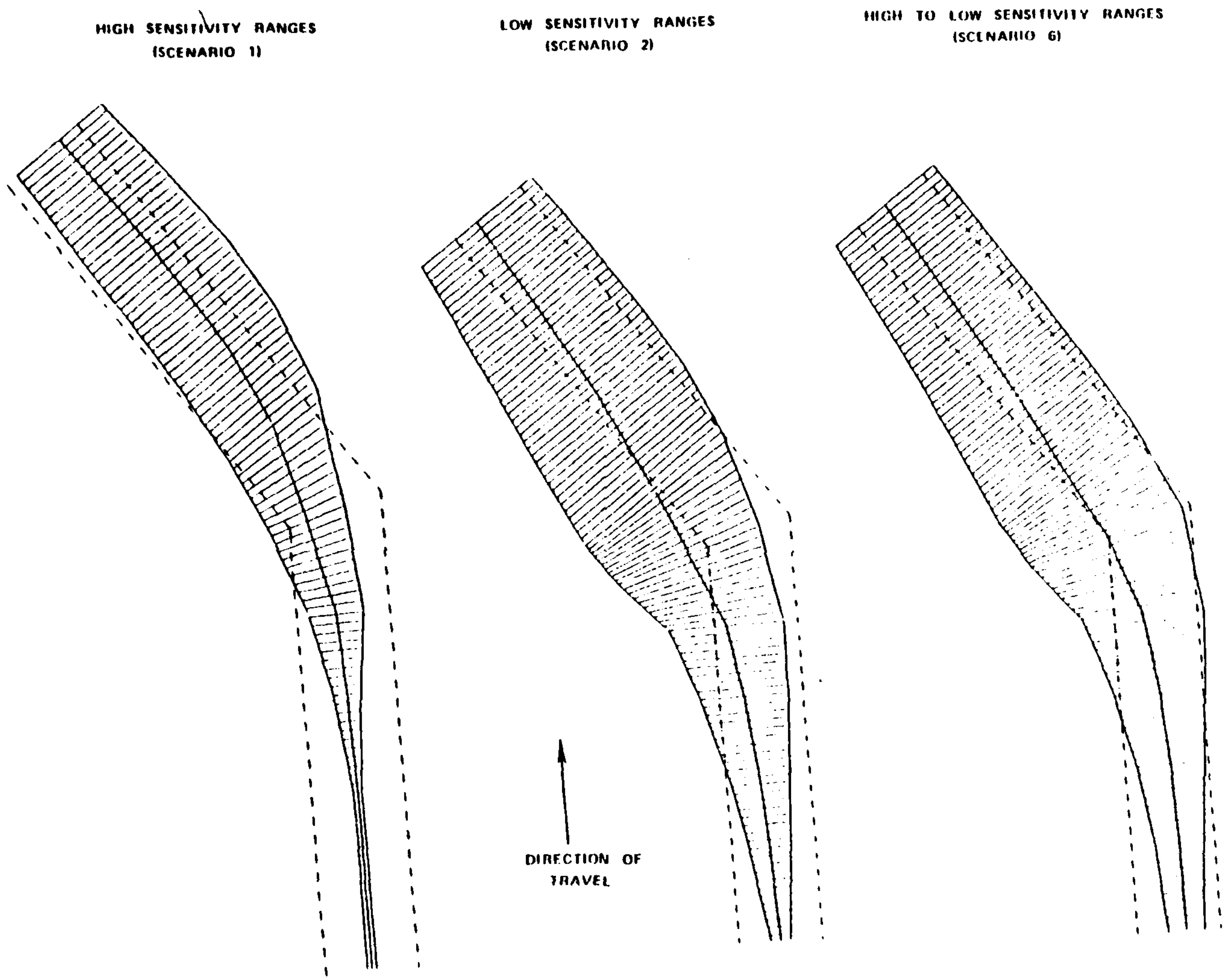


Figure 17. Turn Plots for High, Low, and Mixed Sensitivity Ranges

Section 3

PERFORMANCE AS A FUNCTION OF DESIGNATED TRACK

3.1 OVERVIEW

Two scenarios, differing only by the instructions given to the pilot regarding designated track, were developed to evaluate trackkeeping and maneuvering off the ranges. Pilots used high sensitivity ranges that marked the channel centerline to transit on the range axis (scenario 1) and to transit 125 feet to the right of the range axis (scenario 4). It was found that pilots could not find and maintain the quarterline under any crosswind or crosscurrent conditions. Therefore, ranges are only effective when the ship is heading directly on the range axis and not for transit off the centerline.

3.2 EFFECT OF DESIGNATING A QUARTERLINE TRACK VERSUS A CENTERLINE TRACK ON PILOT PERFORMANCE

Scenario 4, shown by Figure 18, has two high sensitivity ranges marking the center of the channel and is identical to scenario 1 with the exception of the instructions to the pilots. While scenario 1 required the pilots to keep the ship heading on the range or on the centerline, scenario 4 required the pilots to keep the ship 125 feet to the right of the range or on the right quarterline of the channel. This scenario was designed to evaluate pilot performance when trackkeeping or maneuvering off the axis of the range. It was expected that pilots would experience difficulty finding and maintaining the quarterline so performance would be better in scenario 1 when the pilot was trackkeeping on the range.

Piloting performance for these scenarios is shown by Figure 19. Comparison of the track envelopes shows performance is equally good in leg 1 with both means on the designated track and with a small dispersion between tracks. Performance in the turn is better with the quarterline scenario; however, it is poorer in leg 2 since the mean never reaches the quarterline and half the tracks transited outside the right channel boundary.

Figure 20 statistically compares the crosstrack mean track location and the standard deviation for both conditions. Each mean track should be compared to its designated track, which is indicated by dashed lines, rather than to each other since the objective for these is different. The standard deviation between scenarios, however, can be statistically compared since this measures the variability between tracks within each condition. Performance will be discussed by region to identify difficulties and differences.

Region 1 shows both means are close to their designated tracks with the dispersion between tracks minimal until the turn is initiated. In this region, pilots can determine quarterline location because they can reference the initial offset. Since the ship was initialized 92 feet to the right of the centerline, the pilots only needed to move the ship 33

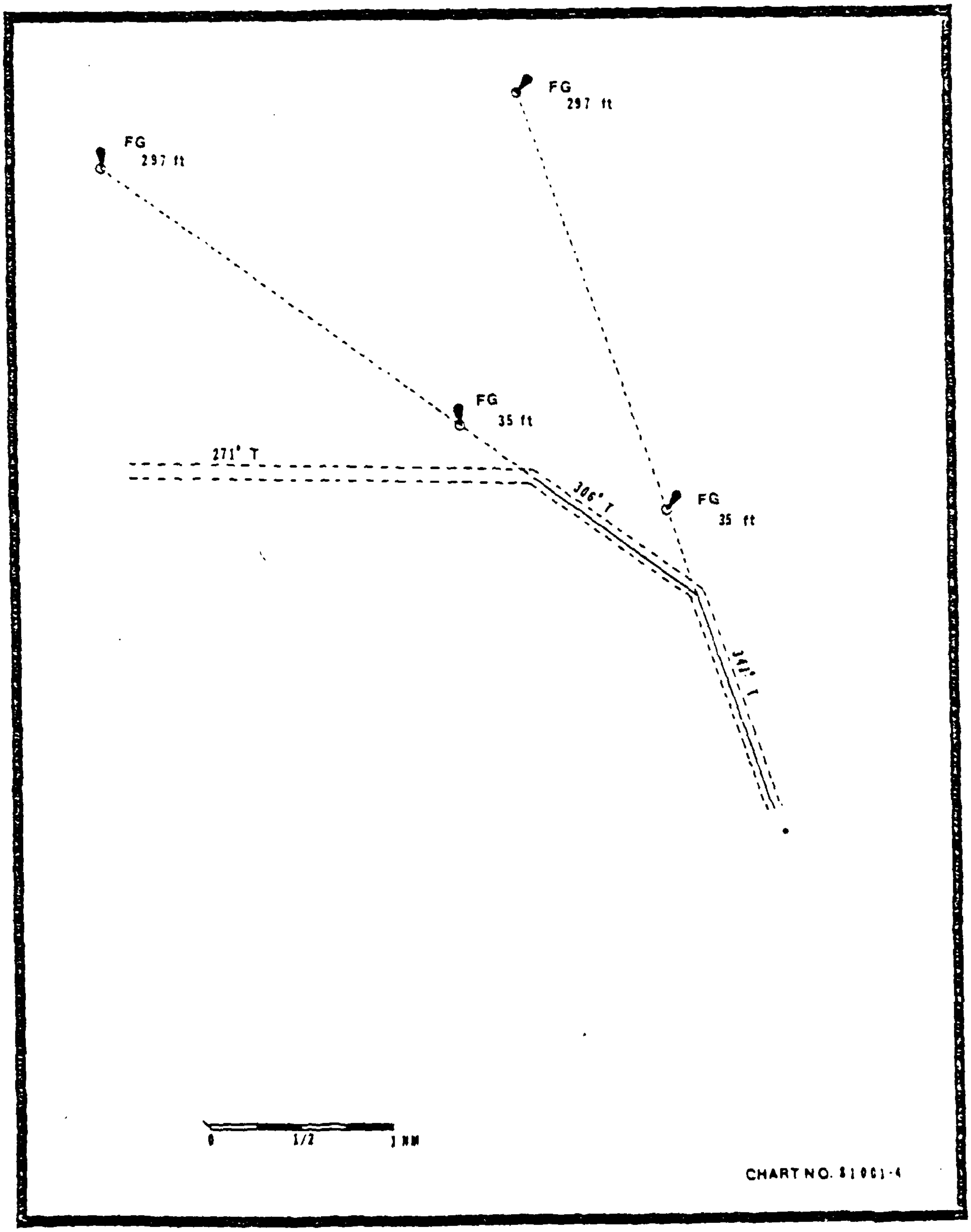
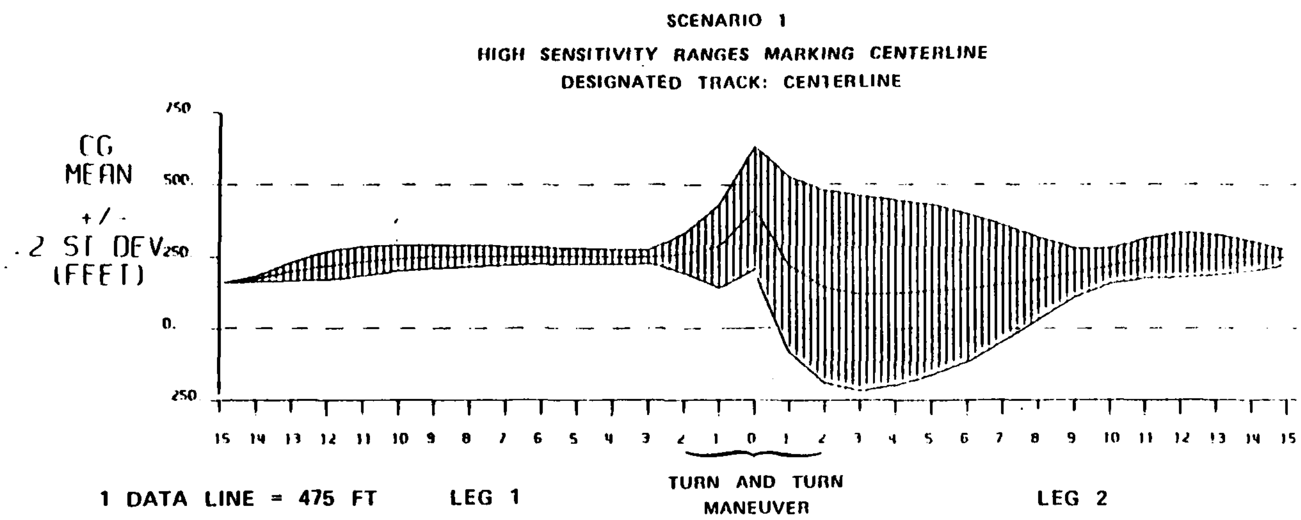


Figure 18. Scenario 4: Piloting on the Quarterline



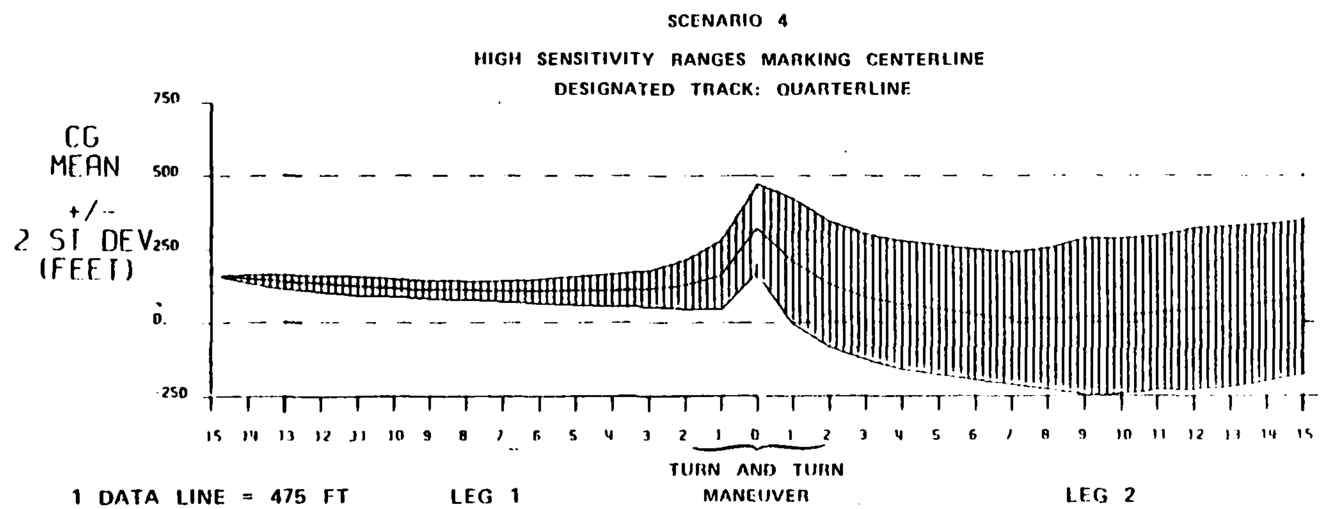


Figure 19. Combined Plots of Piloting Performance When Tracking on the Range on the Centerline Versus Tracking Off the Range or on the Quarterline

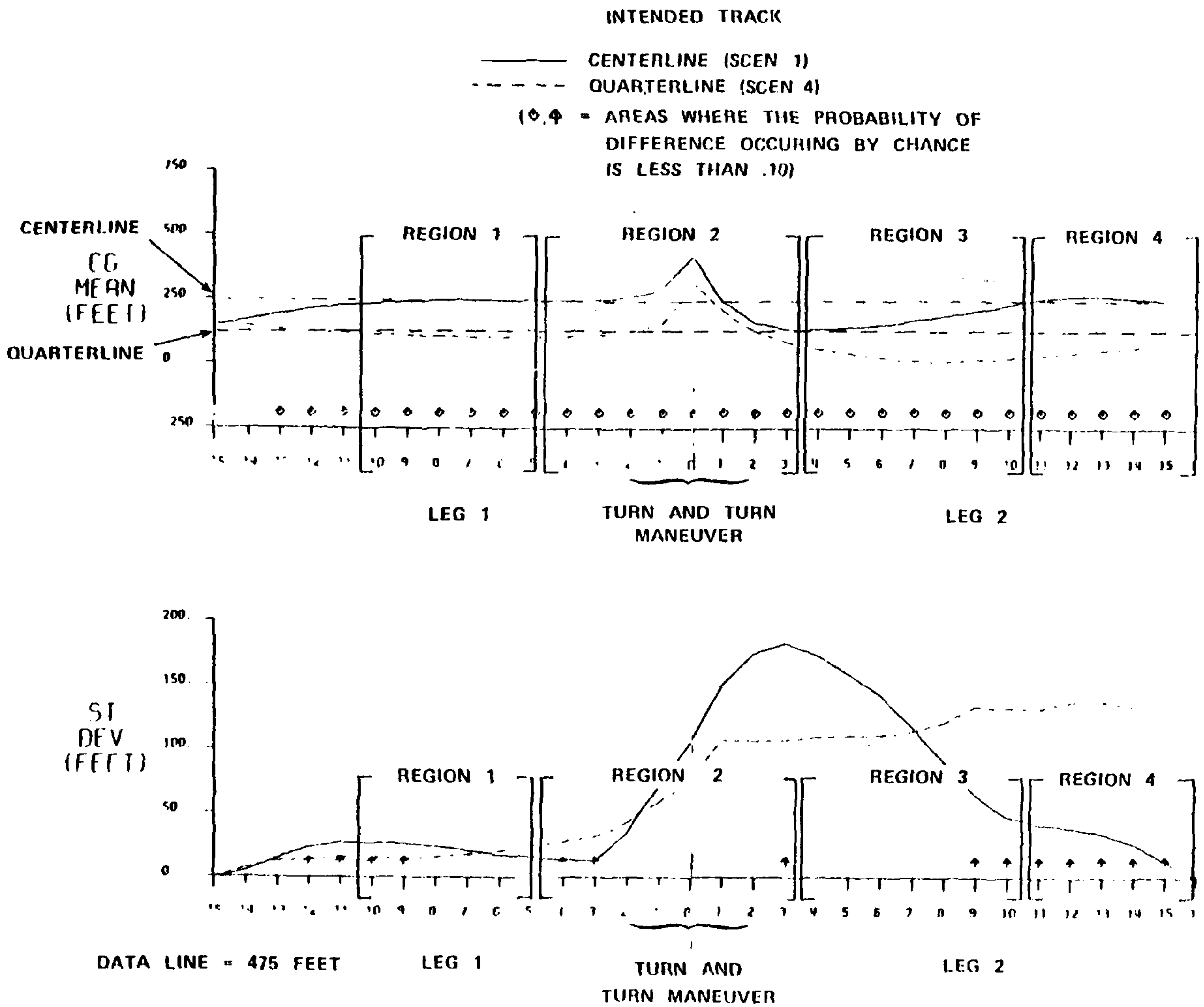


Figure 20. Crosstrack Mean and Standard Deviation of Piloting Performance for Designated Track: Centerline Versus Quarterline

feet further to the right or approximately one-third the distance the ship was already off the range. The pilots had no difficulty maintaining this track because the wind and current were following and had no crosstrack effect on the ship.

Region 2 shows the turn maneuver was satisfactorily executed when the pilots transited on the quarterline. It seems that since the ship was positioned to the right of the channel at the time the turn was initiated, this inhibited the pilots from turning too early and therefore avoided cutting the inside corner. However, once the turn was completed and the pilots began checking the rudder, the wind and current set the tracks to the right. This is illustrated by Figure 21.

Throughout leg 2 the quarterline scenario resulted in unsatisfactory performance because the mean track was too close to the right channel boundary and the standard deviation shows some tracks were set as far as 250 feet outside the channel. When pilots were forced to transit on the quarterline, the usable channel is reduced as is their margin for misjudging in a safe region. Table 9 exemplifies this. As can be seen in region 3, the maximum mean crosstrack position off the centerline and the maximum crosstrack standard deviation is smaller for scenario 4 than scenario 1; however, performance is much worse in the quarterline track. In region 4, performance should improve because wind and current diminish and no further maneuvering is required. This occurs when pilots trackkeep on the range (scenario 1) but does not exist when they trackkeep off the range (scenario 4) because pilots have no reference to reposition their ship. Also, it becomes more difficult for them to judge the distance the ship is off the range because as the ship's alongtrack distance comes closer to the range lights, the vertical angle between the lights widens so the absolute distance is impossible to assess. A similar conclusion was found in an at-sea experiment[19] which evaluated the effectiveness of various fixed, floating, and electronic aids to navigation on harbor pilotage. In this experiment it was found that visual ranges are excellent for defining the absolute center of the channel; however, when ranges are used to estimate absolute distance off the centerline, it is less effective. Therefore, ranges are not useful for trackkeeping off the centerline.

3.3 CONCLUSIONS REGARDING TRACKING FLEXIBILITY WITH RANGES

Trackkeeping off the range depends on the range sensitivity and the distance off the range of the intended track. The pilots were able to make a small maneuver onto the quarterline with a following wind and current. Performance was poor, however, when pilots had to find the quarterline after the turn with the crosswind and crosscurrent. Therefore, ranges are only effectively used when heading directly on the axis.

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[19] R.B. Cooper and W.R. Bertsche. "An At-Sea Experiment for the Comparative Evaluation of Radar Piloting Techniques." U.S. Coast Guard, Washington, D.C., September 1981.

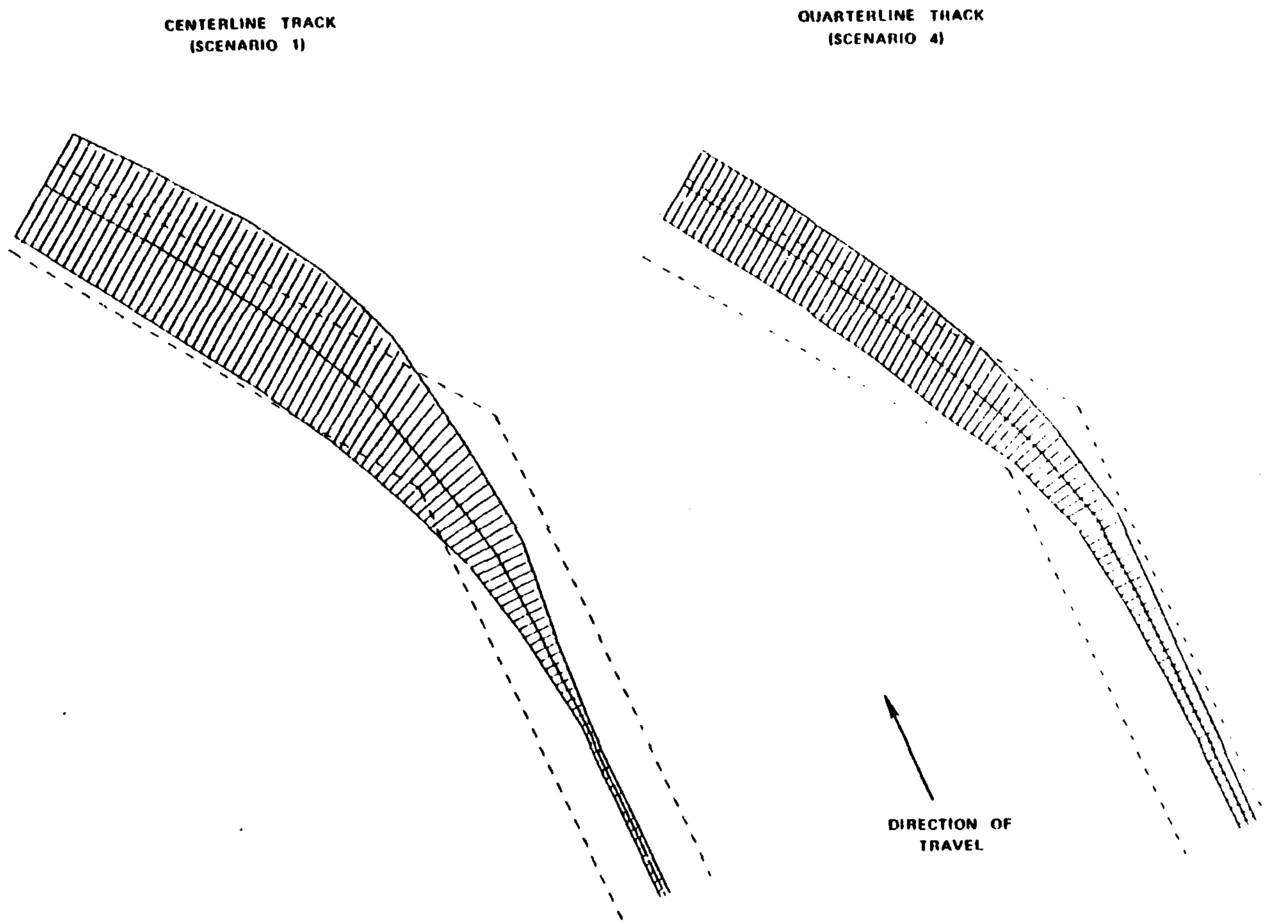


Figure 21. Turn Plots for Centerline and Quarterline Track Designation

TABLE 9. CROSSTRACK PERFORMANCE DATA FOR CENTERLINE VERSUS QUARTERLINE TRACKS

Maximum Mean Crosstrack Position		
Region	Centerline Track Scenario 1	Quarterline Track Scenario 4
1	4R	18R
2	131R	82R
3	128R	113R
4	5R	91R
Maximum Crosstrack Standard Deviation		
Region	Centerline Track Scenario 1	Quarterline Track Scenario 4
1	21	25
2	170	107
3	160	134
4	39	138

R = right of centerline

Section 4

PERFORMANCE AS A FUNCTION OF TURN ANGLE

4.1 OVERVIEW

Pilot performance with a 15-degree turn and a 35-degree turn were compared to analyze differences resulting from an easy and a difficult turn in a channel marked by ranges only. It was found that ranges are useful for turning in only the most restricted circumstances with a very low turn angle and with a high sensitivity range. The angle of the turn has an effect in turn and recovery; low angle turns are possible with ranges and by extension wide cutoff turns are probably possible. Ranges are not adequate for turning with any degree of severity.

4.2 EFFECT OF A LOW TURN ANGLE VERSUS A HIGH TURN ANGLE ON PILOT PERFORMANCE WHEN USING HIGH SENSITIVITY RANGES

Scenario 5, shown by Figure 22, has two high sensitivity ranges marking the centerline of the straight legs and a 15-degree bend joining them. Other than turn angle, this scenario is identical to the baseline scenario (scenario 1). Although the wind and current is the same, their effect is milder since the 15-degree bend is less abrupt so wind and current in leg 2 are closer to following. This difference is appropriate for the experiment since turn performance from range to range can be analyzed with a difficult and easy turn.

Figure 23 compares piloting performance for a 15-degree turn to that of a 35-degree turn and illustrates that under certain restricted conditions, it is possible to successfully turn on ranges which mark straight legs. When questioned, pilots believed this scenario was easiest because a 15-degree turn was more forgiving since it was less severe than the 35-degree turn. Pilot opinion was mixed regarding if buoys were necessary to mark the turn with half believing they were and half believing they were not. Pilot's technique for transiting through the turn was to use less rudder for a shorter time since the smaller course change in the second leg was affected less by current.

Figure 24 which statistically compares the mean and standard deviation of these conditions shows pilot performance was superior with the 15-degree turn in all areas except region 1 where performance was identical and excellent. For the 15-degree turn, region 2 contained a mean slightly to the inside but within channel boundaries and a very narrow standard deviation. Table 10 compares crosstrack performance data and shows the amount the mean track was displaced from the centerline and that the amount of variability between tracks was significantly less with the 15-degree turn than the 35-degree turn. Since the second range for the 15-degree turn was positioned only slightly to the left of the first range, pilots tended to start the turn closer to the axis of the second range, that is, waited longer before starting to turn. This positioned the ship closer to the centerline and since the mean track was only slightly offset (20 feet to the right for the 15-degree turn compared to 128 feet to the right for the 35-degree turn), returning to the centerline was easier. The pilots completely

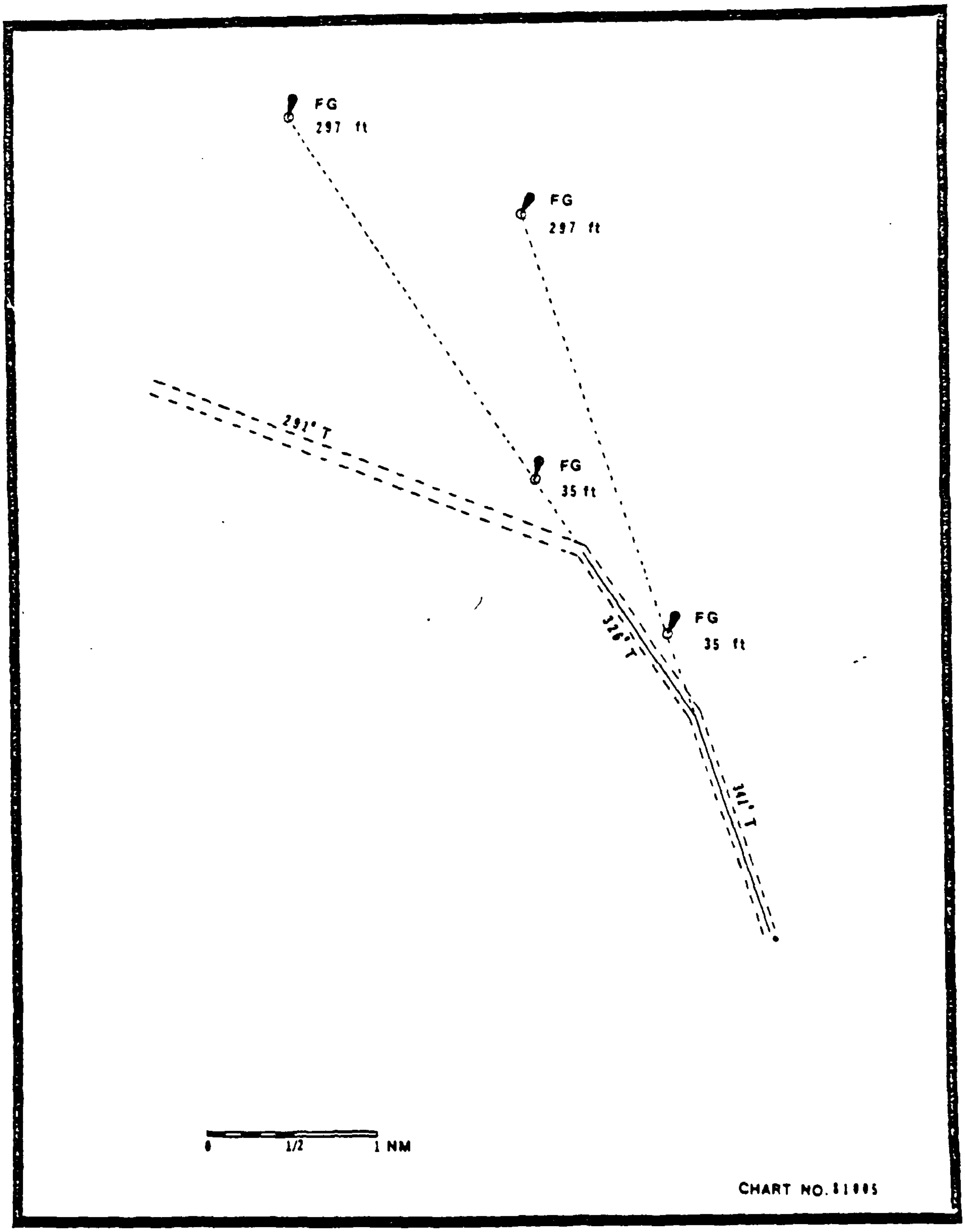


Figure 22. Scenario 5: High Sensitivity Ranges and a 15-Degree Turn

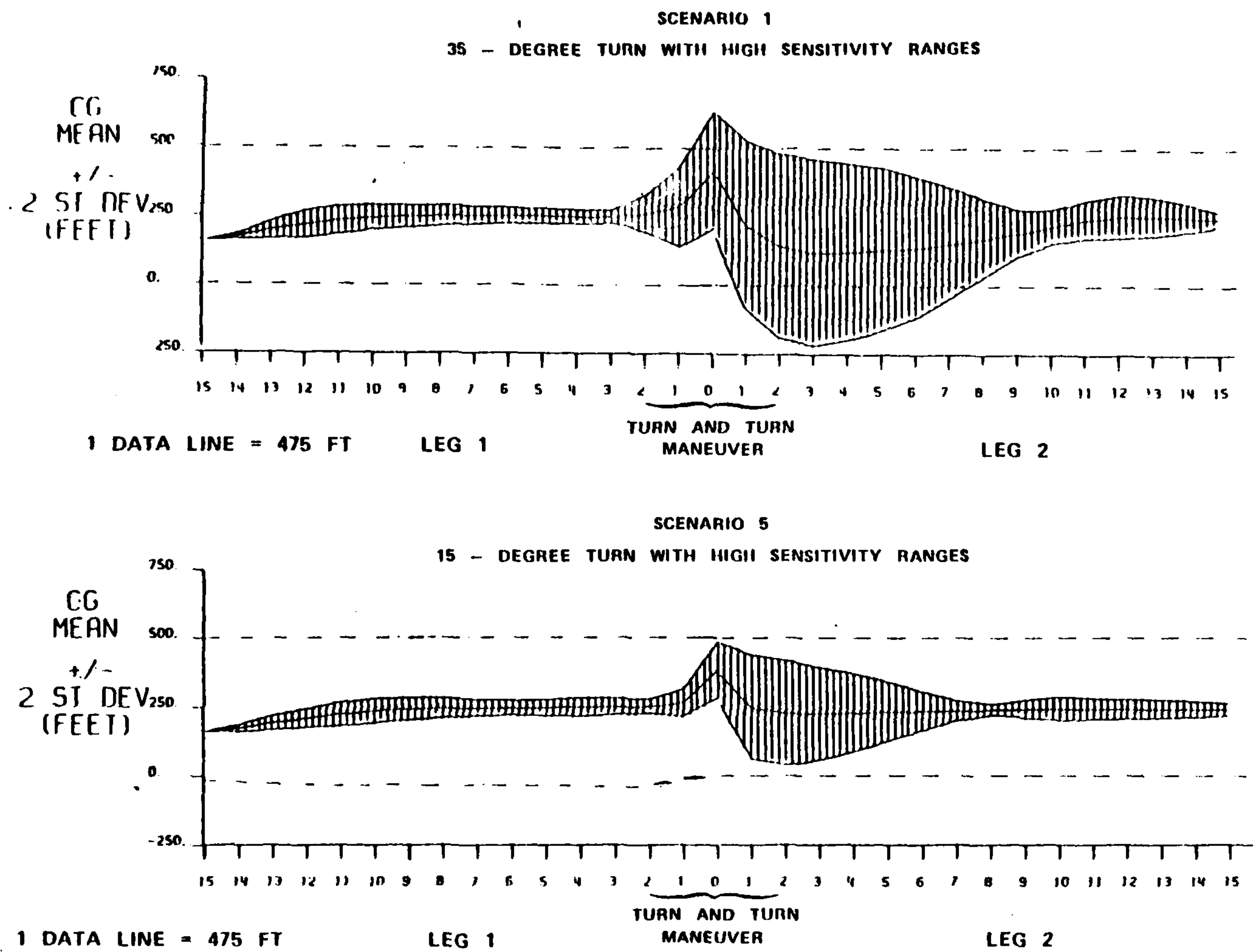


Figure 23. Combined Plots of Piloting Performance:
15-Degree Turn Versus 35-Degree Turn

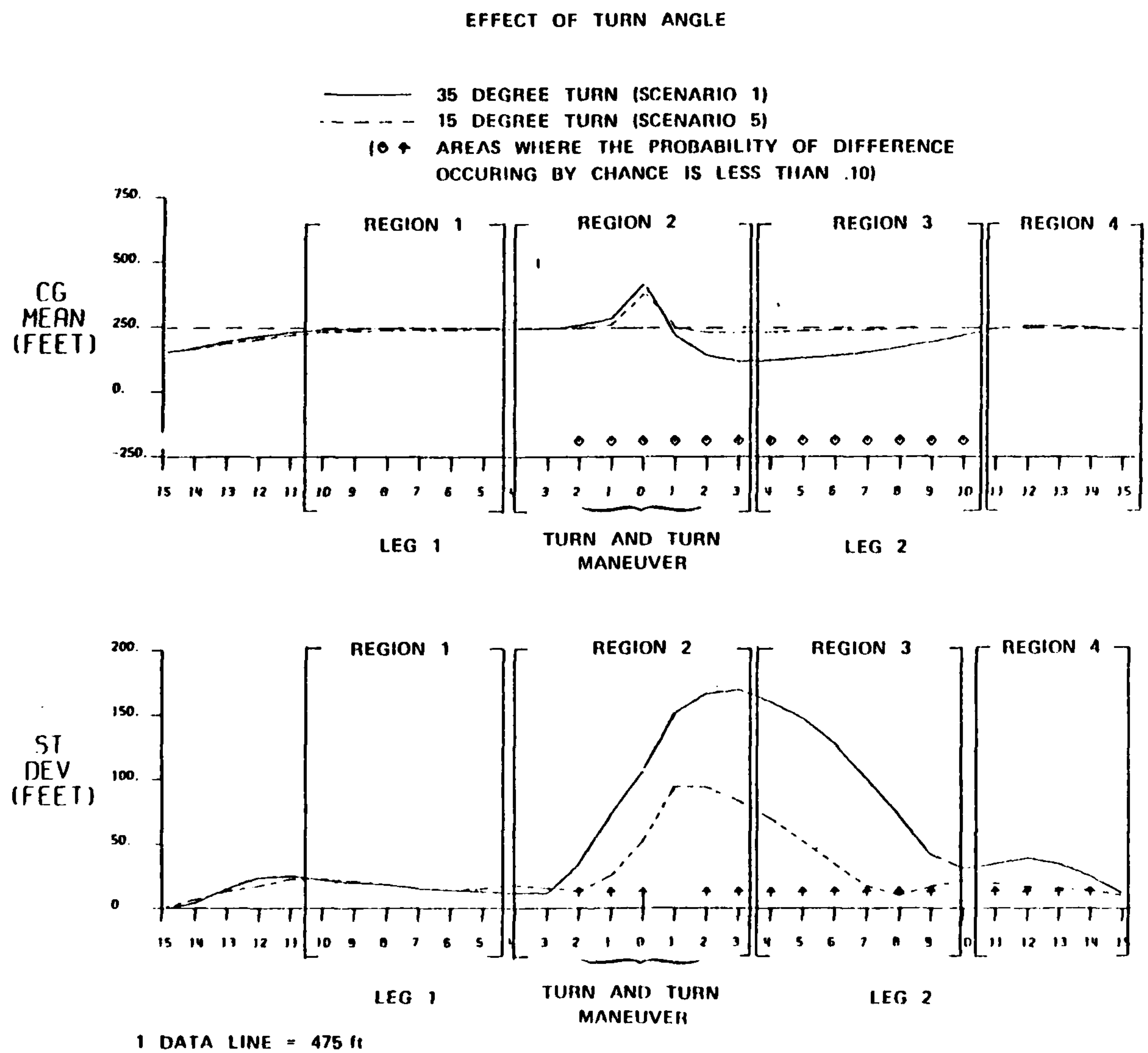


Figure 24. Crosstrack Mean and Standard Deviation of Piloting Performance for 15-Degree and 35-Degree Turn Angle

TABLE 10. CROSSTRACK PERFORMANCE DATA FOR
15-DEGREE TURN VERSUS 35-DEGREE TURN

Maximum Mean Crosstrack Position		
Region	High Sensitivity Ranges and a 35-degree Bend (Scenario 1)	High Sensitivity Ranges and a 15-degree Bend (Scenario 5)
1	4R	11R
2	131R	23R
3	128R	20R
4	5R	5R
Maximum Crosstrack Standard Deviation		
Region	High Sensitivity Ranges and a 35-degree Bend (Scenario 1)	High Sensitivity Ranges and a 15-degree Bend (Scenario 5)
1	21	21
2	170	94
3	160	69
4	39	19

R = Right of Centerline

recovered from the turn 1188 feet sooner with the 15-degree turn and tracks were made uniform throughout the second leg.

4.3 CONCLUSIONS REGARDING TURN ANGLE

Pilots can successfully complete a turn maneuver using ranges only under the most favorable circumstances. These include low angle turns that do not require the ship to move far off the axis of the ranges and low environmental effects such as crosswind and crosscurrent. Ranges cannot be useful for turning with any degree of severity. From analyzing performance with the 35-degree turns, it appears that with high sensitivity ranges, pilots may be able to successfully complete a turn if the turn was a cutoff configuration which would allow the pilots to take a lot of room to maneuver and still remain in the channel. Another possible situation where pilots could maneuver would be in a very wide channel which would accommodate the spread of the tracks.

Appendix A

STATIC TESTS OF RANGE LIGHT SENSITIVITY ON THE USCG/EA SIMULATOR

This section treats ranges as static presentations of two lights on the screen of the simulator. The United States Coast Guard and International Association of Lighthouse Authorities (IALA) have published equations derived from laboratory and field tests describing the relationship between the vertical separation of the lights and the detectability of the horizontal separation (representing crosstrack movement of the ship). Tests are described here of the USCG/EA simulator's ability to match those equations.

It is concluded that a match is achieved over a useful set of values. Appendix B relates these findings to the design of ranges for the dynamic experimental runs.

A.1 EQUATIONS DESCRIBING PERCEPTUAL EFFECTS

The United States Coast Guard and the IALA have published equations[20,21] derived from laboratory tests describing the relationship between the vertical separation of the range light and the horizontal separation (representing crosstrack movement of the ship) that will be detected. The purpose of the static tests is to compare perceptual data collected on the USCG/EA simulator with values predicted by these equations. A close match establishes the validity of the simulator for simulating range lights.

Range lights exist in three-dimensional space in the real world as illustrated in Figure A-1. The observer sees only the two lights as illustrated in Figure A-2. The vertical separation between the lights can be expressed as:

$$\Delta = 3438\ (H-h)/(D+R)\ \text{min arc} \qquad \text{(A-1)}$$

where:

H = height of rear light (feet)
h = height of front light (feet)
D = distance from front light to observer (feet)
R = distance between lights (feet)

The larger the vertical angle of separation, Δ, the larger is the horizontal angle of separation that will not be detected. Experimentally derived equations relate Δ to θ_Q, the standard deviation of θ values that observers will judge to be still vertically aligned:

[20] United States Coast Guard. Range Design. Report Number: COMDTINST M16500.4, U.S. Department of Transportation.

[21] International Association of Lighthouse Authorities. "Recommendation for Leading Lights." IALA Bulletin, May 1977.

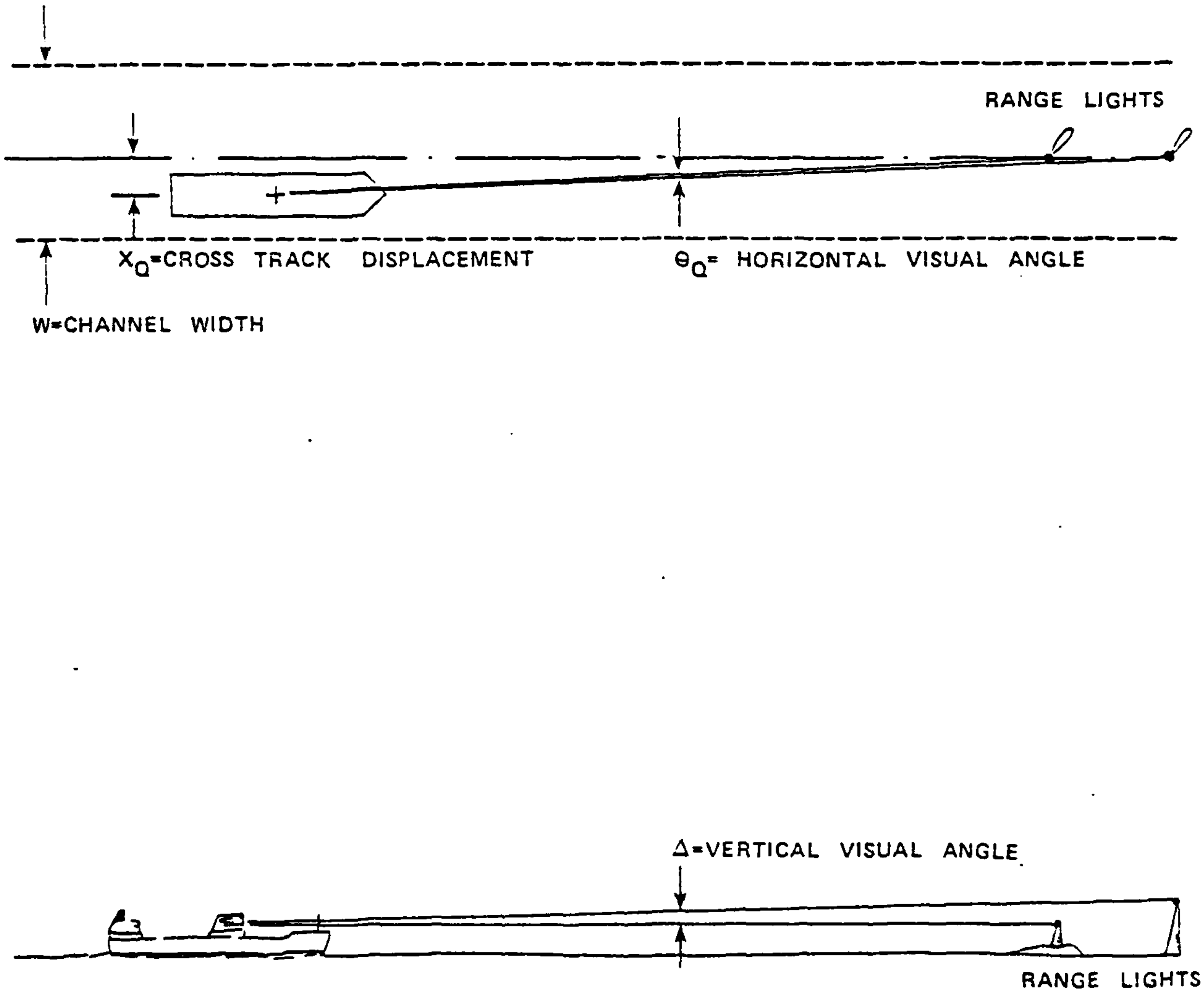


Figure A-1. Relationship Between the Range Lights in Three-Dimensional Space

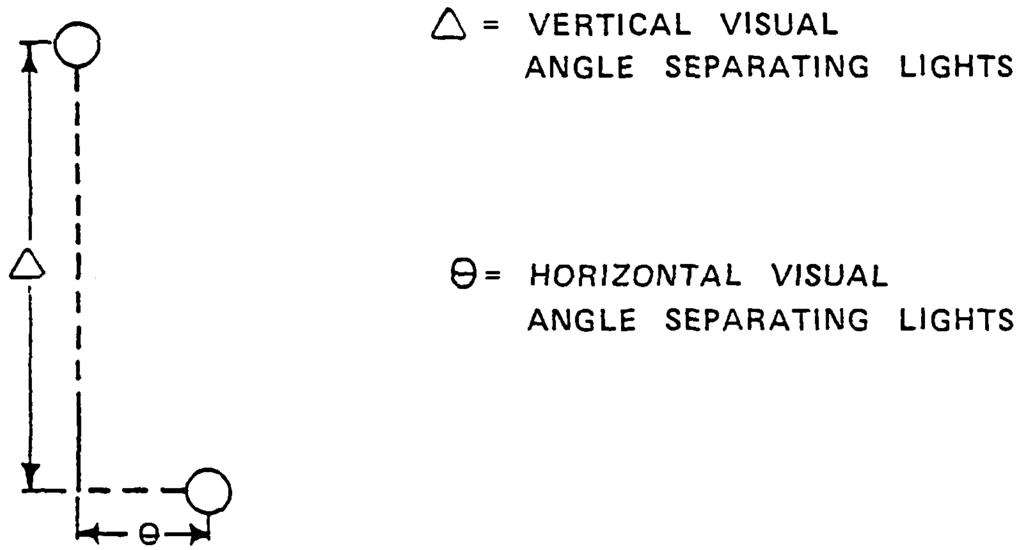


Figure A-2. Vertical and Horizontal Separation of the Lights

$$\theta_Q = 0.172 + 0.038\ \Delta \text{ min arc for } 4.47 \leq \Delta \leq 17.19 \text{ min arc} \qquad \text{(A-2)}$$

$$\theta_Q = 0.344 + 0.028 \text{ min arc for } 17.19 \leq \Delta \text{ min arc} \qquad \text{(A-3)}$$

The value, θ_Q , is the expected standard deviation of θ values eliciting a response that indicates the observer sees no bearing difference between the lights or sees no displacement of the ship from the centerline of the channel. That θ_Q predicts the standard deviation means that a horizontal separation of $\pm\,\theta_Q$ is expected to enclose 65 percent of the "centerline" reponses. By definition $\pm 3\,\theta_Q$ (99 percent) is taken as the threshold of the perception of displacement from the centerline. The Coast Guard design criteria specifies that 100 percent of all observers detect a separation of 5 θ_Q to be off the centerline of the range.

A more convenient method of representing horizontal angular separation for a specific range design is to convert the angles to the crosstrack displacement of the ship from the centerline that will be detected. The crosstrack displacement represented by a horizontal visual angle of θ_Q can be calculated in feet as:

$$X_Q = \theta_Q\ D\ (R+D)/3438R \text{ feet)} \qquad \text{(A-4)}$$

A.2 SELECTION OF VALUES FOR TESTS OF THE USCG/EA SIMULATOR

The characteristics of the simulator set two important limitations to the simulation of range lights. First, while range lights can move as a continuous variable, the simulator can depict changes only as discrete steps. Second, the resolution of the system sets a lower limit to the size of those discrete steps. The lights can move only in steps of 2.44 min arc. Values were chosen to make the greatest use of the possibilities available.

For the first instance to be depicted, θ, the horizontal angle was set equal to the smallest separation that can be depicted: 2.44 min arc.

$$\theta = 2.44 \text{ min arc}$$

The vertical angle, Δ , required to yield that value as the vertical angle, θ_Q, or the standard deviation of centerline responses, is:

$$\Delta = [(\theta_Q - 0.344)/0.028] = 74.86 \text{ min arc for } 17.19 \leq \Delta \text{ min arc}$$

For Δ equal to 75 min arc the value of θ_Q, or the predicted standard deviation is a value of θ that can actually be depicted on the simulator.

Other values of the vertical angle, Δ , were arbitrarily chosen for inclusion. They were: 100, 50, 25, and 12.5 min arc. The corresponding θ_Q values are listed in Table A-1.

TABLE A.1. PREDICTED STANDARD DEVIATION OF THE HORIZONTAL VISUAL ANGLES CALLED "CENTER," θ_Q

Vertical Visual Angle Δ	Horizontal Visual Angle θ_Q
100 min arc	3.144 min arc
75	2.440
50	1.744
25	1.044
12.5	0.647*

*Use equation $\Delta = (\theta_Q - 0.172)/0.038$ min arc for $4.47 \leq \Delta \leq 17.19$ min arc

A.3 EXPERIMENTAL DESIGN

The experiment consists of five conditions, one constructed for each of the five values of Δ described in section A.2. Each value of Δ was combined with 11 values of θ in increments of 2.44 min arc as in Table A-2.

TABLE A-2. EXPERIMENTAL CONDITIONS AND STIMULI

Conditions: Δ (Min Arc)	Stimuli: θ (Min Arc)
100	
75	-12.12 -9.76 -7.32 -4.88 -2.44
50	0
25	+2.44 +4.88 +7.32 +9.76 + 12.12
12.5	

The five conditions of Δ were run in random order. Within each condition, the subjects were shown the 11 stimuli of θ, twice each in random order. In all there were 110 stimuli shown to the subjects.

A.4 COLLECTION OF DATA

Two sets of data were collected. Before the ranges were designed for the dynamic simulation experiment, a preliminary group of seven naive subjects with no marine background was run. This preliminary group was to provide assurances that a range of experiments could be run on the simulator and to determine possible limits to the values of Δ that would be incorporated into the experiment. The second, pilot group, consisted of nine individual pilots/subjects from the presimulation and the experiment run through the stimulus sequence at the beginning of the experimental day. This was to discover any differences between naive observers and experienced pilots and to increase the total sample size.

The subjects stood on the darkened bridge (as a group or as individuals) and were shown the prepared stimuli one at a time. They were asked to judge each stimulus as "left," "center," or "right." Because some of the subjects were naive as to the use of range lights, they were not asked to judge the position of the "ship." Instead, they were asked to judge the position of the top light, a judgment analogous to the judgment of the ship's position. A copy of the instructions and the data sheet appears here as Figures A-3 and A-4.

A.5 RESULTS OF STATIC TESTS

With increases in the Δ, the vertical separation, the number of "center" responses increased, indicating increased difficulty of detecting horizontal separation. This was true for both groups as illustrated in Figure A-5. The responses of the preliminary and pilot groups are plotted separately to illustrate another point. The pilots gave many more "center" responses than did the unselected subjects. (This difference was a group effect. There was some overlap. Some pilots gave few "center" responses and some naive subjects gave a great many.) The pilots were given the same instructions; they were to make judgments on the orientation of the lights (not the "ship") and the judgments were to be as exact as possible. However, their comments during the test indicated they persisted in judging the location of the "ship." "The ship is close enough to the center. I wouldn't bother to bring her closer." This difference between the two groups supports the necessity of using appropriate or representative subjects in an applied research project. Here, pilots were needed to investigate the performance of aid to navigation systems.

The bottom half of Figure A-6 plots the standard deviation for each value of Δ for the two groups. Notice that the standard deviation is larger for the pilot group when Δ is larger and there is more opportunity for interpretation. The differences between the two groups are not statistically significant but are reported here because they are consistent with the pilots' comments.

The top half of Figure A-6 shows the means of the distribution. For both groups the mean is not at the center but to the left. Those means that are statistically different from zero (the center) at the 0.05 level of significance are indicated on the plot. Stimuli with horizontal displacements that were not detected were more likely to be arranged as in Figure A-2 with the top light to the left; when the top light was to the right, the horizontal separation was more likely to be detected. If these lights are to be interpreted as range lights, the pilot is more likely to detect the "ship's" displacement to the right than to the left. When a similar evaluation of range lights was done at the Maritime Administration's Computer Aided Operations Research Facility (CAORF) in New York, a bias of the mean to the left was also found.[22] In addition, field tests of range light sensitivities

[22] Computer Aided Operational Research Facility Staff. Simulation Experiment Report: Restricted Waterways Experiment IIIA. Data Analysis and Findings. The National Maritime Research Center, Kings Point, New York, October 1978.

RANGE LIGHT STATIC TEST INSTRUCTION SHEET

- This is an experiment in psycho physical judgment. This means we want to measure the relationship between the physical stimulus and the psychological judgement. You will see a series of light combinations and be asked to make a judgment about their relationship.

- For each trial you will see two green lights on the center screen, one above the other. Sometimes they will be lined up exactly, sometimes the top one will be displaced to the left or the right. When you see each combination, decide whether the top one will be displaced to the left or to the right. When you see each combination, decide whether the top one is to the left, is center, or is to the right of the bottom one. Indicate your decision on the answer sheet by L, C, R. Make each judgment independently of those that came before. There is no systematic relationship between trials.

- There are 120 judgments to be made. Each will take a few seconds to put up on the screen and a few seconds to judge. You may have as much time for each judgment as you need. There will be a 10-minute break after the first 66 trials -- the first three columns on the answer sheet. The whole experiment should take just over an hour.

- Three sample trials follow:

  1.

  2.

  3.

Figure A-3. Instructor Sheet
Range Evaluation

IS THE TOP LIGHT LEFT, CENTER, OR RIGHT?					
Order	20	31	5	10	41
1					
2					
3					
4					
5					
6					
7					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					
21					
22					

Figure A-4. Data Collection Sheet for Static Range Light Test

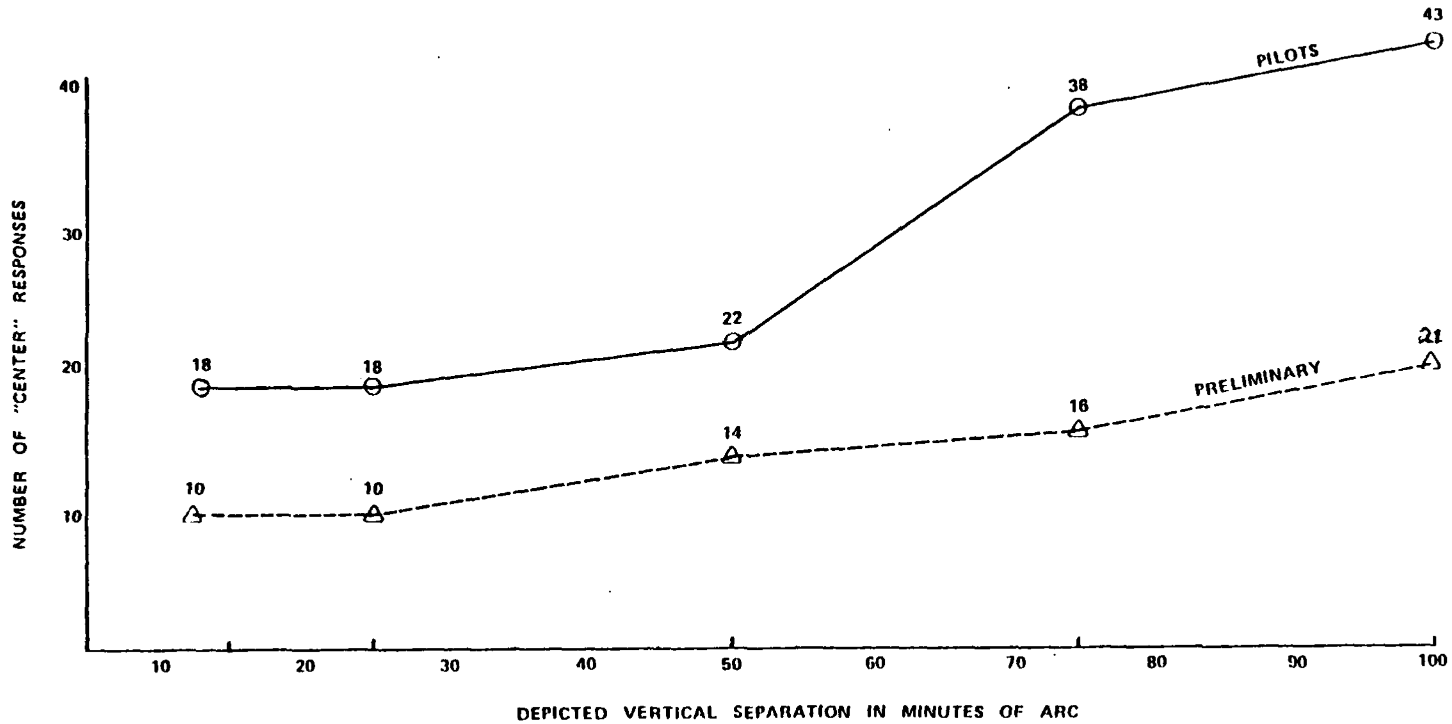
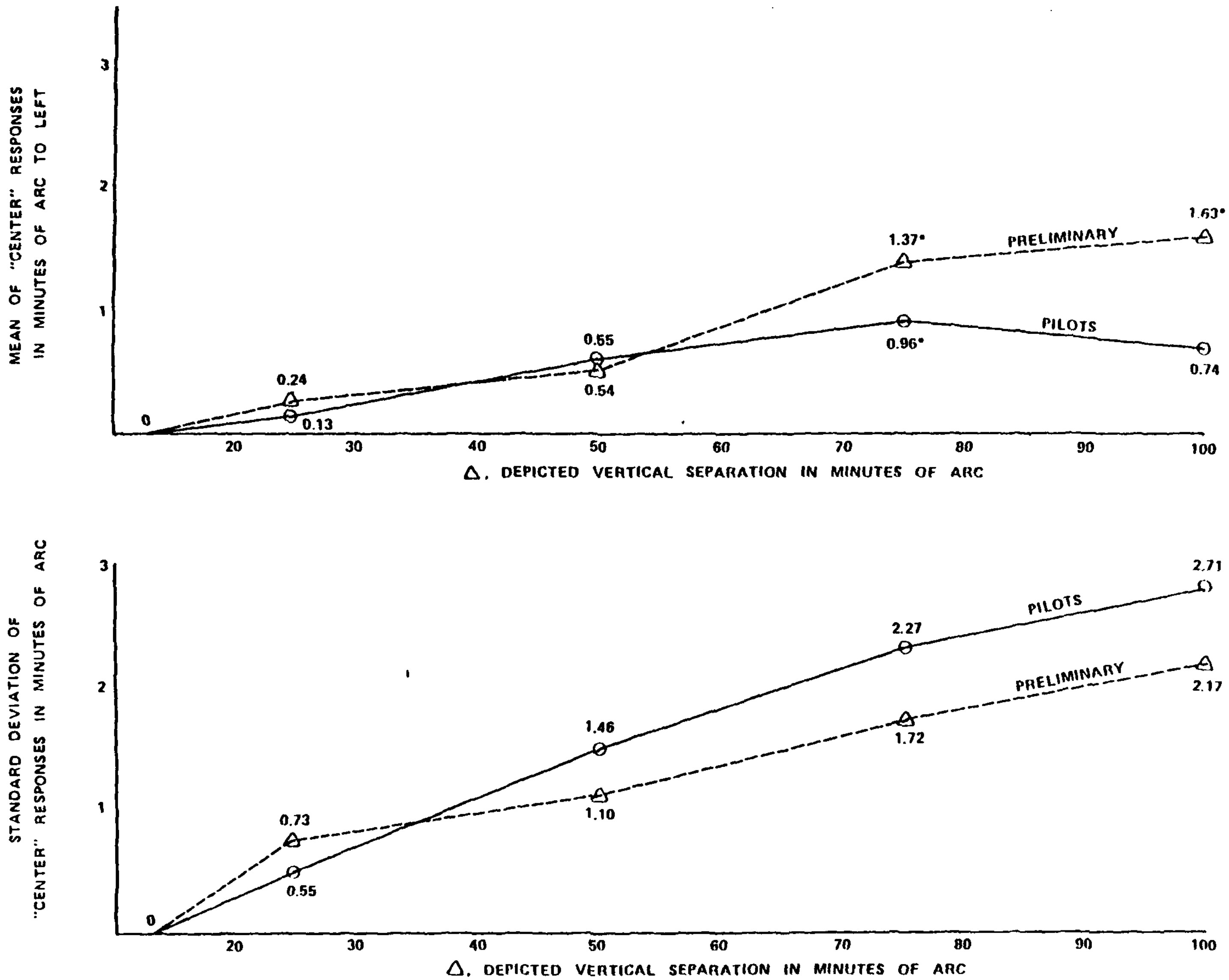


Figure A-5. Number of Center Responses as a Function of *Vertical Separation for the Two Groups*



* MEANS MARKED ARE STATISTICALLY DIFFERENT FROM 0 AT THE .05 LEVEL OF SIGNIFICANCE

Figure A-6. *Performance in the Static Tests* conducted aboard ships demonstrated a bias but assumed it to be an error in the ship tracking equipment.[23] This asymmetry in the use of range lights is consistent with recent basic research in psychology that finds humans, especially males, performing asymmetrically over a wide range of behaviors.

Several more points should be made about the means. First, the displacement is less for the pilots than for the unselected subjects. Although the difference is not statistically significant, it is unlike the difference in standard deviations in the direction that gives the advantage to the pilots. It seems the experience of the pilots made for greater accuracy (the mean) in placing a more relaxed (the standard deviation) "center" in the channel. Notice the size of the displacement of the mean is absolutely small for both groups compared to the ± 5 standard deviations that are to be accommodated in the channel.

To summarize the findings:

1. There were suggestive differences in the performance of the preliminary and pilots groups both in mean and standard deviation, but these differences were not signficant and the data may be pooled.

2. There is a bias in the mean of the distributions but it is absolutely small and of no concern for range design.

A.6 IMPLICATIONS FOR USE OF RANGE LIGHTS IN DYNAMIC SIMULATIONS

The purpose of the simulator is not static presentation but the use of the range lights in dynamic simulation. In a dynamic simulation the position of the two lights and of the ship in three-dimensional space determine the vertical and horizontal positions of the two lights as they appear on the two-dimensional screen. For each range design as the ship moves alongtrack and crosstrack the simulation changes the values of Δ and θ in discrete steps of 2.44 min of arc. The emphasis in this discussion is on θ. Since the simulator cannot move the lights in a continuous or analog manner, the movement of the lights must be discrete and in intervals which are multiples of 2.44 min arc. If it could, there would be a simple one-to-one relationship between an intended value of θ and one depicted on the screen as illustrated in Figure A-7a. The static tests depicted values of θ as multiples of 2.44 min arc as illustrated in Figure A-7b. The dynamic range-light subroutine on the other hand determines how much movement of the ship must occur before a discrete change is made in the depicted value of θ. The relationship between the intended (actual) and depicted values of θ are illustrated in Figure A-7c for the dynamic subroutine. When the movement of the ship is such that the intended value of θ is between 2.44 and 4.88 min arc, the depicted vaue of θ will be 2.44 min arc. Thus, a depicted value of θ of 2.44 min arc represents an average intended θ of 3.66 min arc; a depicted value of θ of 4.88 min arc represents an average intended θ of 6.10 min arc., etc.

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[23] United States Coast Guard. "Residual Error in Using a Range to Obtain a Line of Position." Technical Report, Department of Transportation, January 1977.

To evaluate the adequacy of the range lights for dynamic simulation, the samples of θ depicted in the static test were assigned the average intended values of θ determined by the dynamic range-light subroutine. θ_Q was then calculated as the standard deviation of the average intended values. These values are compared with values predicted by the range sensitivity equations in Figure A-8. The calculated values of θ_C and the predicted standard deviation of "center" responses, θ_Q, are shown for each vertical visual angle used in the static tests. The corresponding values for CAORF are included for comparison.[24]

The experimental values for the USCG/EA simulator are not statistically different from the predicted values of θ_Q for Δ equal to 25 min arc or greater. These data support the use of range lights on the USCG/EA simulator for values of Δ between 25 and 100 min arc. For such values the sensitivity of the range lights to the detection of crosstrack movement can be considered valid. Further test results derived for large vertical visual angles can be extrapolated to smaller vertical visual angles according to the USCG and IALA equations A-1, A-2, A-3, and A-4.

[24] Computer Aided Operational Research Facility Staff, op. cit.

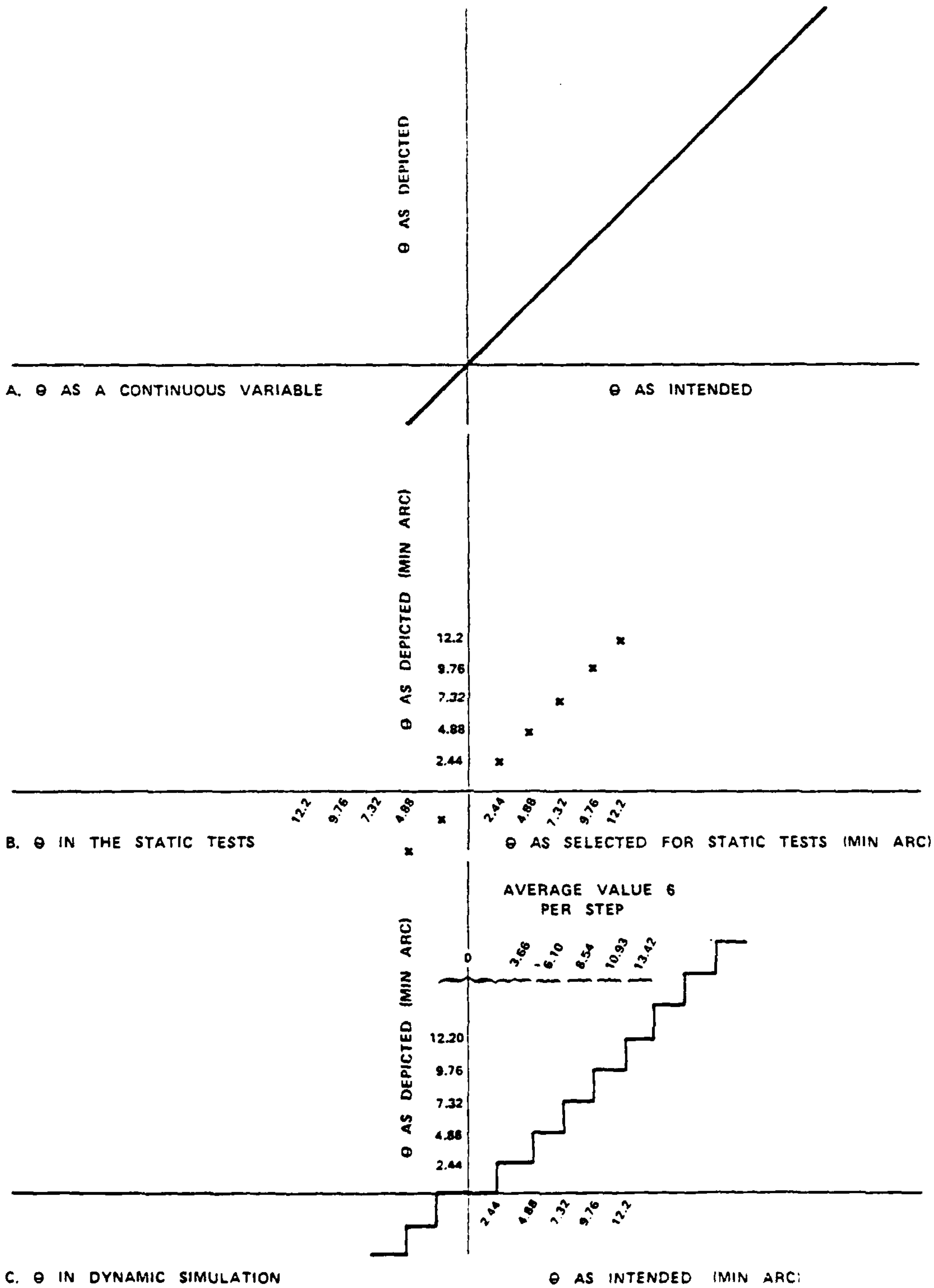


Figure A-7. Interpretation of Depicted θ

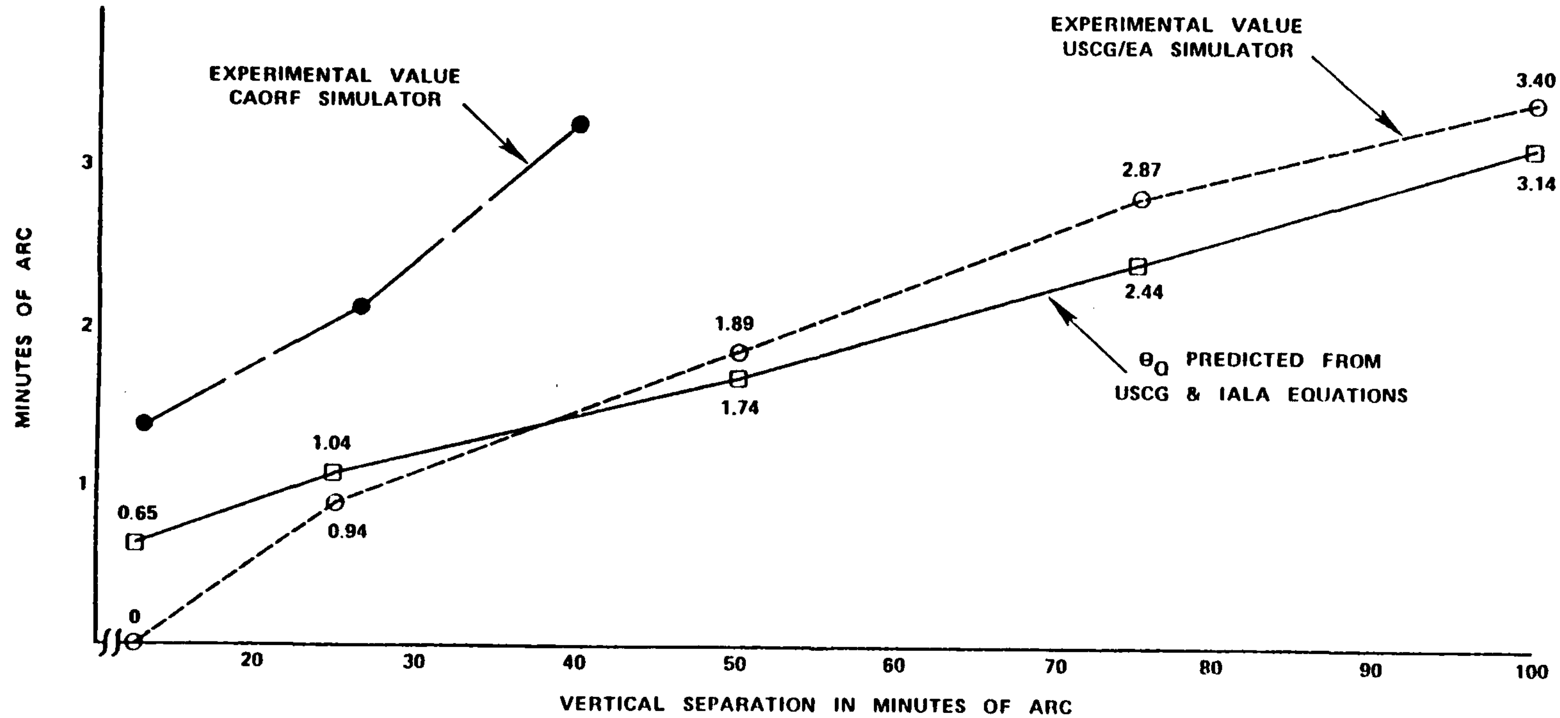


Figure A-8. Match Between θ_Q and Observed Standard Deviations

Appendix B

DISCUSSION OF RANGE SENSITIVITY AND RANGE DESIGN FOR THE EXPERIMENT

B.1 RANGE DESIGN CRITERIA

The dynamic experimental runs are selected to evaluate the dependence of piloting performance on "high" and "low" sensitivity ranges. The parameter normally used as an indicator of sensitivity is K, lateral sensitivity. Table B-1 provides a description of range sensitivity as a function of K: for a low sensitivity range $K \approx 0.5$ and for a high sensitivity range $K \approx 4.5$. K can be calculated by:

$$K = (W/X_Q)(\theta_Q/\Delta) \tag{B-1}$$

where:

- W = channel width (feet)
- X_Q = crosstrack displacement in feet when the horizontal visual angle is θ_Q
- θ_Q = the horizontal visual angle of separation between range lights which 65 percent of the subjects judge to be still vertically aligned (min arc)
- Δ = the vertical visual angle of separation (min arc)

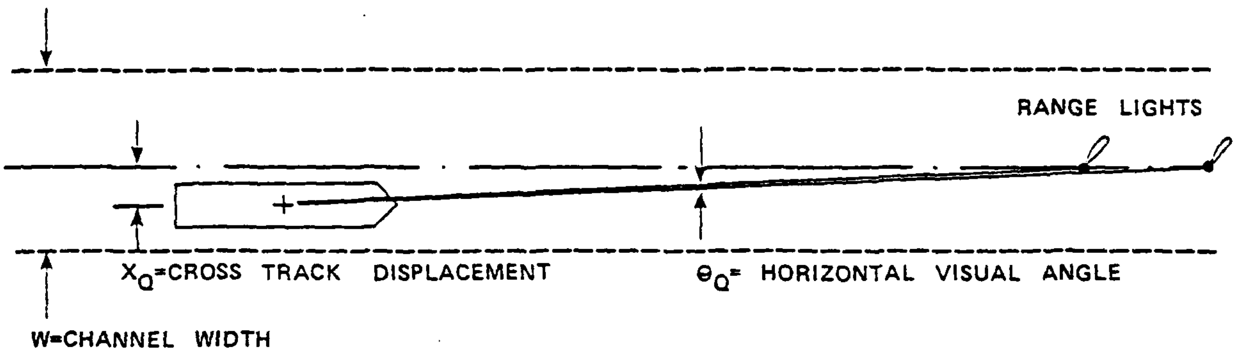
Figure B-1 shows the relationships between these parameters.

Historically, the lateral sensitivity value has been used by the Coast Guard to design ranges. Its nondimensional form, however, prohibits an intuitive understanding of its application in design. It is therefore suggested that X_Q be considered as the principal design parameter where:

$$X_Q = (W/K)(\theta_Q/\Delta) \tag{B-2}$$

Using the dependence of θ_Q on Δ (equations A-1 and A-3) and assessing a value of Δ = 35 min arc, it is possible to derive typical values for X_Q as a function of channel width (W) and lateral sensitivity (K = 0.5 and K = 4.5). Table B-2 shows these values.

The values of X_Q provide us with an indication of "crosstrack position sensitivity" at the design point (i.e., θ_Q). X_Q is seen to vary from 2.6 feet (high sensitivity, narrow channel) to 62.4 feet (low sensitivity, wide channel). These data indicate that to achieve applicability to channels between 300 and 800 feet wide, the "high" sensitivity range design should achieve values of X_Q between 2.6 to 6.9 feet and the "low" sensitivity ranges should achieve values of X_Q between 24 and 60 feet.



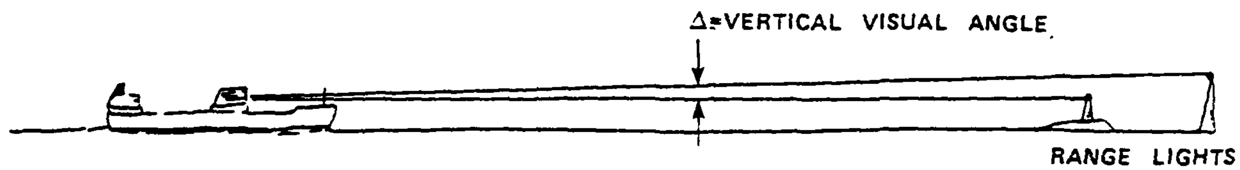


Figure B-1. Relationship Between Visual Angles and Crosstrack Displacement

TABLE B-1. LATERAL SENSITIVTY (K)

Values of K	Description of Sensitivity	Interpretation
Under 0.5	Not acceptable	Range must be improved or will be unworkable
0.5 to 1.0	Poor	Increase the sensitivity if physically possible, even if considerable cost is involved
1.0 to 1.5	Fair	Increase the sensitivity if doing so involves only moderate cost
1.5 to 2.5	Good	Increase the sensitivity only if very little cost is involved
2.5 to 3.5	Very good	Do not expend more funds to increase sensitivity
3.5 to 4.5	Excellent	Sensitivity should not be increased beyond this upper limit; might cause navigator to fear using those portions of the channel near the edge

TABLE B-2. VALUES FOR CROSSTRACK DISPLACEMENT X_O AS A FUNCTION OF CHANNEL WIDTH AND LATERAL SENSITIVITY

Channel Width	Low Sensitivity $K \approx 0.5$	High Sensitivity $K \approx 4.5$
800 feet	62.4 feet	6.9 feet
500 feet	39.0 feet	4.3 feet
300 feet	23.4 feet	2.6 feet

B.2 RANGE DESIGN

The range designs selected for the experiment were derived by a trial and error method which achieved: the desired values of X_Q, had a minimum vertical visual angle of 35 min arc, and exhibited realistic dimensions in terms of light locations and elevations.

Several limitations in the design were encountered and compromises were made. First, as with all ranges the sensitivity increased as the ship approached the range structures. Designs were, therefore, selected which exhibited X_Q values in the range of "high" and "low" sensitivity of Table B-2. Secondly, very long ranges designs which reduced the variability of X_Q over the channel leg resulted in unrealistically high range light elevations. Designs were therefore selected with exhibited light elevations below 300 feet. Finally, the length of the scenarios was limited to 7000 feet in each leg of the channel to achieve the desired range sensitivities over the leg.

Figures B-2 and B-3 illustrate the designs for high and low sensitivity ranges. The sensitivity parameters at both the beginning (position A) and end of each leg (position B) are listed in Table B-3. These parameters show that the X_Q values effectively encompass the high and low sensitivity values which appeared in Table B-2 for channel widths 300 to 800 feet. The one value of X_Q not addressed is for a low sensitivity range in an 800-foot wide channel where X_Q = 63 feet. Had this value been used as a design point, the sensitivity would have been far below that required as a minimum for a 500-foot channel (i.e., 39 feet). It is believed that piloting performance for X_Q = 63 feet may be extrapolated from the data with X_Q 38 feet.

Figure B-4 shows how crosstrack position sensitivity, X_Q varies as a function of alongtrack position. The relationship in the high and low sensitivity values are shown for comparison. This plot verifies that the "high" and "low" sensitivity ranges evaluated in this experiment are generally representative of ranges which exist in U.S. harbors where the majority of channel widths fall between 300 and 500 feet.

TABLE B-3. PARAMETERS FOR HIGH AND LOW SENSITIVITY RANGE DESIGNS

High Sensitivity	Crosstrack Position Sensitivity X_Q	Lateral Sensitivity K	Vertical Visual Angle Δ
Position A	6.3 feet	3.0	35 min arc
Position B	1.8 feet	10.0	48 min arc
Low Sensitivity			
Position A	38.0 feet	0.5	35 min arc
Position B	23.0 feet	0.8	48 min arc

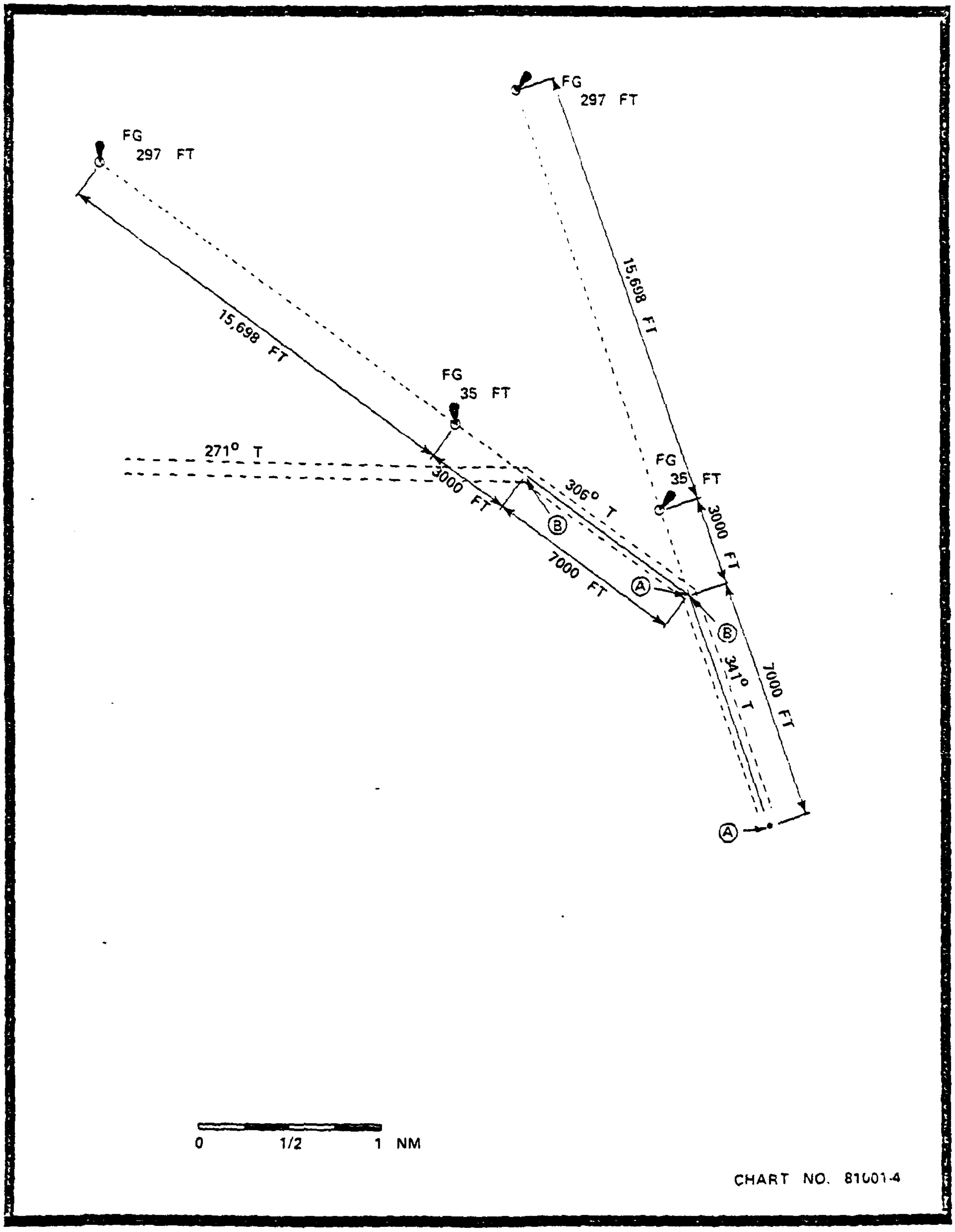


Figure B-2. Design Details for High Sensitivity Ranges

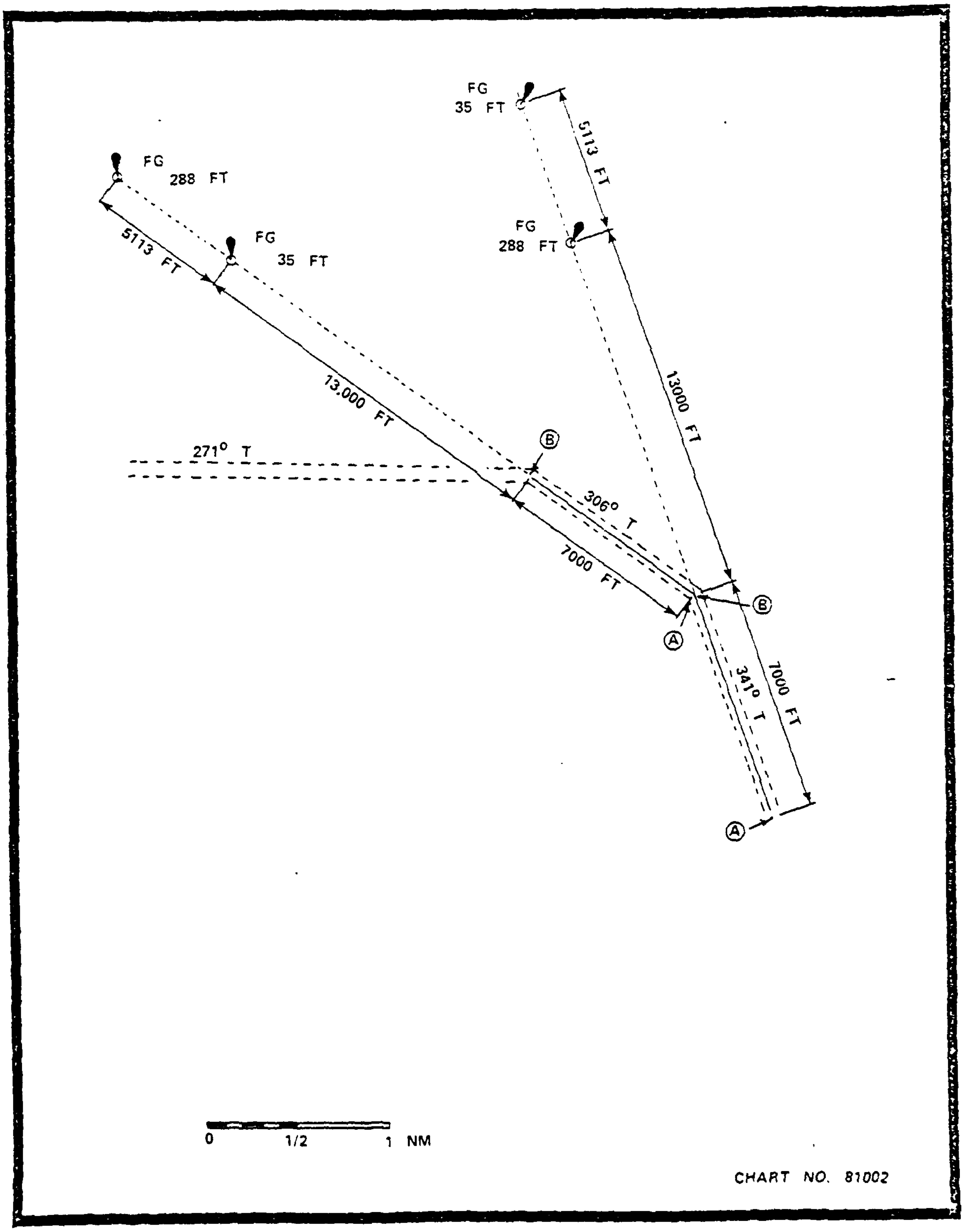


Figure B-3. Design for Low Sensitivity Ranges

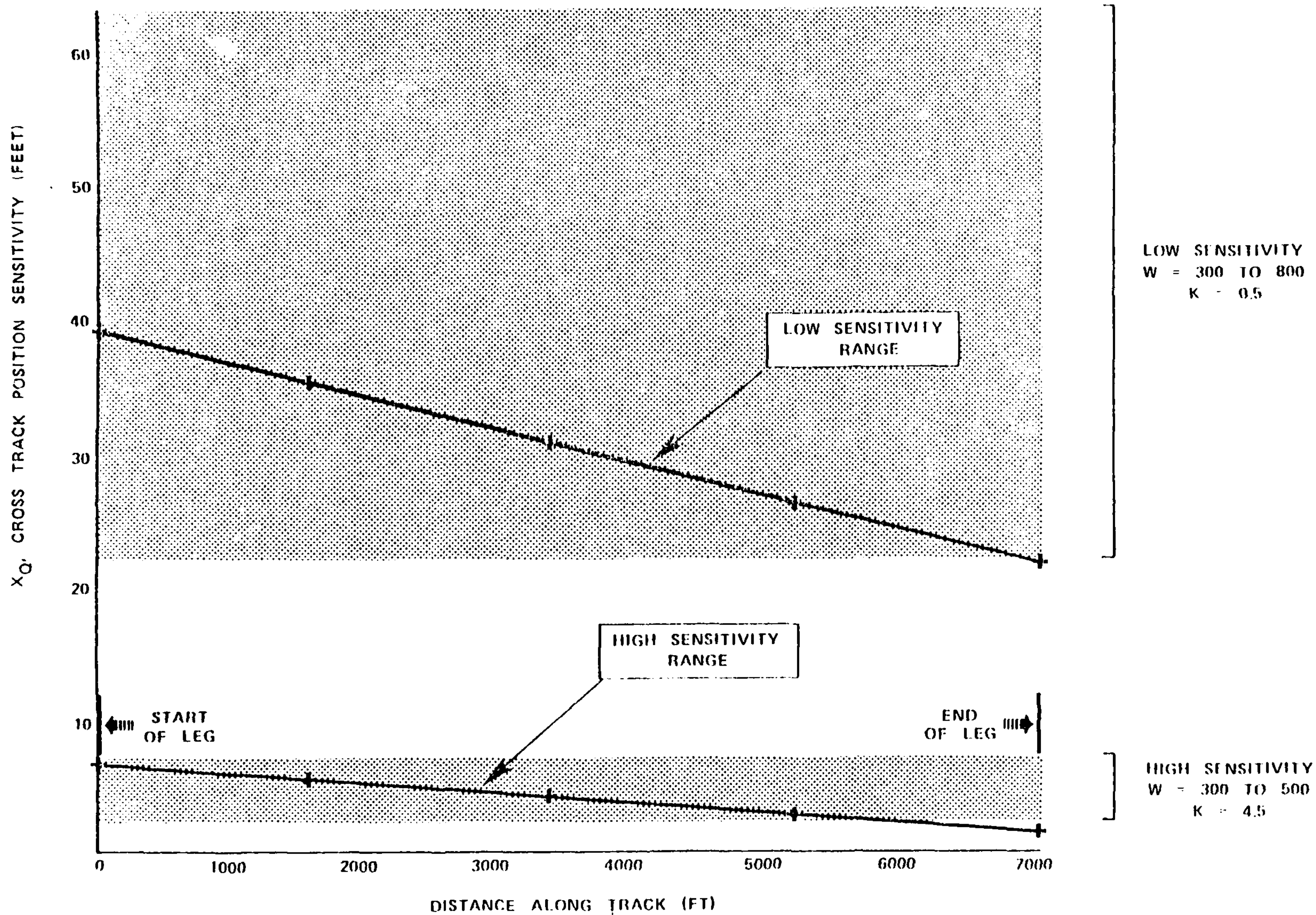


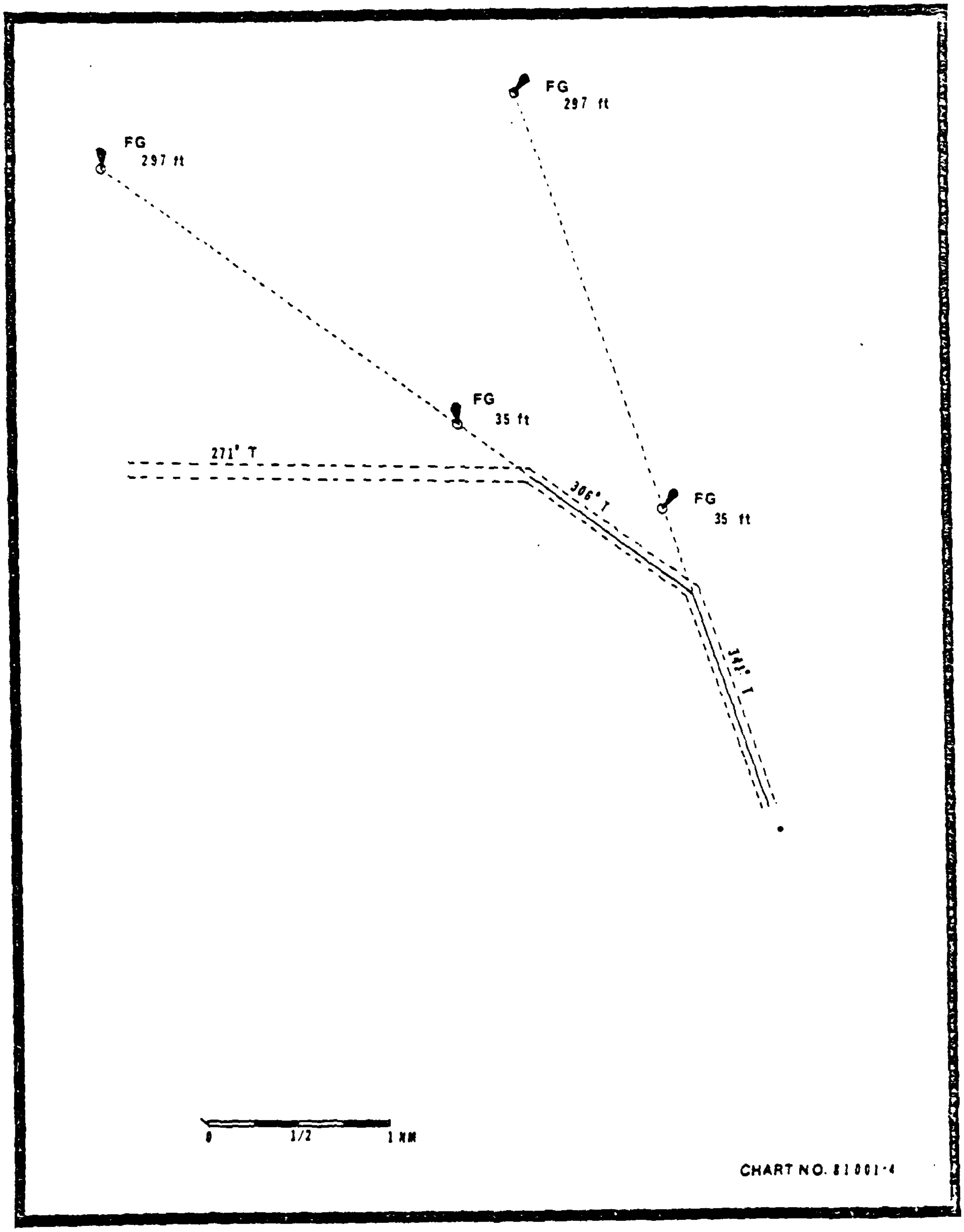
Figure B-4. Crosstrack Position Sensitivity as a Function of Alongtrack Position

APPENDIX C

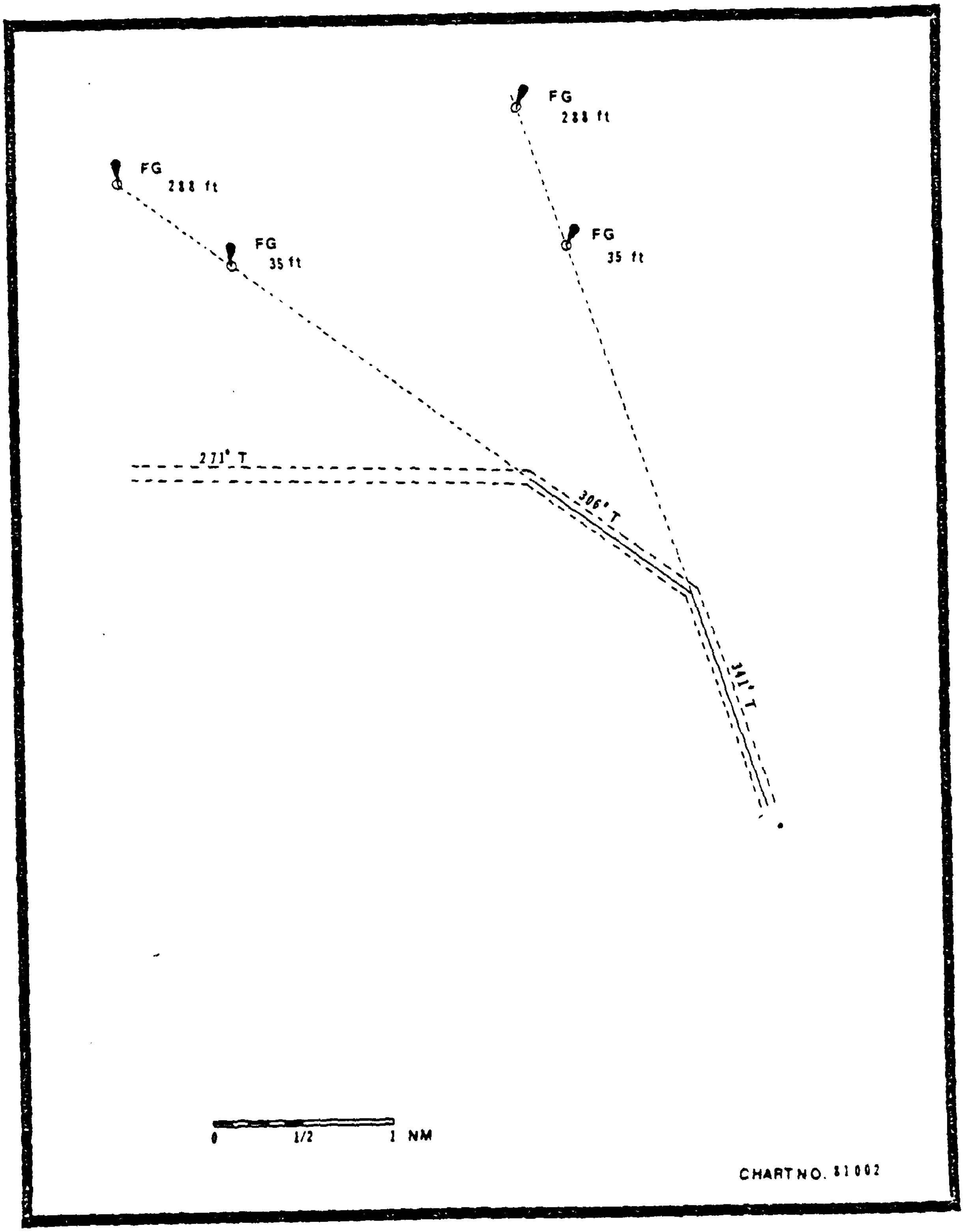
EXPERIMENTAL SCENARIOS

Scenario*	Degree of Turn	Range Sensitivity		Intended Track
		Leg 1	Leg 2	
1	35 degree	High ($K \approx 4.5$)	High ($K \approx 4.5$)	Centerline
2	35 degree	Low ($K \approx 0.5$)	Low ($K \approx 0.5$)	Centerline
4	35 degree	High ($K \approx 4.5$)	High ($K \approx 4.5$)	Quarterine
5	15 degree	High ($K \approx 4.5$)	High ($K \approx 4.5$)	Centerline
6	35 degree	High ($K \approx 4.5$)	Low ($K \approx 0.5$)	Centerline

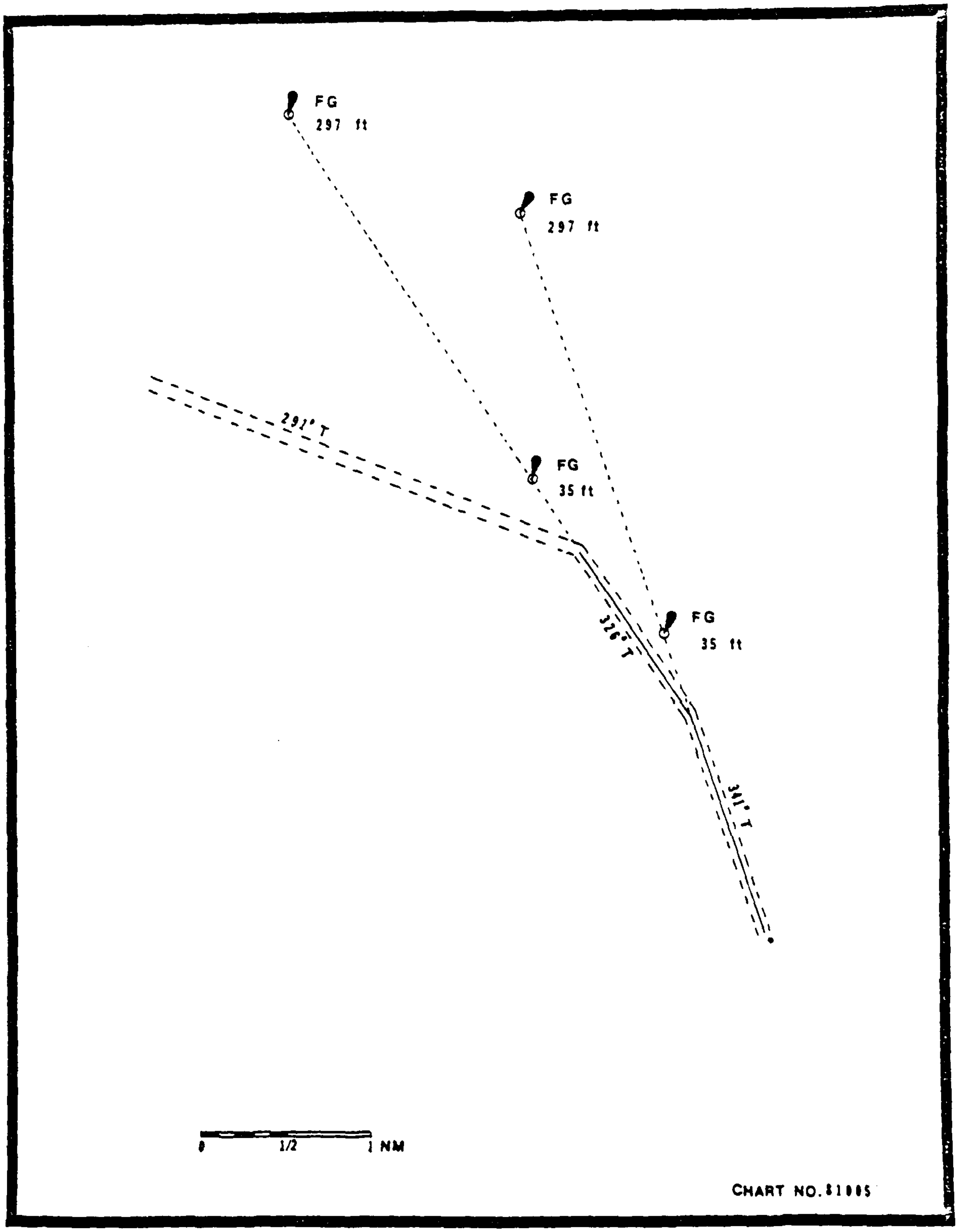
*Note: Scenario 3 eliminated from experiment.



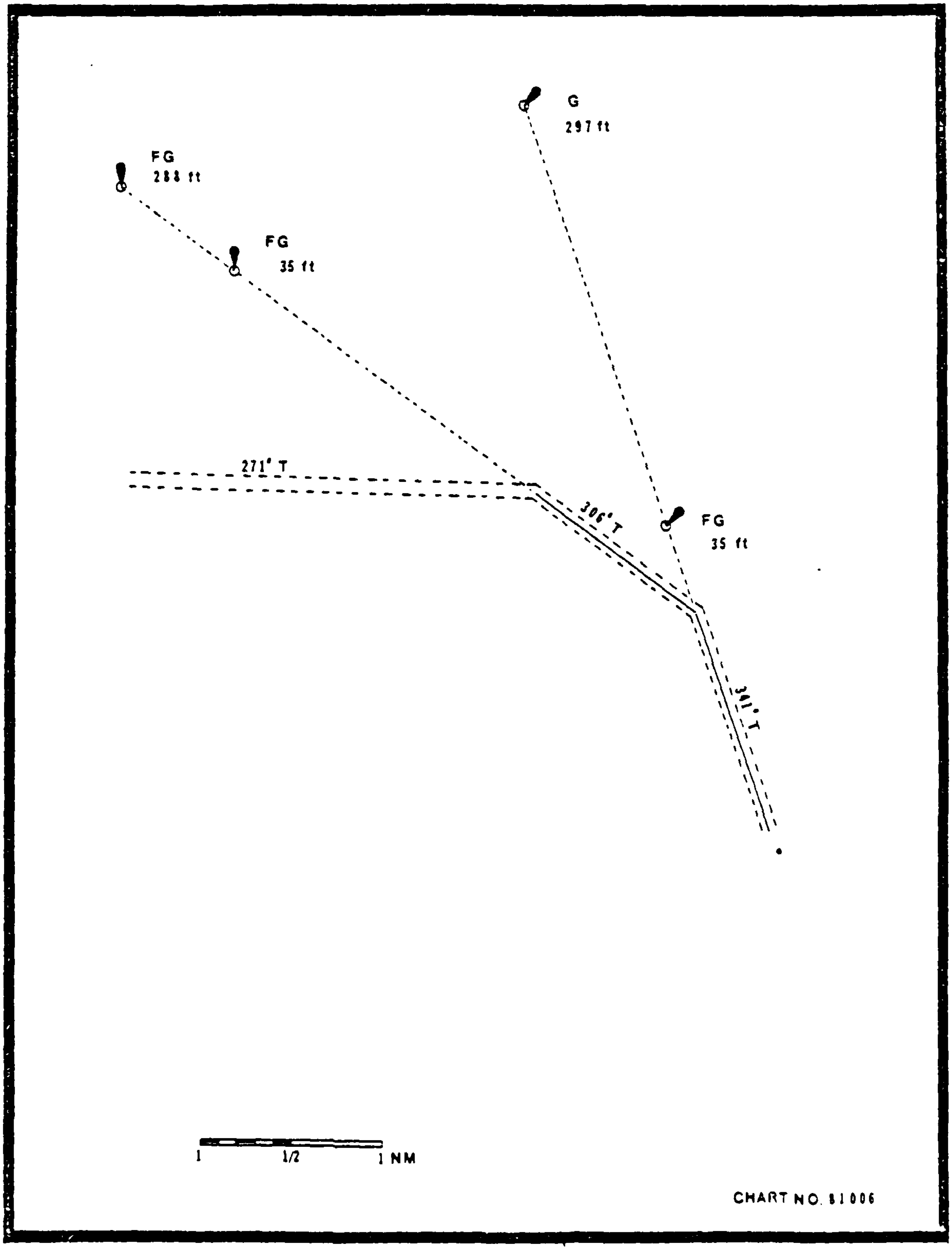
Scenario 1 and 4: Two High-Sensitivity Ranges



Scenario 2: Two Low-Sensitivity Ranges



Scenario 5: A-15-Degree Turn



Scenario 6: Turning From Low-To High-Sensitivity Range

Appendix D

RANGE LIGHT EXPERIMENT: INSTRUCTIONS TO THE PILOT

D.1 INTRODUCTION

The purpose of this experiment is to evaluate range lights for piloting. The present experiment provides range lights as the only aid for a variety of piloting tasks. These tasks include trackkeeping on the centerline, the tasks for which range lights are obviously suited. It is also of interest, however, to examine the usefulness of range lights for tasks for which they are less suited. The scenarios will also include maneuvering through turns, maneuvering to track both on and off range, and trackkeeping off the range.

There will be a total of six scenarios. The first will allow you to familiarize yourself with the ship and the wind and current. The other five are the experimental scenarios. They will be approximately a half hour each.

D.2 CONDITIONS COMMON TO ALL SCENARIOS

a. The Channel and Environmental Conditions: The general layout of the channel for the 35-degree turns is illustrated in Figure 1. The channel is 500 feet wide and 35 feet deep (one foot below the keel). There is a 35-degree turn to the left without a cutoff. The whole scenario has shallow water effects. There are no bank effects in the channel.

For the channel with 35-degree turns, the current is 1-1/4 knots at 341 degrees T at the beginning of the run. It moves up the channel in its first leg, decreasing to 3/4-knot at the turn. There, it is broad on the port quarter at the pullout. In the second leg, the current gradually turns to follow the channel again. It decreases in speed until it is zero knots when the scenario ends.

For the channels with 35-degree turns, there is a gusting wind averaging 30 knots throughout the scenario. It maintains an average direction of 161 degrees T throughout the run. A description of the 15-degree turn will be given later.

b. The Ship: The ship is a 30,000 dwt tanker with a split-house configuration and a viewing point located 75 feet forward from the ship's center of gravity. It has a 595 LOA, an 84 foot beam, a 45 foot height of eye, and a 34 foot draft. It will handle as if it were in shallow water.

c. Speed: Speed at initialization will be 6 knots through the water. Please maintain the set speed. You may change speed to negotiate the turn if you think it necessary. Please return to the initial speed as soon as possible in the second leg.

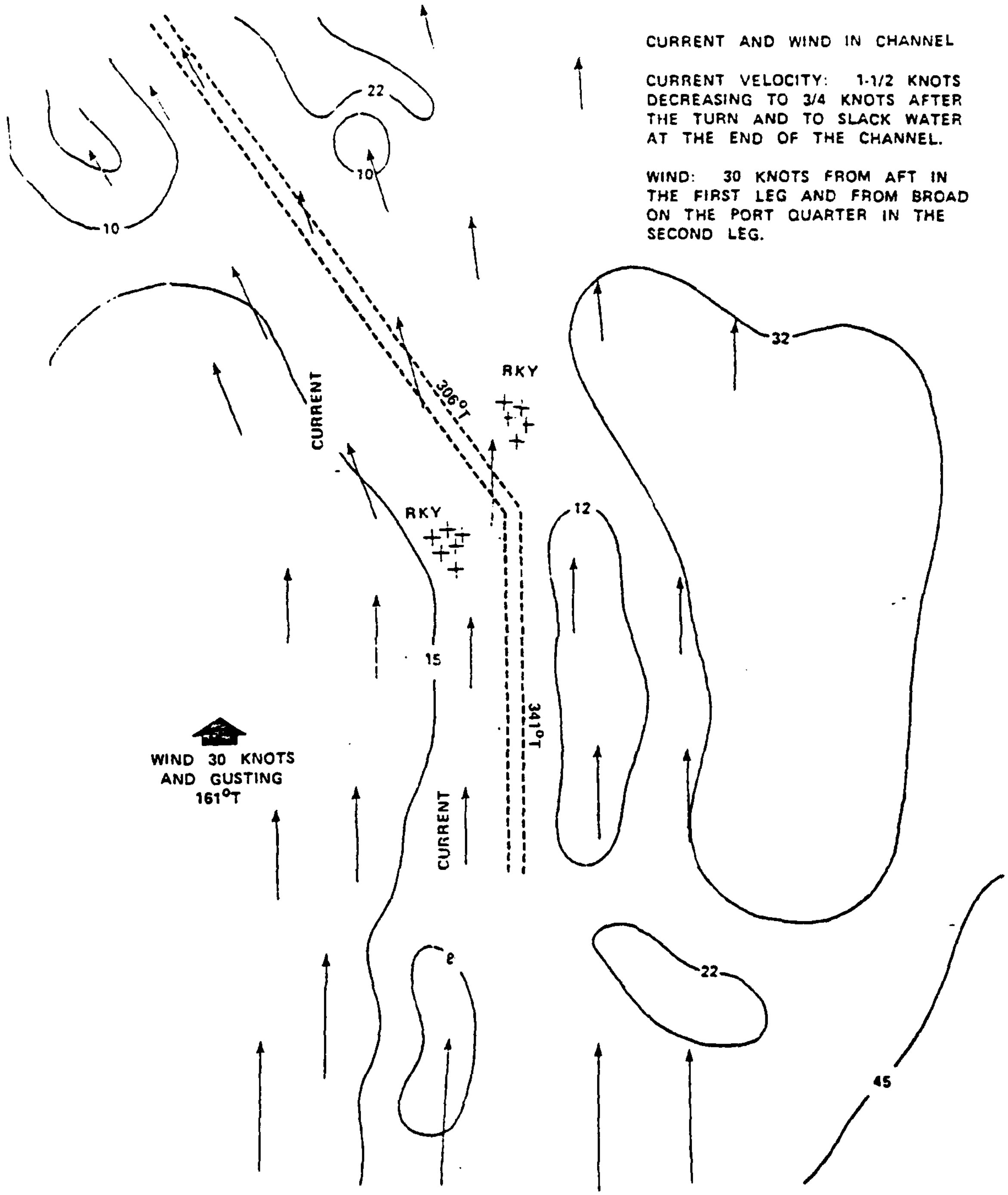


Figure D-1. Current and Wind in Channel

d. Initialization Conditions: In all five scenarios the ship will be initialized 1.3 nm before the turn and 92 feet to the right of the centerline with a heading equal to the channel course of 341 degrees T. You will be requested to maneuver the ship and maintain it on either the centerline or the right quarterline. The information as well as the other experiment variables will be provided to you on individual cards for each scenario.

D.3 FAMILIARIZATION SCENARIO

This scenario will be run under daylight conditions with a high density of buoys marking the channel to give you the opportunity to familiarize yourself with the ship and the wind and current. The ship will be initialized 1.3 nm below the turn and 92 feet to the right of the centerline. Please move the ship to the centerline as quickly as you think prudent and keep it on the centerline until you approach the turn. You may move off the centerline and negotiate the turn as you prefer. Figure 1 illustrates the wind and current effects in leg 1. Please return to the centerline as soon as practical.

D.4 SCENARIO 1 - THE HIGH SENSITIVITY RANGE

Scenario 1 will be run under nighttime conditions with two ranges as the only aid. Please study the chart to acquaint yourself with the ranges. Notice that there is a considerable difference in the heights of the two lights as if the rear light is on a hill above the water. Notice that the channel is close to the front light and that there is a relatively long distance between the two lights. This combination of dimensions means:

a. The vertical distance between the lights on the screen will be large.

b. The ranges will be quite sensitive -- it will be relatively easy to judge the crosstrack motion of the ship.

The ship will be initialized 1.3 nm below the turn and 92 feet to the right of the centerline with a heading of 341 degrees T equal to the course of the channel. Please move the ship to the centerline as quickly as you think prudent and maintain the centerline until ready to make the turn. It is a 35-degree turn. Make the turn by your preferred strategy. For the turn, the ranges marking the two legs are the only aids available. The first range enables you to judge the ship's crosstrack position in leg 1. The appearance of the range for leg 2 is the only aid for judging the distance to the turn. After the turn, please return to the centerline and maintain it until the end of the scenario.

D.5 SCENARIO 2 - THE LOW SENSITIVITY RANGES

Scenario 2 will be run under nighttime conditions with two ranges as the only aid. Please study the chart to acquaint yourself with the ranges. Notice there is a considerable difference in the heights of the two lights as if the rear light were on a hill above the water. Notice that the channel is far from the first light and that there is a relatively short distance between the lights. This combination of dimensions means:

a. The vertical distance between the lights on the screen will be large.

b. The ranges will be of low sensitivity -- it will be relatively difficult to judge the crosstrack motion of the ship. The ship will have to move a relatively large crosstrack distance before the move is apparent.

The ship will be initialized 1.3 nm below the turn and 92 feet to the right of the centerline with a heading of 341 degrees T equal to the course of the channel. Please move the ship to the centerline as quickly as you think prudent and maintain the centerline until ready to make the turn. It is a 35-degree turn. Make the turn by your preferred strategy. For the turn, the ranges marking the two legs are the only aids available. The first range enables you to judge the ship's crosstrack position in leg 1. The appearance of the range for leg 2 is the only aid for judging the distance to the turn. After the turn, please return to the centerline and maintain it until the end of the scenario.

D.6 SCENARIO 4 - TRACKKEEPING ON THE QUARTERLINE

Scenario 4 will be run under nighttime conditions with two ranges as the oly aid. Please study the chart to acquaint yourself with the ranges. Notice there is a considerable difference in the heights of the two lights as if the rear light were on a hill above the water. Notice that the channel is close to the front light and there is a relatively longer distance between the two lights. This combination of dimensions means:

a. The vertical distance between the lights on the screen will be large.

b. The ranges will be quite sensitive -- it will be relatively easy to judge the crosstrack motion of the ship.

The ship will be initialized 1.3 nm below the turn and 92 feet to the right of the centerline with a heading of 341 degrees T equal to the course of the channel. Please move the ship to the center of the right-nand half of the channel. That is, 125 feet to the right of the centerline or 33 feet to the right of the initialization position.

Please maintain this track until the turn. Make the turn by your preferred strategy. For the turn, the ranges marking the two legs are the only aids available. The first range enables you to judge the ship's crosstrack position in leg 1. The appearance of the range for leg 2 is the only aid for judging the distance to the turn. After the turn, please return to the quarterline track.

D.7 SCENARIO 5 - A 15-DEGREE TURN

Scenario 5 will be run under nighttime conditions with two ranges as the only aids. Please study the chart to acquaint yourself with the ranges. Notice there is a considerable difference in the heights of the two lights as if the rear light were on a hill above the water. Notice that the channel is close to the front light and there is a relatively longer distance between the lights. This combination of dimensions means:

a. The vertical distance between the lights on the screen will be large.

b. The ranges will be quite sensitive -- it will be relatively easy to judge the crosstrack motion of the ship.

Notice that the wind and current conditions are slightly different for the 15-degree turn. The average direction of the wind is 161 degrees T. In leg 2, with the 15-degree turn, the wind is closer to following then for the 35-degree turn. The current is also closer to following.

The ship will be initialized 1.3 nm below the turn and 92 feet to the right of the centerline with a heading of 341 degrees T equal to the course of the channel. Please move the ship to the centerline as quickly as you think prudent and maintain the centerline until ready to make the turn. It is a 15-degree turn. Make the turn by your preferred strategy. For the turn, the ranges marking the two legs are the only aids available. The first range enables you to judge the ship's crosstrack position in leg 1. The appearance of the range for leg 2 is the only aid for judging the distance to the turn. After the turn, please return to the centerline and maintain it until the end of the scenario.

D.8 SCENARIO 6 - TURNING FROM A HIGH SENSITIVITY TO A LOW SENSITIVITY RANGE

The two channel segments in Scenario 6 are marked by two differently designed ranges. Please study the chart to acquaint yourself with their characteristics. Notice that for both ranges there is a considerable difference between the heights of the front and rear lights as if the rear light was on a hill above the water. This means that for both ranges there will be a considerable vertical distance between the lights on the screen. The range in leg 1 is relatively close to the channel with a relatively long distance between the lights. This results in a range that is quite sensitive; crosstrack motion of the ship is easily detected by movements of the lights. The range in leg 2 is relatively far from the channel with a relatively short distance between the two lights. This results in a range of low sensitivity; relatively large crosstrack motion of the ship is necessary before such movement is apparent.

The ship will be initialized 1.3 nm below the turn and 92 feet to the right of the centerline with a heading of 341 degrees T equal to the course of the channel. Please move the ship to the centerline as quickly as you think prudent and maintain the centerline until ready to make the turn by your preferred strategy. For the turn, the ranges marking the two legs are the only aids available. The first, high sensitivity; range makes it relatively easy to judge the ship's crosstrack position in the leg. Only the appearance of the low sensitivity range for leg 2 is available for judging the distance to the turn. After the turn, please return to the centerline and maintain it until the end of the scenario.

D.9 RANGE LIGHT EXPERIMENT: POSTSIMULATION QUESTIONNAIRE

(The instructions, charts, and cards are available as reminders of the experimental conditions.)

1.0 The simulation of the ranges.

1.1 Were the designs, or configurations, of the ranges as presented on the charts realistic?

1.2 Were the appearance and behavior of the ranges during the simulation what you would have expected from the charts?

1.3 Was it helpful to have the charts available beforehand?

1.4 Did the ranges, as simulated, have any effect on your piloting you would like to describe? In other words, did you use them as you would have used real world ranges?

2.0 Scenario 1 -- The High Sensitivity Ranges as a Standard

2.1 Were the ranges adequate aids for a safe transit in your opinion?

2.2 Was the range adequate for finding the centerline and for track-keeping in leg 1? Would you describe your use of the range for doing this?

2.3 Were the ranges adequate for making the turn? Would you describe the technique you used for turning from range to range?

2.4 Do you think there was an improvement in your turns over successive scenarios even though each was different in some way? For how many scenarios did there continue to be an improvement? What changes did you make with practice?

2.5 Was the range adequate for finding the centerline in leg 2? Would you describe your technique for using the ranges for this?

3.0 The Other Conditions Compared to Scenario 1

3.1 Scenario 2 - The Low Sensitivity Ranges

Was there a difference in piloting techniques with the low sensitivity ranges? Was there a difference in the results?

3.2 Scenario 4 - The Quarterline Track

Was there a difference in piloting technique with the quarterline track? Was there a difference in the results? Was performance on the quarterline track disadvantaged because the familiarization run had been made on the centerline?

3.3 Scenario 5 - The 15-Degree Turn

Was there a difference in piloting technique with the 15-degree turn? Was there a difference in the results? Was performance on the quarterline track disadvantaged because the familiarization run had been made with a 35-degree turn?

3.4 Scenario 6 - High Sensitivity to Low Sensitivity Turn

How did turn technique and results differ from those in Scenario 1?

Scenario 2?

Appendix E

WIND AND CURRENT VARIATIONS

E.1 INTRODUCTION

The wind and current variations are the same that were used in the Ship Variables experiment. (In the presimulation report for that experiment, they are compared to the effects in the Channel Width and CAORF experiments.) Both parameters are time varying functions which produce difficult (but realistic) piloting and steering tasks.

E.2 CURRENT

The current direction is constant throughout the one-side experiment. The magnitude of the current, however, decreases with elapsed simulation run time such that the current reaches 0 knots near the end of the scenario. The current direction and magnitude functions are listed below. A plot of current magnitude versus time is shown in Figure C-1.

Current Direction

TWC = 341 (degrees)

Current flows towards this bearing.

Current Magnitude (calculated for four points (I) along the hull)

$$RVWC(I) = VWC(I) \text{ cosine } [(TMULT)(T1MAIN + TADD)(\pi/180)]$$

where:

VWC(I) = 2.5317 feet/second (1.5 knots)
TMULT = 2
T1MAIN = elapsed run time (minutes)
TADD = 18.0 (minutes) = initial offset time

C.3 WIND

The wind direction and speed are both time varying. The wind functions for the one-side experiment are listed below. A plot of the magnitude function is shown in Figure C-2. A plot of the direction function is shown in Figure C-3.

AD-A109 716 ECLECTECH ASSOCIATES INC NORTH STONINGTON CT F/G 17/7
AIDS TO NAVIGATION PRINCIPAL FINDINGS REPORT: RANGE LIGHT CHARA--ETC(U)
DEC 81 K L MARINO, M W SMITH, W R BERTSCHE DOT-CG-835285-A
UNCLASSIFIED EA-81-U-077 USCG-D-66-81 NL

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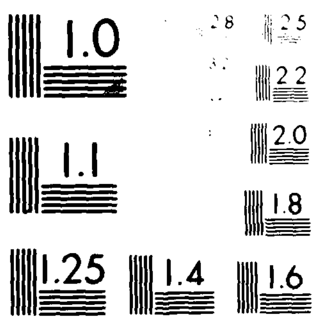
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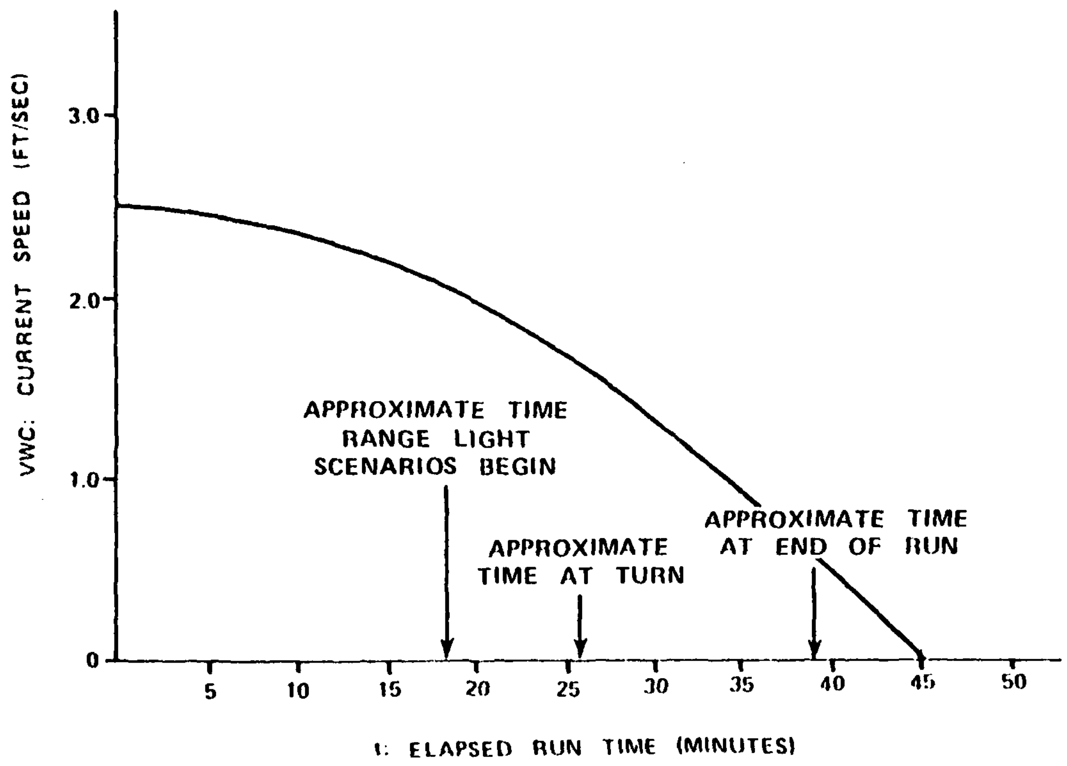

VWC = 2.53 cos (t + to) ft/sec

Figure E-1. Current Speed Function

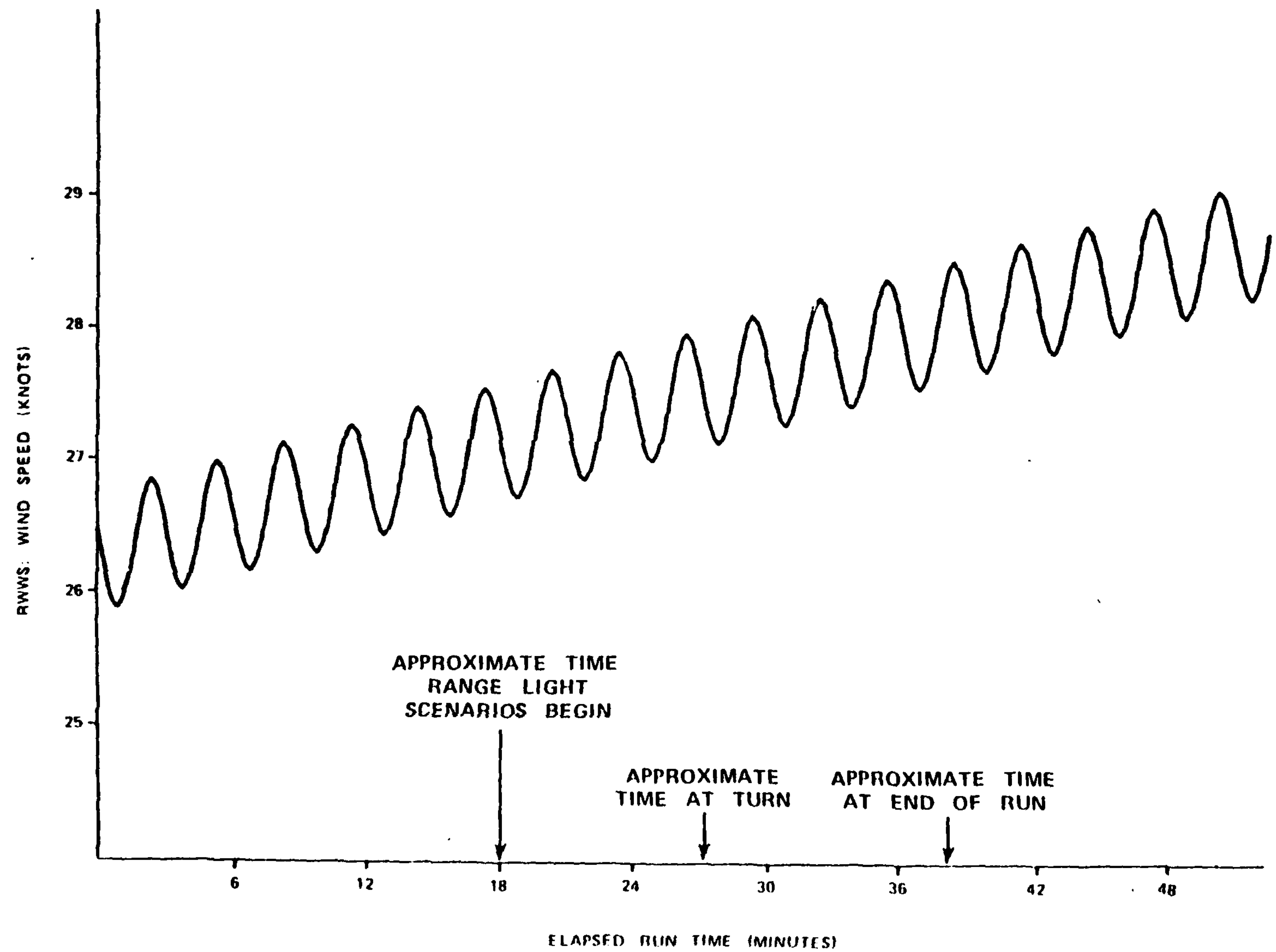

Figure E-2. Wind Speed Function

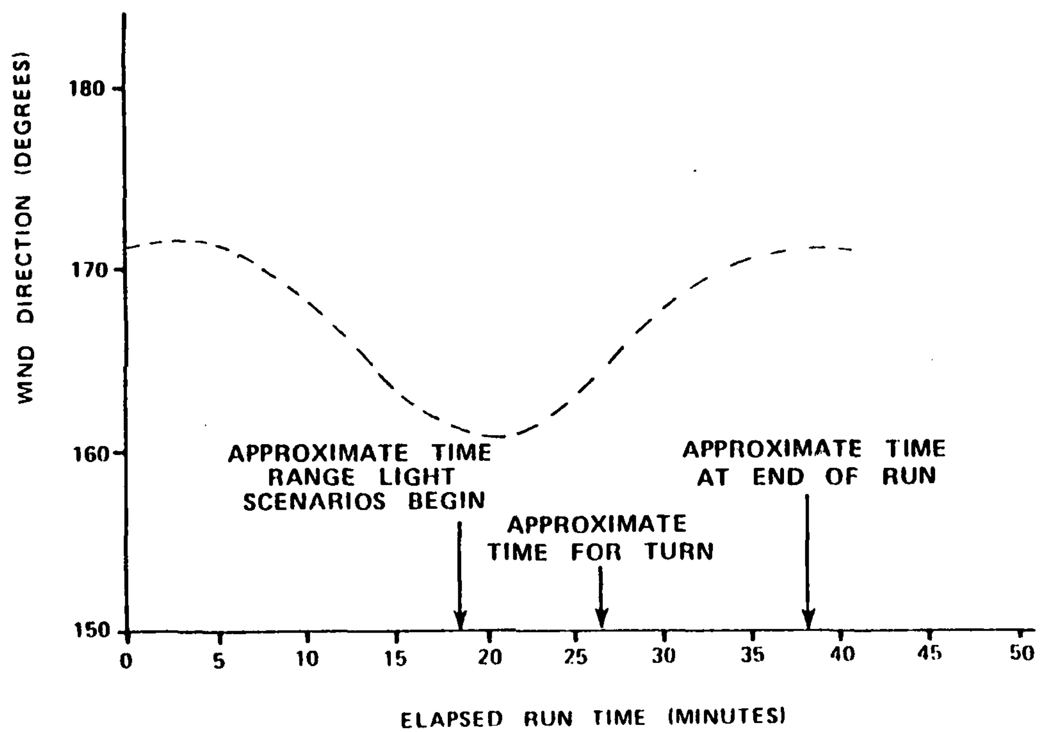

Figure E-3. Wind Direction Function

Wind Speed

$$RWWS = WWS + (0.0019)\ (T1MAIN + TADD - 18.0)\ (WWS) + (0.02)\ (WWS)\ \text{sine}\ [(T1MAIN + TADD - 18.0)\ 2\ \pi/3]$$

where:

WWS = 26.75 knots
TADD = 18.0 (minutes)
T1MAIN = elapsed run time (minutes)

Wind Direction

$$RWWD = WWD + (6)\ \text{cosine}\ [(T1MAIN + TADD - 6)2\ \pi/36]$$

where:

WWD = 166 degrees (direction from which wind blows)
T1MAIN = elapsed run time (minutes)
TADD = 18.0 (minutes)

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