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SIMULATOR EVALUATION OF ELECTRONIC RADIO AIDS TO NAVIGATION DIS--ETC(U)

JUL 81   R B COOPER, K L MARINO, W R BERTSCHE   DOT-CG-835285-A

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SIMULATOR EVALUATION OF ELECTRONIC RADIO AIDS TO NAVIGATION DISPLAYS

THE RA-2 EXPERIMENT

Eclectech Associates, Incorporated
North Stonington Professional Center
North Stonington, Connecticut 06359

July 1981

Interim Report

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16. Abstract

The report describes a ship's bridge simulation evaluation of an electronic radio aids to navigation display for use by pilots in restricted waterways. The experiment known as RA-2 is the third in a series of experiments to trade off display information effectiveness with operational requirements and shipboard system cost. The RA-2 evaluation used a "benchmark" true motion, trackup GRAPHIC display recommended in the previous experiment to conduct simulated poor visibility runs of a 30,000 dwt tanker around a 35-degree left bend in a 500-foot-wide channel. Experimental variables included two different navigation system noise levels which translated to random position errors of 16 and 32 meters RMS, and the use of an ALPHA-BETA tracker with 3-, 12-, or 24-second rise time, or gyro aiding, to represent a state-of-the-art navigation system filtering capability. Evaluation criteria included pilot trackkeeping and maneuvering performance as well as system acceptance. The report describes the rationale for variable selection, how they were simulated, and their potential effect on restricted waterway pilotage when the "benchmark" display is used.

17. Key Words
ship simulator, bridge display, bridge equipment, electronic aids to navigation, navigation displays, digital navigation display, graphic navigation display (see 17 cont'd)

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17. KEY WORDS (CONTINUED)

perspective navigation display, shiphandling, trackkeeping, crosstrack variability, crosstrack distance, rudder actuations, magnitude of rudder, turning cues, orientation cues, ownship image cues, vector cues

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Our special gratitude to the members of the Northeast Marine Pilots Association who took time from their busy schedules to act as subjects for the experiment. Each acquired an enthusiastic interest in the project and provided valuable insight as potential users of radio aids to navigation systems.

PREFACE

The simulation experiment described herein is the third of a multiple experiment program for the operational evaluation of radio aids to navigation displays. The intent of the overall program is to investigate navigational safety as a function of display cost, complexity and system error characteristics. The results will define the requirements for an electronic display which will allow safe pilotage of vessels in poor visibility conditions keeping in mind all economic, technological and feasibility constraints.

The report briefly reviews the conduct and results of each of the previous experiments which led to the present RA-2 experiment. It also describes in detail the RA-2 simulator evaluation which consisted of sixty-four 35-minute runs to determine the effects of electronic navigation system noise, tracking filter design and tracking filter aiding technique on restricted waterway pilotage. Using the "benchmark" true motion, track-up GRAPHIC display recommended in the RA-1 experiment, the RA-2 evaluation was conducted in controlled levels of random noise to simulate potential real world operating conditions. An ALPHA-BETA tracker with three preselected rise times and gyro aiding was introduced to represent the potential capability of a state-of-the-art navigation system. With the exception of a shortened first leg of the waterway, conduct of the RA-2 experiment was identical to the RA-1 experiment. Some performance measures which were shown in the RA-1 experiment to be ineffectual for examining pilotage behavior, are omitted in the RA-2 analysis. Results of the entire program including recommendations for display design, system implementation, and additional experimentation are presented.

"The ultimate objective of the program will be realized by a combination of the performance metric, the various signal-to-noise ratios, and filter bandwidths into a definitive statement about the ability of a pilot to navigate a restricted waterway in limited visibility conditions."[1]

---

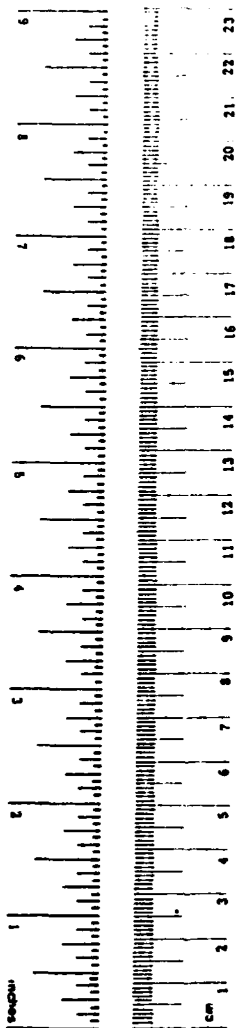
[1]United States Coast Guard. An Approach to the Study of Electronic Displays for Use in Restricted Waterways, a Position Paper. December 1979.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

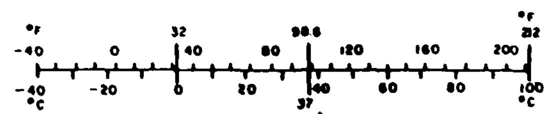
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	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

[illegible] 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

SUMMARY OF CONCLUSIONS

This summary of conclusions is derived from a review of the entire simulator evaluation of electronic radio aids to navigation displays project. The review included the miniexperiment and RA-1 experiments which presented ownship on the display using "perfect" position information. These experiments were conducted to select a "benchmark" display for further evaluation. The review also included the RA-2 experiment reported herein which was conducted to determine the effects of noise environment and tracker filter design on the benchmark display. Evidence in support of these conclusions as well as a detailed description of the experimental variables can be found in the respective interim reports. Evidence in support of RA-2 conclusions is presented in Section 5 of this report.

1.1 EFFECT OF DISPLAY FORMAT

Selection of a format design for the benchmark display was based upon (1) its safety and operational effectiveness for the conduct of restricted waterway pilotage under poor visibility conditions, (2) its acceptance as an aid to navigation by potential users, and (3) its cost-effective implementation and usage. Results of the initial experiments showed that while certain formats excelled in one or the other criteria, only the GRAPHIC display was deemed favorable in all of them. Table 1 presents the categories of displays which were evaluated along with a brief description of the deficiencies and attributes which were revealed. Displays are listed in their order of preference with the first (GRAPHIC) being recommended as the benchmark display.

As a result of the pragmatic approach adopted by this project and an appreciation that the final RA-2 experiment should employ the display with the "best chance for success", the true motion, track-up GRAPHIC display with a heading vector and own ship's scaled image was selected.

1.2 EFFECT OF NOISE AND TRACKER DESIGN

Simulation of the benchmark display as though it were being used with an actual navigation system produced a previously unaddressed problem; the effects on pilotage of display lag and jitter. A detailed description of the causes for display lag and jitter and their relationship to system noise levels and jitter design is presented in Section 2.3.

Briefly, jitter is the "jumping around" of own ship on the display as a function of random position errors from the navigation system. As noise to the navigation system increases, so does the magnitude of the jitter. Mathematical tracker filters can be introduced into the system to reduce the jitter effects of noise. They, however, produce a display lag which, once ownship begins to maneuver, produces a bias error proportional to their filtering capability. The better the tracker is at noise filtering, the larger its potential lag. To compensate for the lag deficiency, tracker filters can be aided by gyro compass inputs which modify their filter computation. This in turn enables the tracker to produce minimal display jitter from noise and minimal lag during a maneuver; both, however, at the potentially substantial cost of a gyro input.

TABLE I. CONCLUSIONS OF THE DISPLAY FORMAT EVOLUTION

DISPLAY	ATTRIBUTES AND DEFICIENCIES
GRAPHIC Display	• Superior maneuvering performance with scaled ownship's image. • Superior trackkeeping performance in track-up orientation. • Superior maneuvering performance with heading vector. • Superior trackkeeping performance with course vector. • True motion feature compatible with existing navigation system (i.e., PILOT). • Moderate cost system. • Very high user acceptance (preferred display); minimal familiarization required; perceived to have moderate accuracy but high reliability in the real world application.
Simplified Predictor STEERING Display	• Satisfactory overall performance. • Potential for achieving superior overall performance through familiarization, experience, training, etc. • Moderate cost system. • High user acceptance; some difficulty understanding predictor indication.
Predictor STEERING Display	• Superior overall performance. • High cost • High user acceptance; perceived to have high accuracy but low reliability in the real world application.
PERSPECTIVE Display	• Superior maneuvering performance with 90-degree field of view (point of the bend was visible longer). • Poor trackkeeping performance with both 60-and 90- degree fields of view (difficulty returning to the centerline.' • Moderate cost system. • Moderate user acceptance (subjects originally anticipated high performance with this display but could not achieve their goals).

TABLE 1. CONCLUSIONS OF THE DISPLAY FORMAT EVOLUTION (CONT.)

DIGITAL Display with Turn Recommendations	• High variability in overall performance among subjects. • Decreased variability in maneuvering performance when turn information was initiated automatically instead of operator selected. • Major difficulty in recovering from the turn and steadying up on the centerline. • Some difficulty in determining when to initiate the turn, even when the information was provided automatically. • Comparable performance regardless of whether course error, heading to steer, or no steering cue was displayed. • Comparable performance regardless of whether distance to leadline or time to leadline was displayed. • Low cost system. • Low user acceptance resulting from inability to "prove" the display and become familiar with it to the subjects' satisfaction; perceived to have high accuracy and high reliability in the real world application.
Simplified DIGITAL Display	• Poorest overall performance, highest overall variability in maneuvering and trackkeeping among pilots. • General inability to safely negotiate the bend. • Difficulty in determining the amount and timeliness of initial turn rudder, subsequent turn rudder, and check rudder. • Excessive overshoot by some subjects and undershoot by others both in the bend and attempting to steady up on the centerline. • Low cost system. • Very low user acceptance primarily the result of insufficient experience with the display; but also the premise that no pilot would attempt this maneuver in the real world with such scant information.

Table 2 summarizes pilotage performance as a function of the trade-offs in noise and tracker design. It suggests that use of the electronic radio aids to navigation display alone never achieved trackkeeping or maneuvering performance comparable to those simulations in which pilots could view out the windows. There is evidence, however, that if pilots were given the opportunity to "prove" the display during good visibility, and if the display design was made somewhat more effective, the system's safe use under these operating conditions could be assured.

The following conclusions are derived from Table 2 and the detailed analysis described in Section 5:

- Those same difficulties in negotiating the bend during the previous experiments, namely, a tendency to overshoot the bend and high crosstrack variability in steadying up, were also in evidence during the best pilotages with simulated noise and tracker characteristics.

- The lag characteristic of trackers in this scenario made it appear that pilotage performance was actually improved. This lag caused pilots to apply more rudder than they normally would, thus reducing the characteristic overshoot problem discussed above. Although it appeared from the tracks-made-good that the pilotage was superior; the fact that pilots were not where they thought they were, and that they had experienced considerable anxiety over the ship's lack of initial response indicates a relatively unsafe pilotage. Further, were the display made more effective, or were a different scenario used (e.g., different speed or type of maneuver) this particular effect of lag might not occur.

- Lag resulting from tracker design was shown to have more deleterious effects on overall pilotage performance than jitter from noise for the variables and conditions tested in the experiment.

- The relatively large lag exhibited by the trackers with 24-second rise time produced difficulty in all aspects of maneuvering. This was evidenced in the pilots' perceived shiphandling difficulties as well as a potential for major undershoot of the bend.

- The moderate lag exhibited by trackers with 12- second rise times produced potential for undershooting the bend, some difficulty recovering from the turn maneuver, but more importantly, there was less pilot anxiety through the maneuvers and relatively good trackkeeping as a result of minimal jitter.

- For pilots who negotiated the bend keeping ownship in the center of the channel on the display (i.e., their best performance), the effects of lag caused their ship to pass inside the bend, steadying up on the left side of the channel, and very gradually returning to the centerline. In the event of approaching traffic, this maneuver is potentially unsafe.

- The effects of tracker lag are virtually unknown to the pilot except for the perceived unpredictable handling characteristics of the ship during a maneuver. This results in the track-made-good being off-set from the intended track for a distance approximately equivalent to the lag error and in the direction opposite the lag error. If the lag error were biased to the outside of the turn maneuver (such as occurred in this experiment), ownship would actually track inside (i.e., undershoot) the bend, unbeknownst to the pilot.

TABLE 2. SUMMARY OF PILOTAGE PERFORMANCE BY TRACKER DESIGN

EFFECTS OF TRACKER RISE TIME

	Shortest Rise Time (3-second)	Middle Rise Time (12-second)	Longest Rise Time (24-second)
Lowest Noise Level (16 meter rms)	• perceived as accurate • perceived minimal difficulty steadying up and staying on the centerline • small random error throughout the pilotage • minimal bias error when maneuvering through the bend • piloting performance comparable to "perfect position" display (RA-1)	• perceived as accurate • no perceived shiphandling difficulties • excellent return to centerline and steady up beyond the bend • potential for moderate bias error when maneuvering through the bend • minimal random error throughout the pilotage • most desirable display from user and performance standpoint	• perceived as very accurate • potential for large bias error when maneuvering through the bend • potential for major undershoot of the bend • some shiphandling difficulty perceived - sluggish initial response - difficulty returning to centerline • extreme rudder required in turn • least desirable display from overall performance standpoint
Highest Noise Level (32 meters rms)	• perceived as moderately accurate • perceived difficulty steadying up and staying on the centerline • large random error throughout the pilotage • minimal bias error when maneuvering through the bend • high trackkeeping variability when steadying up • least desirable display according to pilots	• perceived as accurate • no perceived shiphandling difficulties • excellent return to centerline • potential for moderate bias error when maneuvering through the bend • small random error throughout the pilotage • no major performance difference from low noise level	• perceived as very accurate • potential for large bias error when maneuvering through the bend • potential for major undershoot of the bend • major shiphandling difficulty perceived - sluggish initial response - slow returning to centerline - difficulty steadying up • extreme rudder required in turn • pilot anxiety over lack of ship response

• When lag occurs during a maneuver such as that simulated, ownship is perceived by the pilot as (1) responding sluggishly to initial turn rudder and any subsequent larger turn rudder, (2) responding excessively to check rudder and subsequent steady-up rudder, and (4) responding sluggishly again in the event a large steady-up rudder is required.

• Jitter of ownship on the display was visibly obvious proportional to the amount of noise and filtering capability of the tracker. Since pilots were unaware of lag effects, they related jitter to positioning accuracy and assumed this "accuracy" to be the major difference between displays. If users are required to be aware of lag and its effects, the users must be given an opportunity to "prove" the display. This can be accomplished through exercises in which ownship's position on the display can be continuously compared with its actual position in the waterways.

• Ownship jitter as a result of noise was the sole contributor to trackkeeping difficulties which occurred; although in all the noise conditions and for all the filter designs tested, trackkeeping performance was considered to be adequate and safe.

• Tracker lag as a result of tracker rise time was the major contributor to maneuvering difficulties which occurred. In cases of long tracker rise time in high noise conditions, the benefits of reduced jitter did not overcome the detriments introducted by lag.

• The combined effects of noise and tracker design were manifest in (1) subjects' perception of system accuracy resulting from ownship jitter, (2) subjects' perception of shiphandling difficulties when maneuvering and (3) a major crosstrack bias between where subjects thought they were and where they actually were.

• While pilots were able to "visually filter" even the largest jitter (i.e., a tracker with 3-second rise time in 32 meter rms noise) without significant degradation in trackkeeping; their apprehension to do this is reflected by more conservative maneuvers and very negative responses pertaining to their own performance and the display's usefulness.

• Subjects' perception of the jitter was linear from minimal on the longest rise time trackers in low noise, to extreme on the shortest rise time tracker in high noise. There was no clear demarcation as to when it became an annoyance or difficulty for them.

• Learning to use the display in the noise and operational environment had no significant effect on overall pilotage. This is attributed to a lack of feedback on ownship's actual status and its position in the waterway.

• Subjects' overall pilotage performance and user acceptance indicates the following.

1. Due primarily to jitter, the tracker with 3-second rise time is unacceptable from the users' standpoint in the high noise level, but acceptable from a performance standpoint in both noise levels.

2. Due primarily to lag, the tracker with 24-second rise time is unacceptable both from a user's standpoint and from a performance standpoint.

3. The tracker with 12-second rise time is acceptable from a user's standpoint and a performance standpoint in both noise levels. The potential for bias error exists as a result of tracker lag.

4. The gyro-aided tracker with 24-second rise time is acceptable from all aspects and has minimal potential for bias error.

Section 2
INTRODUCTION

As a result of technological advances in electronic information processing, integration and display, new design alternatives for shipboard navigation systems that were previously considered too expensive, inaccurate or unreliable for the maritime industry are emerging. The U.S. Coast Guard in its endeavor to ensure safe pilotage of vessels in restricted waterways, yet accommodate cost-effective ship operations, is undertaking several programs specifically to develop and evaluate such alternatives. The Coast Guard recognizes that to effectively develop and implement an electronic navigation system for use in restricted waterways, both technological advantages and wide acceptance by potential users must be achieved. To accomplish this, performance and design requirements in support of operational effectiveness, safety, and cost are required. This, in turn, has led the Coast Guard to engage in two parallel but diverse research efforts.

The first effort, under contract to the Applied Physics Laboratory (APL) of Johns Hopkins University, is for development, fabrication, installation, and shipboard evaluation of the precision intracoastal loran translocation (PILOT) navigation system.[1] This system specifically utilizes the mini-LORAN C chain located on the St. Mary's River, the Great Lakes region. While the PILOT experiment makes use of state-of-the-art processing, data storage and display technology, its primary function is to evaluate information processing and user acceptance within the LORAN C system. Several units have been installed on ships which frequent the St. Mary's River. Bridge personnel are requested to use the equipment at their convenience and report their results. Experimental limitations result from the system's design and the daily environment. The PILOT display format which was engineered based upon previous research[2] is not easily modified or reconfigured. Difficulties in achieving experimental control with the PILOT system as it is deployed precludes using it to investigate the effects of design alternatives on pilot performance. It does, however, appear to be receiving constructive criticism through exposure and continued use, the purpose for which it was intended.

As a result of modern miniaturization, high speed, and mass storage computer capabilities, it is possible for a shipboard system to provide accurate positioning information from a variety of navigation sources. This information can be processed using different filtering or tracking techniques and can be presented to the pilot in the most usable format. All of these variables, of course, affect overall operational effectiveness. It is this operational effectiveness which must be defined and understood so that intelligent tradeoffs in the design of the pilot's navigation system can be achieved. Since the PILOT experiment cannot vary system and display parameters, a parallel program for methodically examining their effects using highly controlled simulation was conducted. This simulation evaluation is the subject of this report.

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[1] C. R. Edwards and J. M. Ligon. "PILOT: Precision Intracoastal LORAN Translocation – Exploiting LORAN-C in the Harbor and River Environment." Paper delivered at the Wild Goose Association Eighth Annual Technical Symposium, Williamsburg, Virginia, October 1979.

[2] Ibid.

The program known as the "Simulator Evaluation of Electronic Radio Aids to Navigation Displays," was conducted in three individual experiments, all employing the same simulator and simulation scenario.

The program implicitly addressed the restricted waterway environment in which the pilot is faced with a plethora of task demands. Here, reduced visibility, the removal or relocation of floating aids, as well as pressures of communication, collision avoidance, channel maneuvering and traffic regulations all continuously encumber him. In this environment, the electronic navigation system must supplant the visual, providing immediate information not only about present position, but about future position, maneuver timing and vessel motion. The navigation system, electronic processing, display, ship, and environment all function together in a complex interaction which at present cannot be modeled. This research used simulation as a means of parametrically and functionally studying certain features of the shipboard system that are design controllable or specifiable.

The ultimate objective of the program is realized by a combination of the performance metric, various signal to noise ratios and filter bandwidths into a definitive statement about the ability of a pilot to navigate a restricted waterway in limited visibility conditions.[3]

Figure 1 shows the sequence of tasks required to fulfill the goals of the program. Specifically, three experiments were conducted each dependent upon the results of the previous one. The miniexperiment compared pilotage performance for 18 different display formats of navigation information using an abbreviated simulation scenario. These displays were designed in accordance with traditional human engineering criteria. From the miniexperiment, five of the most effective displays were selected and two more added to a full length RA-1 experiment. Both the miniexperiment and RA-1 experiment were conducted in a "no noise" environment. Ownship was shown on the display in the exact same position as it was in the real world. This is known as "perfect" position information. The single most effective display from the RA-1 experiment was selected as the benchmark display. This display was further evaluated in the RA-2 experiment which simulated real world noise conditions and different tracker filtering techniques. Effects on pilotage performance which were seen in the RA-2 experiment are attributed to jitter and lag of ownship on the display. These, of course, were the result of the different noise levels and tracker characteristics.

[3] United States Coast Guard. "An Approach to the Study of Electronic Displays for Use in Restricted Waterways." A position paper. December 1979.

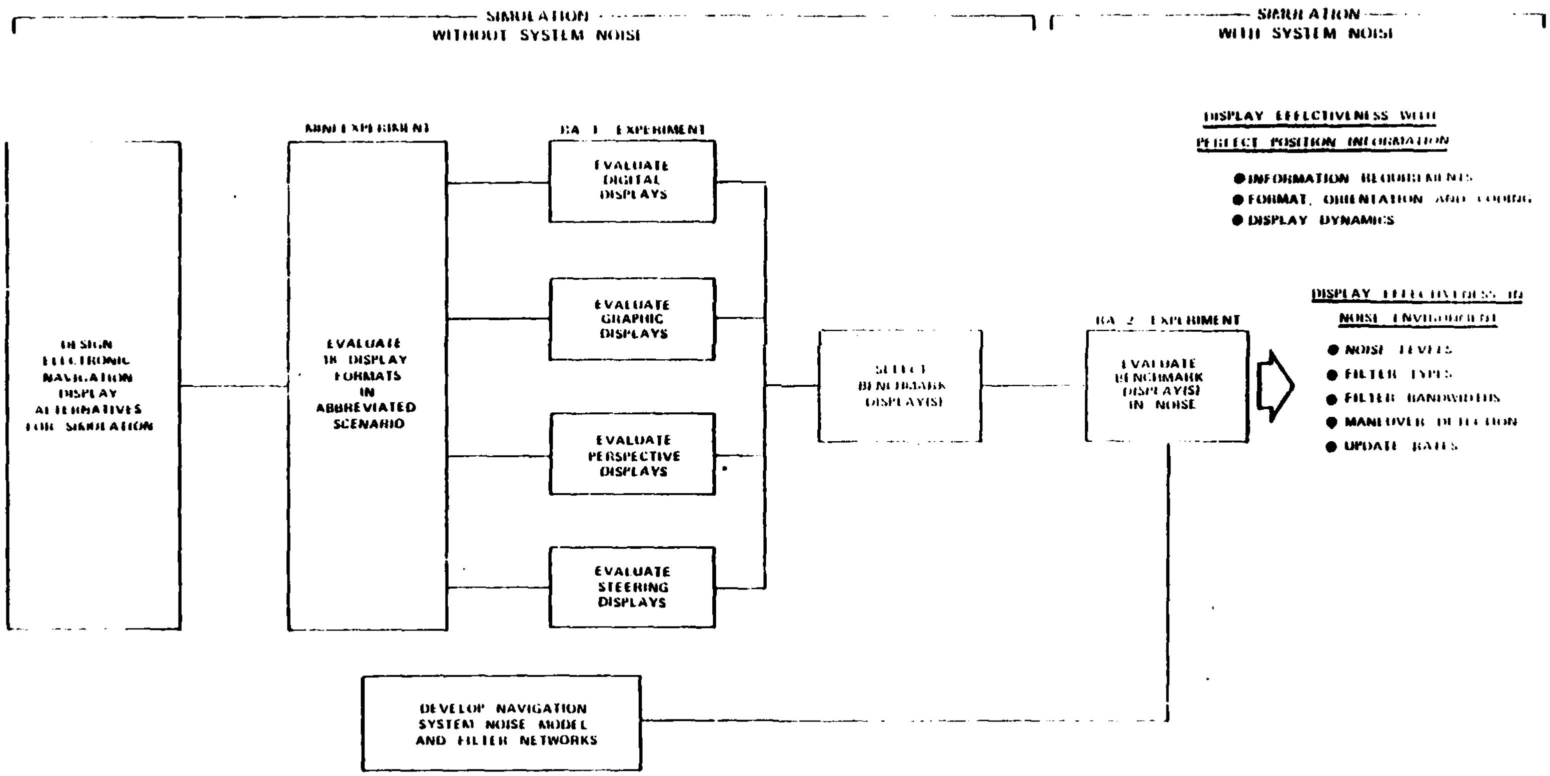

Figure 1. Program for the Simulation Evaluation of Electronic Radio Aids to Navigation Displays

2.1 THE MINIEXPERIMENT

As a result of preliminary critiques of the PILOT system, it was recognized that information provided by a navigation system for use by pilots is only as effective as the human interface through which the information is presented. For a display to be beneficial during pilotage and thereby accepted by pilots, it must be easily understood, relevant to the immediate task, appear clear and concise within perceptual limits, and instill confidence in the user. It was further recognized that independent of the information contents which a navigation system provides, the effectiveness with which this information is presented will depend upon display format and consequently display cost. That is not to say that the optional display will necessarily be the most costly. Determining this relationship was the primary objective of the miniexperiment.

The miniexperiment evaluated three unique display technologies that were selected based upon their estimated cost and potential for actual shipboard use. Low, moderate and high cost categories were compiled based upon the required visual display capabilities, computer characteristics, and the effort for computer program development. Front end electronics such as the navigation receiver and filter processor were considered constant across all displays and were not included in the cost tradeoff.

The lowest cost display was represented as an all DIGITAL readout of navigation parameters such as shown in Figure 2. Actual applications of this type display might use light emitting diodes (LED), liquid crystal displays (LCD), plasma or gas discharge panels, or multiple-projection readouts. The device could be small enough to be hand held.

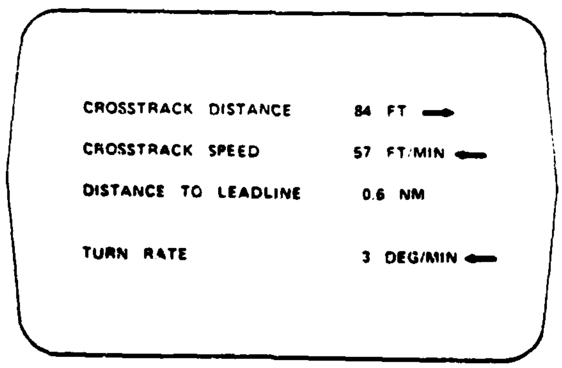

Figure 2. Example of Digital Display

The moderate and high priced systems would both require a mass data display with graphic capabilities, probably a CRT. Two display concepts, a GRAPHIC display or plan view similar to traditional radar presentations (see Figure 3) and a PERSPECTIVE display portraying the perspective scene as viewed out the forward bridge windows (see Figure 4) were considered moderately priced. The high priced display system was a STEERING display requiring extensive high speed processing and massive data storage (see Figure 5). This STEERING display represented a somewhat advanced concept in navigation displays since it integrated position information with a computed track prediction based upon hydrodynamic algorithms and status inputs from ownship.

In consideration of the many design alternatives resulting from each of the cost categories, it was decided to evaluate through simulation different display variables in each of the DIGITAL, GRAPHIC and PERSPECTIVE displays. In order to examine as many variables as possible, only an abbreviated 12-minute segment of the project scenario was simulated. This segment, however, included the 35-degree bend which was considered to be the most difficult maneuver within the waterway.

Format variables examined in the miniexperiment are listed in Table 3. From this, five of the most operationally effective formats were selected for a full length simulation in the following, RA-1, experiment. Based upon conclusions of previous research[4,5,6] the STEERING display was considered adequately effective to be recommended for testing in the full-length RA-1 simulation without being examined in the miniexperiment.

A completely detailed description of the miniexperiment including the design of all displays, the experimental design, scenario and performance measures, and all results and conclusions are presented in the interim report.[7]

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[4] R. B. Cooper, W. R. Bertsche, and C. J. McCue. "Simulator Evaluation of Predictor Steering, Short Range Collision Avoidance and Navigation Displays, Phase III, the Advanced Bridge Design Program." Washington, D. C., U. S. Maritime Administration, November 1979.

[5] Kockums Automation AB. "Precise Maneuvering in Confined Waters, Controlled Radial Steering." Unpublished. Malmo, Sweden.

[6] W. B. Van Berlekom. "Simulator Investigation of Predictor Steering Systems for Ships." In Transactions of Royal Institute of Naval Architects. Paper 2, 1977.

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

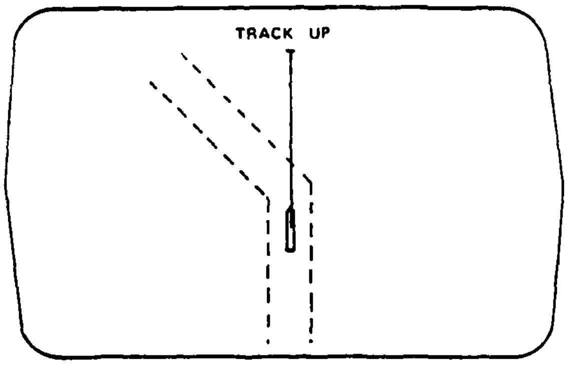

Figure 3. Example of Graphic Display

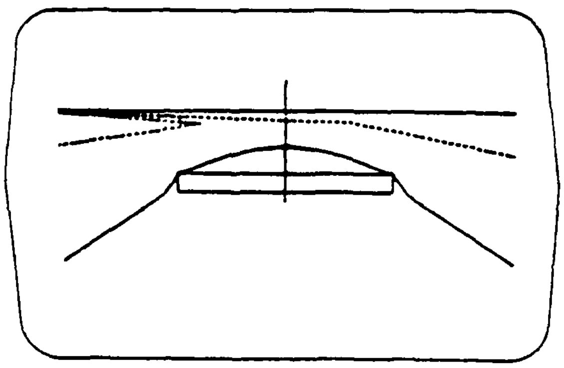

Figure 4. Example of Perspective Display

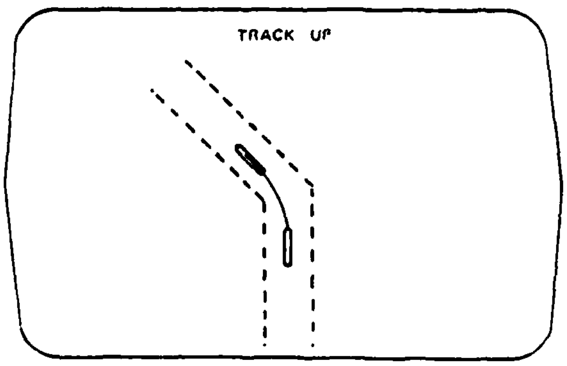

Figure 5. Example of Steering Display

TABLE 3. MINIEXPERIMENT DISPLAY VARIABLES

DIGITAL DISPLAY (low cost)	GRAPHIC DISPLAY (moderate cost)
Crosstrack distance from centerline	Track-up, true motion
Crosstrack velocity	Track-up, relative motion
Course error	Head-up, relative motion
Heading to steer	Ship heading vector
Turn rate	Ship course vector
Recommended turn rate	Scaled ship image
Distance to leadline	Symbolic (cross) ship image
Time to leadline	

PERSPECTIVE DISPLAY (moderate cost)
60 degree field of view
90 degree field of view

2.2 THE RA-1 EXPERIMENT

The objective of the RA-1 experiment was to evaluate, through a full-length simulation of restricted waterway pilotage, the effectiveness of five display formats recommended by the miniexperiment and two predictor steering displays recommended by other research. The full-length scenario employed in the RA-1 experiment was very similar to the RA-2 scenario described in detail in section 3.3 of this report. It differed from the miniexperiment scenario, however, in that it started and ended 2.3 nm from the bend instead of 0.75 nm. Also, ownship was initially off-set 92 feet to the right of the channel centerline necessitating the pilot to maneuver within the straight leg to return to the centerline. In the additional length beyond the bend, the pilot was required to steady-up and maintain a track in varying wind conditions and a gradually decreasing crosscurrent. Trackkeeping and maneuvering performance were judged on how well the subject initially returned to the centerline, steadied up on it, maintained the centerline through the entrance leg, negotiated the turn, steadied up beyond the bend, and maintained the centerline through the exit leg. Speed control and use of the rudder were also analyzed.

Format variables examined in the RA-1 experiment are categorized by cost. (See Table 4.) Results and conclusions of the RA-1 experiment along with a detailed description of the displays, experimental design, scenario and performance measures are presented in the RA-1 interim report.[8] The most important result, however, was a recommendation based on the simulation that the true motion, track-up GRAPHIC displays and the STEERING display were the most effective for pilotage of the waterway as it was simulated.

TABLE 4. COST CATEGORIES OF RA-1 DISPLAYS

Representing low cost systems (less than $500)

- Digital display (alphanumeric only) indicating crosstrack distance, crosstrack speed, and distance to waypoint.

Representing moderate cost systems ($500-$5,000)

- Digital display indicating crosstrack distance, crosstrack speed, distance to waypoint, turn rate and recommended turn rate.

- Graphic display (PPI type presentation) indicating true motion in a track-up orientation, and ownship's image with a heading vector.

- Graphic display indicating true motion in a track-up orientation, and ownship's image with a course vector (direction of ship motion).

- Perspective display (as viewed out the forward windows) indicating ownship's bow and channel boundary lines with a 90 degree field of view.

- Simplified predictor steering display (PPI type presentation indicating true motion in a track-up orientation, and projection of ownship's track computed from speed and present rate of turn.

Representing high cost systems (more than $5,000)

- Predictor steering display indicating true motion in a track-up orientation, and a projection of ownship's track based upon the computed effects of ship hydrodynamics, existing ship motion and the amount of rudder applied.

Based on additional factors such as pilot preference, development cost, and potential accuracy, the true motion, track-up GRAPHIC display with an ownship leading vector was recommended as the benchmark display for RA-2 evaluation.

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[8] R. B. Cooper, K. L. Marino, and W. R. Bertsche. "Simulator Evaluation of Electronic Radio Aids to Navigation Displays, The RA-1 Experiment." Washington, D. C., United States Coast Guard, January 1981.

2.2.1 The Noise and Tracker Model

Having defined a benchmark display whose operating characteristics and format were judged most effective with perfect position information, the research next endeavored to evaluate the display under real world conditions of noise and system limitations. This was accomplished by developing and testing a model of an ALPHA-BETA a - b mathematical filter which would be placed between the traditional navigation receiver and the display input.

Through mathematical processes this filter would average random position errors from the receiver and provide a computed best-estimate of ownship's position on the display. Naturally, the greater the noise level at the receiver, the larger the random error into the filter. For a given noise level, the amount of random error can be calculated, thereby transforming the degree of noise level directly into distance root mean square (rms) about the ship's actual position.

This definition of noise formed the basis for selection of one of the variables in the RA-2 experiment. Any navigation system, hyperbolic line, time differential or other, will incur some error as a result of noise. Since RA-2 was intended to evaluate the benchmark display for a generic navigation system and not a specific one (i.e., LORAN C, Omega, satellite, etc.), noise errors were included which are representative of all potential navigation system candidates.

The evaluation program presupposes the utilization of state-of-the-art tracking filters where high receiver, processor and display technology exist. For the RA-2 experiment a critically damped a - b filter with selectable rise time was modeled. While not a highly sophisticated or optimized filter such as the Kalman, the a - b tracker did enable an examination of the display effects caused by different filter characteristics and the initiation of major maneuvers.

During the development of the tracker model, six different tracker rise times were simulated. The shorter filter rise times tended to give larger variations between each best-estimate position, subsequently producing a display filter. Computation times were short, however, with very little lag between when the position was received and when it was displayed. Longer filter rise times, on the other hand, tended to present a smooth series of best-estimates of position. Here, however, lag times were long, showing ownship considerably behind its actual position in cases of long rise times.

In the transit of a straight leg or channel this lag could be tolerated in favor of the smoother best-estimates. At a bend or other maneuver, however, the long rise times could be deleterious. To retain the advantages of long filter rise time, yet reduce the consequences of lag during a maneuver, inputs from the gyro compass can be used. These inputs would signal that a maneuver has been initiated and that old position data used for the best-estimate should be discounted. While this is an extreme oversimplification of gyro-aiding, it does illustrate the basic effect.

Verification of the noise and tracker models were accomplished by steering, under computer control, a 30,000 dwt tanker through a 35-degree turn at 8 knots. Displayed position was then plotted versus the ship's actual position every 3 seconds. Tracker rise times of 3, 6, 12, 24, 42 and 54 seconds were evaluated both with and without gyro-aidingin each 2, 16, 32, and 64 meter rms noise condition. These plots as well as a detailed description of the models, their development, and their verification is found in Appendices A and B of the RA-1 Interim Report.[9] Table 5 summarizes its conclusions.

TABLE 5. CONCLUSIONS OF THE NOISE AND FILTER MODEL DEVELOPMENT

- The optimal α - β tracker rise time was shown to vary between 2 and 20 seconds, depending on the level of rms noise added to the signal.
- Rise times of 3 to 6 seconds seem appropriate for low rms noise (2 to 16 meters).
- Higher rise times of 10 to 20 seconds seem appropriate for higher rms noise (32 to 64 meters).
- Additionally, this shift occurs principally as a function of the noise masking the tracker lag error for larger noise levels and lower rise times.
- For very long rise times, the errors asymptotically approach the tracker performance with 2-meter noise level. Thus, in the limit, the errors caused by tracker lag dominate the noise errors.
- For moderate to large noise levels without gyro-aiding, course errors can become quite large (i.e., in excess of 15 degrees). Such errors could severely degrade the effectiveness of a display which employs course error information.
- With gyro-aiding of the tracker, there is a dramatic reduction in tracker errors through the turn which results in a reduced maximum crosstrack error, a reduction in the maximum course error, and a reduction in rms crosstrack error.
- Rise times which achieve minimum errors fall between 20 and 42 seconds, compared to 2 to 20 seconds for the unaided trackers. The minimum values are less sensitive to the value of rise time as a function of noise level. Rise times of 24 to 36 seconds seem to be a good choice for signal noise 2 meters to 64 meters.
- A major improvement with gyro-aiding appears to be reduction of the maximum course error. Such a reduction may make feasible the use of displays which depict course and/or velocity information.

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[9] R. B. Cooper, K. L. Marino, and W. R. Bertsche, op. cit.

2.3 THE RA-2 EXPERIMENT

Based upon display recommendations of the previous experiments and specific operational and environmental considerations revealed during development of the noise and tracker models, an experimental design for the conduct of the RA-2 evaluation was proposed. The simulation scenario was identical to the RA-1 experiment except that ownship started about one nautical mile closer to the bend making each run only 35 minutes long. This provided each subject time for eight runs and allowed a post run interview to elicit his perception of the run and the display's usefulness. All runs were conducted using the benchmark display.

Based upon recommendations of the previous experiments and rationale discussed in Section 3 of this report, the following variables were simulated:

Noise Conditions

- 16 meter rms noise
- 32 meter rms noise

Tracker Characteristics

- Tracker with 3 second rise time
- Tracker with 12 second rise time
- Tracker with 24 second rise time
- Gyro-aided tracker with 24 second rise time

Subject selection, experimental design and performance measures were comparable to the RA-1 experiment. Some performance measures which were shown in the RA-1 experiment to be ineffectual for examining pilotage behavior were omitted.

Preliminary observations of track plots showing ownships' tracks by variable indicated that when displays with long lags (i.e., long rise times) were used, subjects tended to execute the bend with considerably less overshoot. To fully analyze this observation, plots were also made of ownship's position as it was shown on the display. By comparing the displayed position plots with actual position plots it was possible to ascertain what type of error (lag or jitter) and how much error was in effect at each instant throughout the maneuver.

Details of the entire RA-2 experiment are contained within this report as are its conclusions and recommendations. While each are of particular interest in the context of the overall program, there are several conclusions which correlate with the findings of APL's paralleling PILOT program. Specifically, there are statistically significant indications that learning effect is a major factor both in the usefulness and acceptance of an electronic radio aids to navigation display. It follows, that if formal familiarization of training in the use of the display is provided, this learning effect will be greatly accelerated. Also, the use of a familiar display format, specifically the plan view or GRAPHIC presentation, is most readily accepted as a navigating aid by pilots. Noise which translates to jitter becomes more obvious to the observer as the update rate of the display increases. The effects of update rate were not examined in this experiment.

Results of the RA-2 experiment suggest that the human individual is an excellent filter of system error providing one is able to see the individual data points (i.e., best-estimate positions); but not at a fast, distracting rate. Finally, considering the many experimental runs and, in some cases, repeated use of the GRAPHIC display by the same subjects, there was no series of runs in poor visibility which equaled or surpassed in performance the best runs which had been made under visual conditions (i.e., the AN-VISUAL experiments.)[10,11]

Figure 6 compares piloting performance of the best (most accurate) radio aid display to the best (gated buoys marking both sides of the channel) visual buoy configuration. Performance differences are most obvious in the turn. The radio aid display resulted in a wide dispersion of tracks and an overshoot of the bend, while the visual scenario resulted in controlled tracks close to the center of the channel. The differences in performance are due to varying certainty as to when to initiate the turn maneuver and how to control the turning maneuver prior to pull out. Turn maneuver actions appear more certain with visual information and less certain (i.e., more variable) with the graphic radio aid display.

While significant contributions have been made by this program toward understanding the effects on pilotage of various navigation displays and operating characteristics, the fact remains that in poor visibility or when all visual aids have been removed, the electronic radio aids to navigation display as evaluated does not produce pilotage performance comparable to visual navigation.

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[10] M.W. Smith and W. R. Bertsche. "Aids to Navigation Principal Findings on the CAORF Experiment. The Performance of Visual Aids to Navigation as Evaluated by Simulation." U.S. Coast Guard Office of Research and Development, DOT-CG-835285-A, Washington, February 1981.

[11] 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." Washington, D.C., U.S. Coast Guard, January 1981.

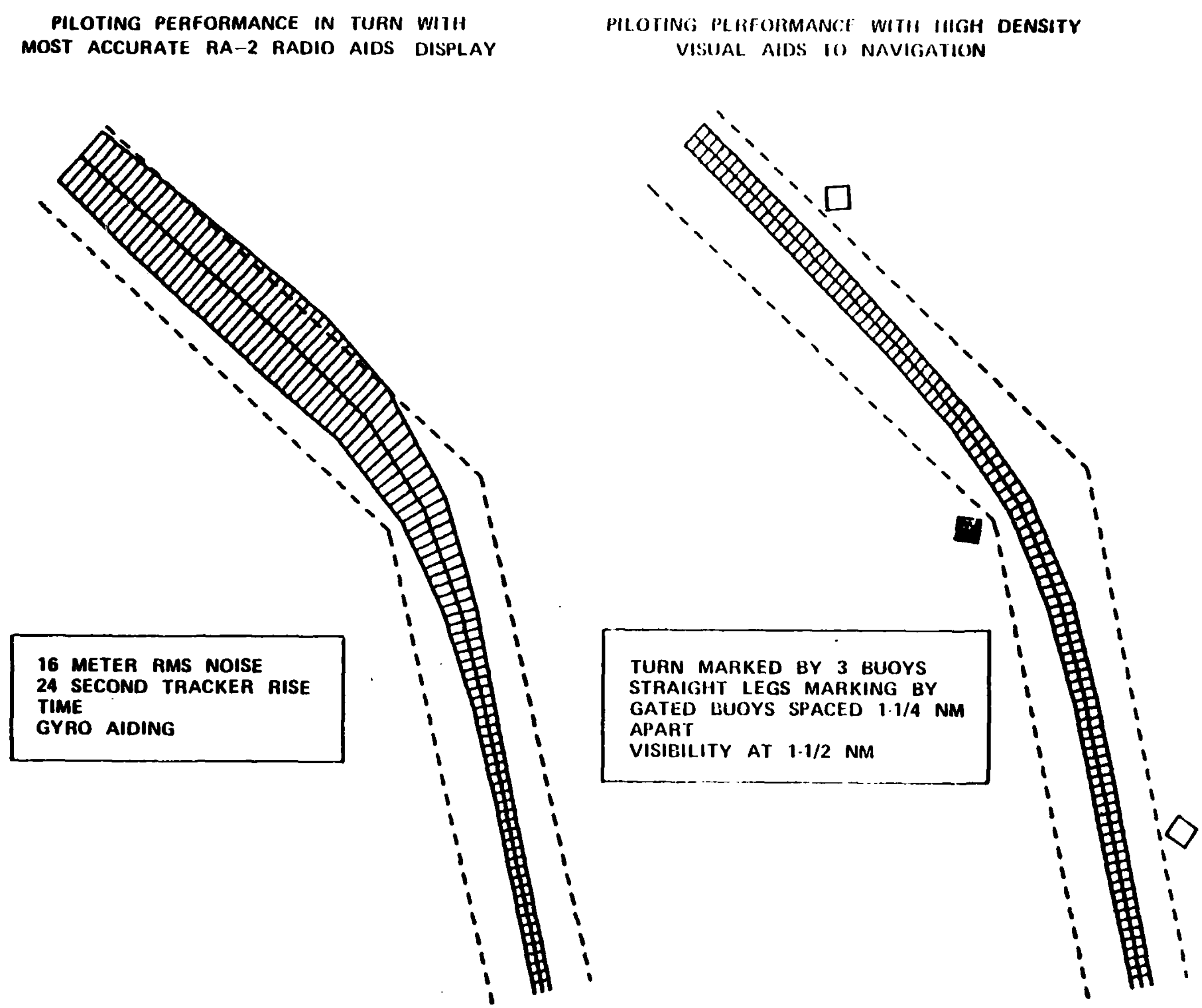

Figure 6. Comparison of Piloting Performance : Most Accurate Radio Aids to Navigation Display Versus Highest Density of Visual Aids to Navigation

Section 3

EXPERIMENTAL DESIGN

The RA-2 experiment was intended to evaluate, through man-in-the-loop simulation, pilots' trackkeeping and shiphandling performance with a GRAPHIC radio aids to navigation display under conditions of simulated system noise and lag errors introduced by the tracker filter system itself. This experiment was conducted similarly to the RA-1 experiment described by Cooper et al, 1980.[12] In conjunction with an earlier miniexperiment[13] the experiment selected a true motion, track-up GRAPHIC display as the benchmark display for evaluation in eight combinations of noise, filter bandwidth, and filter aiding techniques . The RA-1 experiment recommended the GRAPHIC display with either heading or course vectors. Subsequently, the decision was made to employ the heading vector display since estimated course would be severely degraded by the presence of signal noise. Logistics of the experiment precluded the evaluation of both heading and course vector displays with all variables.

The experimental variables were selected as a result of the RA-1 development and derivation of performance data for the critically damped ALPHA-BETA (α-β) position tracker. Conclusions of this development and rationale for the selection of variables are presented in the following section.

The RA-2 experiment was conducted in a full-length scenario, using the same waterway and environmental characteristics (i.e., wind and current) as the RA-1 experiment. Similar data collection and analysis techniques were also employed.

Instructions to subjects were taken from the RA-1 experiment. Due to the seemingly repetitious nature of the RA-2 experiment (i.e., RA-1 used different displays and RA-2 used only one), it was necessary to provide continuous motivation to the subjects to perfect their pilotage. This was accomplished by eliciting from each subject how well he performed in each previous run and then encouraging him to "do better." While this may appear somewhat artificial, previous experience had shown that when runs are repetitious and similar, pilots tend to try new techniques or strategies to overcome boredom. Since no visual feedback was provided other than what the subjects saw on the display, the critique of their perception of own performance compared to their actual performance was a good indication of how effectively the display information was presented.

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[12] R. B. Cooper, K. L. Marino, and W. R. Bertsche, op. cit.

[13] R. B. Cooper and K. L. Marino, op.cit.

3.1 EXPERIMENTAL VARIABLES

The selection of variables for the RA-2 experiment was based on tradeoffs between noise and tracker performance in consideration of real world characteristics and potential system implementation. The earlier research, which examined tracker rise times of 3, 6, 12, 24, 42, and 54 seconds with noise of from 2 meters (6.6 feet) rms to 64 meters (211.2 feet) rms, resulted in the following conclusions:

1. The 2-meter (6.6-foot) rms noise level is probably too close to the RA-1 baseline (zero rms noise) for any performance comparison. Additionally, the 2-meter error probably is accurate enough not to even warrant filtering in the first place.

2. The 64-meter (211.2-foot) rms noise level is considerably greater than presently exists in state-of-the-art navigation systems. As a result, its evaluation would serve only to define the performance on an obsolete system parameter.

3. Both the 16-meter (52.8-foot) and the 32-meter (105.6-foot) rms noise levels were proposed as variables for the RA-2 experiment. Each represents state-of-the-art accuracy of certain navigation systems as well as hypothesized extremes of performance which would benefit from the incorporation of an α-β tracker.

4. An 8-meter (26.3-foot) rms noise level will be tested during the presimulation phase of the experiment along with the 16-meter noise to determine if there is an incremental difference in performance between the two. If there is, the 8-meter noise would be substituted for the 16-meter noise in the RA-2 experiment since it more closely represents potential navigation system capabilities.

5. α-β filters with rise times of 3, 12, and 24 seconds were selected to represent the spectrum of filter characteristics. These rise times were selected because they demonstrated an important range of errors when used in 16- and 32-meter noise but without gyro-aiding. The 3-second rise time results in large errors which are principally the result of signal noise. The 24-second rise time results in large errors nearly equivalent to those for the 3-second rise time, but they are principally the result of filter lag errors. The 12-second rise time represents the nearly minimum error condition.

6. The α-β filter with gyro-aiding would be tested using only a 24-second rise time. Gyro-aiding is considered less essential at slower rise times because lag is minimal. The experiment proposes to determine if gyro-aiding ensures increased system effectiveness at 24 seconds. The 24-second α-β filter with gyro-aiding would be evaluated in both 16- and 32-meter rms noise levels.

As a result, two levels of noise, three levels of tracker rise time and two levels of filter aiding were selected for the RA-2 experiment. They are shown in Figure 7. Plots of the offline verification of performance for each of these variables are presented in Appendix A.

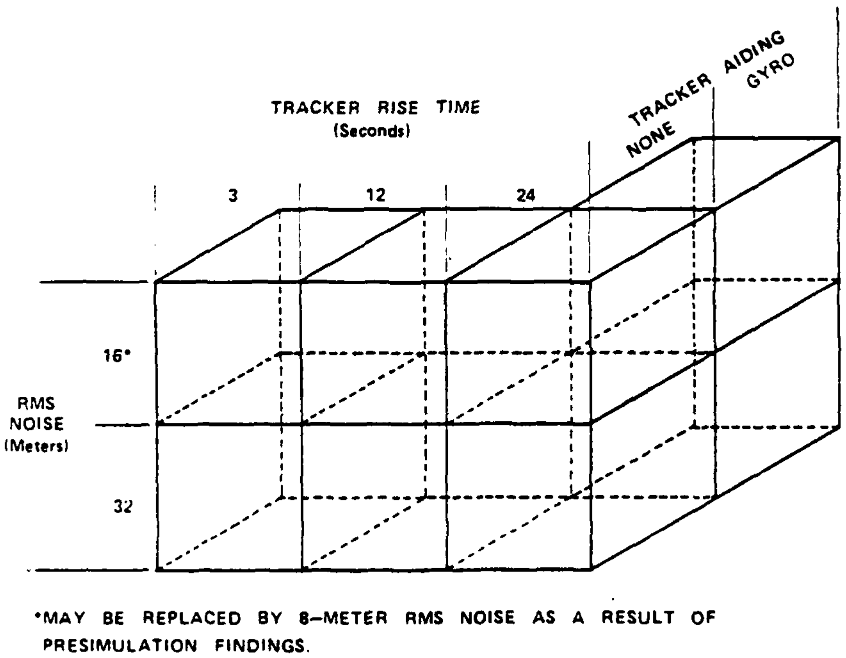

Figure 7. Experimental Design Matrix

3.2 SIMULATOR FACILITY

A comprehensive description of the simulator facility used in the conduct of the RA-1 experiment is provided in section 2.2 of Cooper and Marino.[14] Briefly, the simulator is a fully equipped ship's bridge with a visual simulation capability. It has been developed in conjunction with the U. S. Coast Guard to support their conduct of aids to navigation research. Simulated radar and navigation displays are driven by a Digital Equipment Corporation GT-44 computer graphics system with PDP-11/40 central processor and VT-11 graphic generation hardware. The computer CRT display is mounted in a free-standing pedestal and equipped with required controls/indicators and bearing rings to simulate a PPI type bridge display or various radio aids to navigation formats. Other computers control both the electronic bridge display and visual system although visuals were not used during the radio aids evaluation. The computer program reflects ownship characteristics, maneuverability, hydrodynamic influences, and individual scenario (i.e., waterway and environment) conditions. In the case of the RA-2 experiment, it also modeled navigation system noise and system filter characteristics for the display evaluation. The computer facility provides a continuous automatic recording of ship position, ship status, and bridge control manipulations for post simulation data reduction, graphic and statistical analysis.

3.3 SIMULATION SCENARIO

The RA-2 scenario differed from the RA-1 experiment only in the location of the initiation point which, for RA-2, was 1.2 nautical miles from the bend.

3.3.1 Ownship Characteristics

The ship was similar in all characteristics to the one run during both previous radio aids to navigation experiments and the AN-CAORF[15] and AN-VISUAL[16] experiments.

Ownship:	29,694 dwt tanker ballasted 34.6 foot draft Depth below keel-1 foot Height of eye-45 feet Wheelhouse midships 84 foot beam 595 foot length
Initial speed:	6.5 knots through the water (8 knots ground speed)
Initial heading:	341°T gyro

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[14] Ibid.

[15] M. W. Smith and W. R. Bertsche, op. cit, February 1981.

[16] M. W. Smith and W. R. Bertsche, op. cit, January 1981.

3.3.2 Operating Area

The scenario waterway and starting position of ownship is shown in Figure 8 This waterway was also used in the abbreviated scenario of the miniexperiment and the RA-1 experiment. It is comparable to the AN-CAORF scenarios 17 through 24,[17] and AN-VISUAL scenarios 18, 20, 22, and 24[18]. Unlike these visual experiments, there are no buoys shown on the radio aids to navigation display.

The waterway was a 500 foot wide channel with a 35-degree left bend. Environmental effects were simulated as follows:

For entire scenario:

Current:	1.5 knot flow to 341 degrees true decreasing to 0 knots
Wind direction:	From 161 degrees true variable 13 percent
Wind velocity:	30 knots plus/minus 10 percent variable per 600-second period plus gust at 10 percent velocity per 60-second period.

Ownship originated approximately 92 feet to right of the channel centerline, 1.2 nautical miles south of the bend. Instructions to the subject were to return to the centerline and maintain the center of the channel as much as possible through the transit. There was no traffic and no visual scene (i.e., poor visibility conditions are simulated).

3.4 RADIO AIDS TO NAVIGATION SYSTEM MODEL

Radio navigation systems are presently being implemented to facilitate ship piloting in narrow waterways. Such systems include typically a radio receiver, a signal processing unit or filter, and a position display device. Given state-of-the-art electronics, most systems are now microcomputer based and utilize digital filtering techniques. The basic system elements are diagrammed in Figure 9. The simulation model represents the receiver and the signal processing unit as single trackers (see Figure 10). Experimental results and filter analyses of this experiment should thus not be wholly attributed to either the receiver or the signal processing unit.

A two-axis radio signal system has been assumed for the implementation: north-south signal and an east-west signal. The noise in these signals is assumed to be independent over the sample interval chosen. A white noise source with a Gausian distribution is assumed.

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[17] M. W. Smith and W. R. Bertsche, op. cit, February 1981.

[18] M. W. Smith and W. R. Bertsche, op. cit, February 1981.

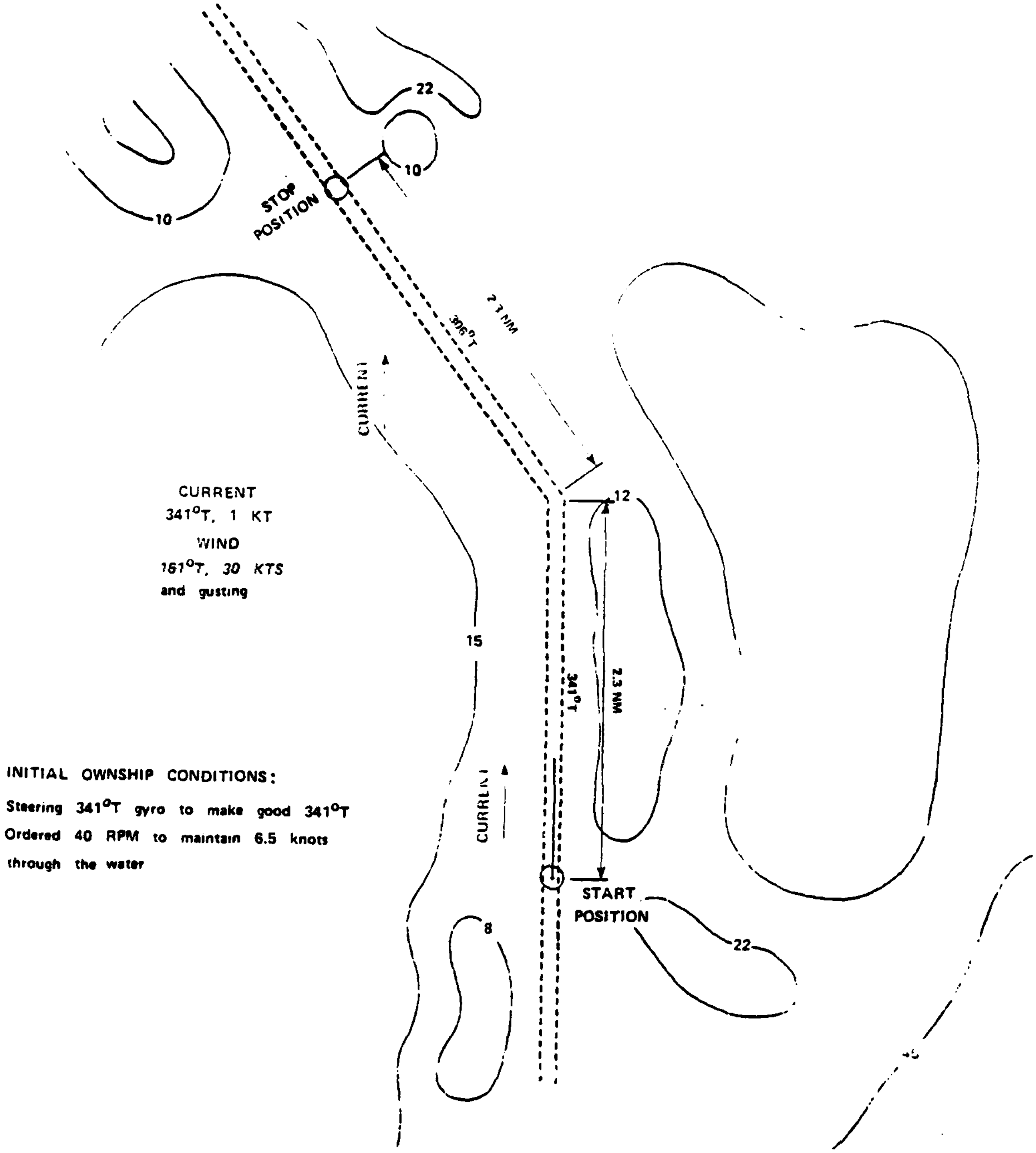

Figure 8. Scenario Waterway

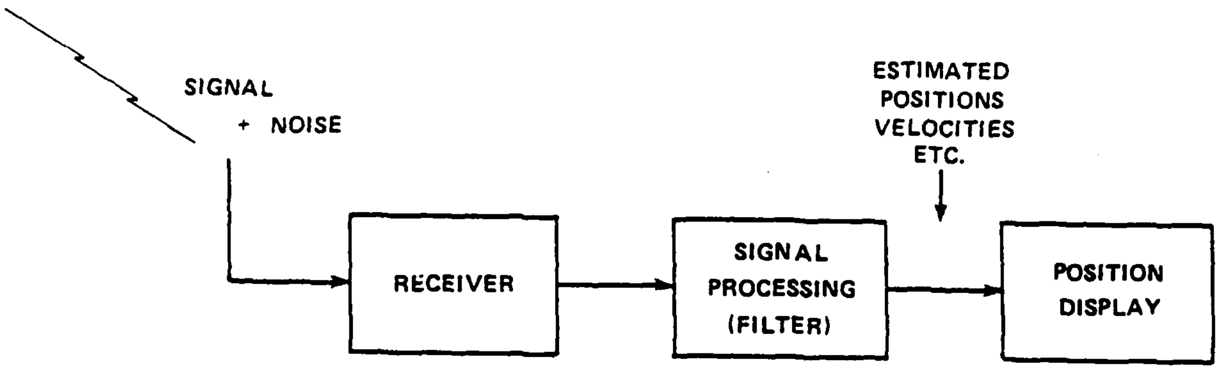

Figure 9. Basic Elements of a Radio Navigation System

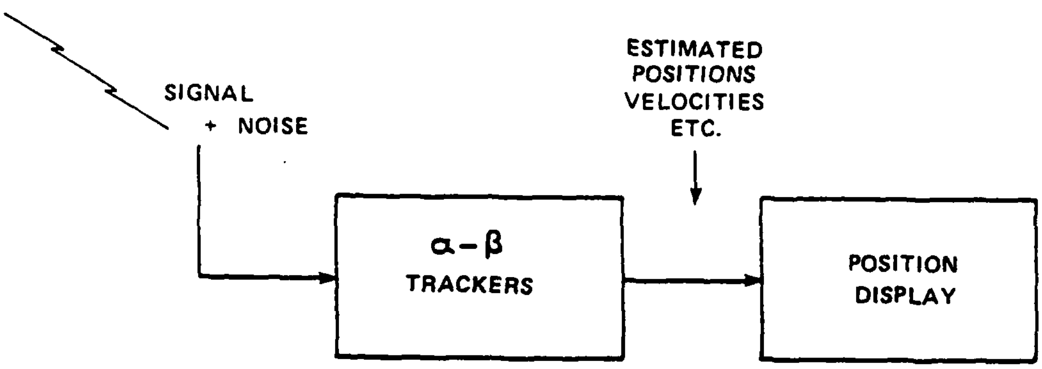

Figure 10. Representation of a Radio Navigation System with α - β Trackers

The navigation system is implemented as shown in Figure 11. Note that the x coordinate is positive in the north direction and the y coordinate is positive in the east direction. All subsequent derivations refer to this coordinate system. Identical values for alpha are used in the x and y coordinate trackers. Critical damping is assumed for both trackers, $\beta = (\alpha^2)/(2-\alpha)$. Identical equations were implemented in each tracker with the appropriate changes to notation (x and y). A detailed description of the α-β tracker characteristics and equations are presented in Appendix A of the RA-1 report.[19]

Performance of the navigation system was evaluated during the RA-1 developmental phase, using the system to track a 30,000 dwt tanker through a 35-degree turn at 8 knots. Full ship hydrodynamic equations were utilized to represent the ship response. This ship is identical to that used in the RA-1 experiment and the miniexperiment. A simple autopilot was utilized for executing the turn to achieve repeatability.

$$\delta_R = 2 \text{ (heading error)}$$

where:

δ_R = rudder angle

This autopilot exhibited approximately a 10 percent overshoot in heading for the 35-degree turn. Typically, this implementation caused a hard over rudder to be applied for most of the turn, resulting in a high turn rate. Such a response presents the trackers with the greatest possible transient for the given ship, turn angle, and initial ship's speed.

The data in Figure 12 show a typical response of the trackers to the 35-degree turn. Such plots allow a quick visual analysis of the tracker performance. As emphasized by the dashed line, an oscillatory response is evident in the turn. This might properly be traced to the nonlinear variations in ship's north and east velocities through the turn. It is interesting to compare performance before and after the turn. Prior to the turn the trackers seem to have settled to rather a smooth response. Following the turn, the trackers seem to be continually perturbed almost in steady state oscillation.

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[19] R. B. Cooper, K. L. Marino, and W. R. Bertsche, op. cit.

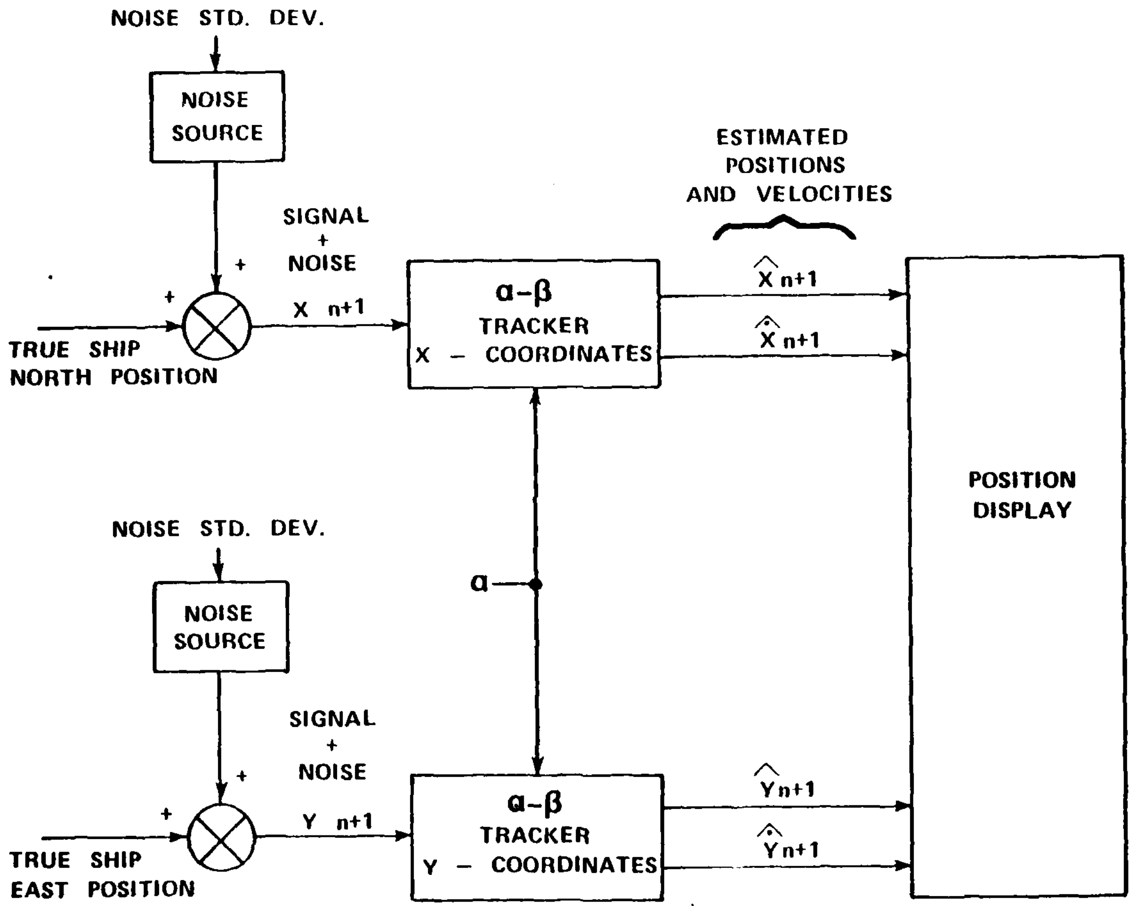

Figure 11. Implementation of Navigation System for Experimentation

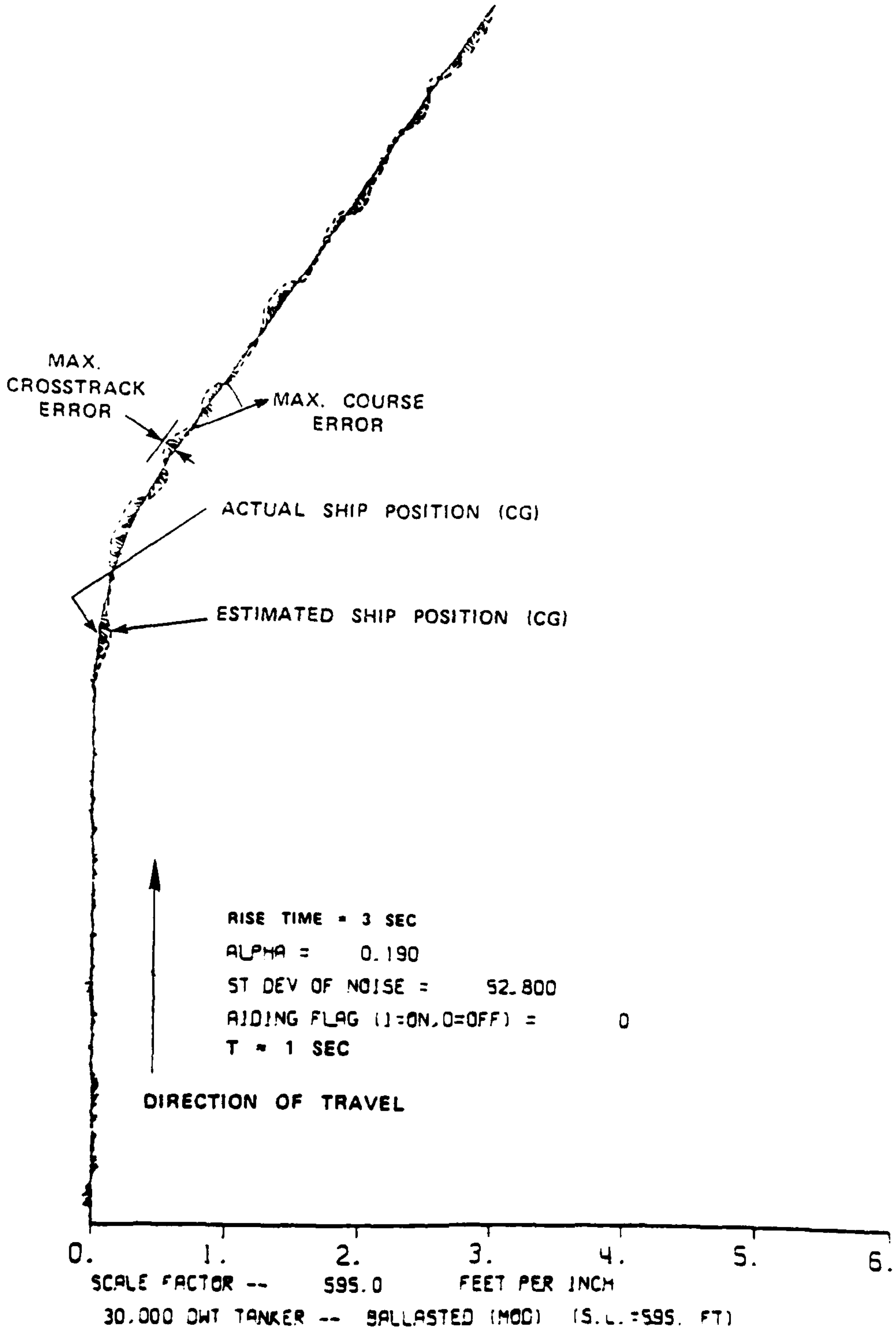

Figure 12. Typical Plot of Tracker Response to 35-Degree Turn

Implementation of the gyro-aiding filter was made as shown in Figure 13. Equations were implemented for both the north and east signal data. An $\alpha - \beta$ tracker was added to filter the gyro signal. Its rise time is independently controlled from the position trackers. The alpha value for this tracker was denoted as α_2. As noted in the figure, the current estimates of ownship's heading, turn rate, and north and east velocities are used to calculate the velocity changes. These estimated changes are used to improve the estimates of ship's position and velocities. The applicable equivalents are described in the RA-1 report.[20]

The RA-1 analysis of gyro-aiding sought to select an appropriate rise time for the gyro tracker. The baseline conditions selected were 32-meter rms signal noise, with a 30-second rise time in the position trackers ($\alpha = 0.027$). The sample period was equal to 1 second. The results implied that a rise time of between 2 and 4 seconds for the gyro tracker achieves good performance. A gyro tracker rise time of 3 seconds was chosen for all subsequent gyro-aiding analyses ($\alpha_2 = 0.19$).

A second analysis effort sought to optimize the multiple of turn rate in the speed change equations. Evaluation runs with zero rms noise were run, and maximum crosstrack error and maximum course error were evaluated. A multiple between 0.85 and 1.0 seems to minimize errors. The multiple of 0.85 was selected for all subsequent gyro-aiding analyses.

3.5 SUBJECT SELECTION

Eight licensed pilots from local and mid-Atlantic pilots' associations acted as subjects for the experiment. Runs were completed within 8 hours to minimize fatigue effects. This included time for an explanation of the display's operation as well as brief postrun interviews. All subjects selected were familiar with the response characteristics of a 30,000 dwt tanker. Nevertheless, they were given an opportunity to maneuver the simulated ship during a preexperiment familiarization run. Every effort was made to enlist the participation of those pilots who were subjects in the RA-1 and miniexperiment. This substantially minimized the display familiarization requirement. In addition to critiquing their own performance following each run, subjects were encouraged to voice their opinions and recommendations both for display design and in regard to the overall simulation.

3.6 ADMINISTRATION

3.6.1 Experimental Design

The simulator experiment was intended as an evaluation of overall operational effectiveness and of potential user acceptance of the GRAPHIC radio aids to navigation display in a systematically varied noise and filter design environment.

Organization of the variables was designed to investigate within-subject effects, thus minimizing individual differences and encouraging a higher probability of finding significance than would be experienced by between-subject effects. This, of course, meant a large number of scenario repetitions for each subject with the resultant possibility of introducing order effect (e.g., learning, anticipation, boredom, etc., caused by repetition). Tests for learning effect were conducted on all data and the results are presented.

[20] Ibid.

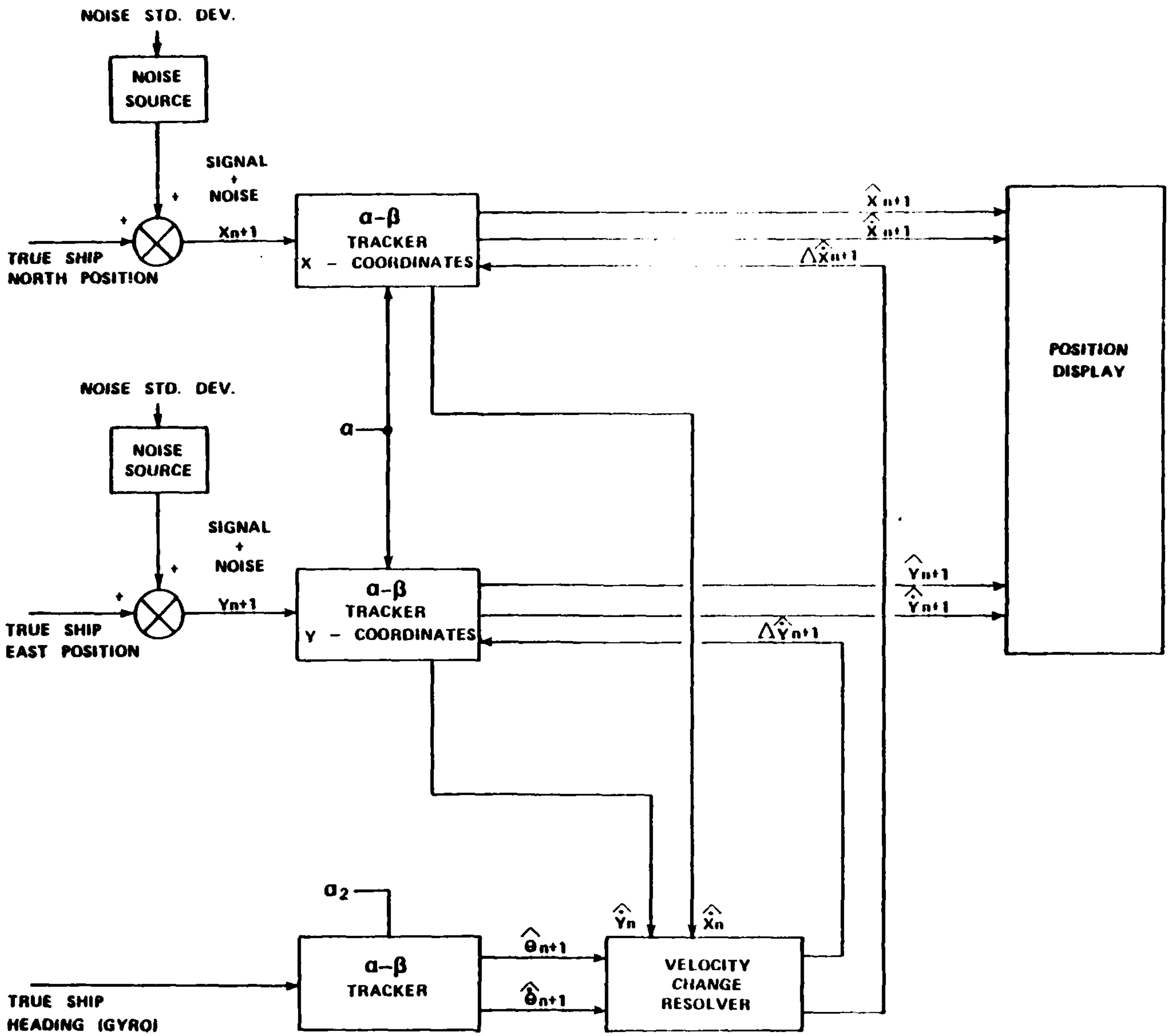

Figure 13. Implementation of Navigation System with Gyro-Aiding

3.6.2 Assignment Schedule

The administration schedule is shown in Table 6. Each subject received all variables described in Figure 6, which were counterbalanced between subjects to minimize the order effect. Two noise levels (16 and 32 meters rms) were arranged so that each appeared before the other an equal number of times. The 3-, 12-, and 24- second unaided tracker rise times and the one 24-second gyro-aided rise time variables were arranged so that every one followed each of the others an equal number of times.

In summary, the experimental design permitted the best mix of administration options to perform the experiment inexpensively and expediently yet enabling it to retain the necessary requirements to ensure statistical validity and adequate levels of confidence.

TABLE 6. SUBJECT ASSIGNMENTS

Order of Administration	Subject Number 1	2	3	4	5	6	7	8
1st	16/3*	32/3	16/24G	32/24G	16/12	32/12	16/24	32/24
2nd	32/12	16/12	32/24	16/24	32/24G	16/24G	32/3	16/3
3rd	16/24	32/24	16/12	32/12	16/3	32/3	16/24G	32/24G
4th	32/24G	16/24G	32/3	16/3	32/24	16/24	32/12	16/12
5th	32/3	16/3	32/24G	16/24G	32/12	16/12	32/24	16/24
6th	16/12	32/12	16/24	32/24	16/24G	32/24G	16/3	32/3
7th	32/24	16/24	32/12	16/12	32/3	16/3	32/24G	16/24G
8th	16/24G	32/24G	16/3	32/3	16/24	32/24	16/12	32/12

*The first number indicates rms noise in meters, the second number indicates tracker rise time in seconds, and "G" indicates the tracker is GYRO aided (see Figure 2).

Section 4

DATA COLLECTION AND ANALYSES

Data collection and analysis of performance for the RA-2 experiment was conducted similar to the RA-1 experiment. Methods of data retrieval, storage and compilation are detailed in the RA-1[21] and miniexperiment[22] reports. Instead of graphically illustrating entrance and exit leg performance separately as had been done in RA-1, however, the RA-2 analysis connected both legs together to show performance through the entire run. This feature enabled the analyst (and subsequently the reader of the report) to subjectively compare performance between variables simply by glancing between pages. Statistical analyses were, of course, employed to indicate where significant differences existed.

4.1 TRACKKEEPING ANALYSIS

The trackkeeping analysis of runs performed during the simulation was conducted by combining all runs within each variable, then computing and plotting the mean track and standard deviation of tracks for the variable. An example of the resultant plots is shown in Figure 14. Note that this example shows only Leg 1. The RA-2 plots show both legs, the entrance (Leg 1) and exit (Leg 2), connected together. The horizontal axis in the graphs represent discrete along channel positions at equal 475-foot intervals. These intervals, called "data lines," originate at the waypoint or center of the bend on the RA-2 graphs. In other words, data line zero occurs midway through the bend.

The performance measure plotted on the upper graph in Figure 14 is the trace of the mean across channel position of the ship's center of gravity averaged at each data line. The vertical axis of this graph represents across channel distance in feet. The starboard channel boundary is at 0, the channel centerline is the dashed line plotted at 250, and the port channel boundary is at 500.

The vertical axis in the center graph is an absolute scaler quantity in feet. The solid plotted line represents the standard deviation of the ship's center of gravity for all transits calculated at each data line.

The vertical axis of the lower graph is cross channel distance in feet. The dashed horizontal line at 500 is the port channel boundary. The dashed line at 0 is the starboard channel boundary. The information contained in the crosshatched plot is a modified-combination of that shown in the upper two plots. The center solid line inside the crosshatched area is the mean track line of the center of gravity. The upper and lower lines bounding the crosshatched area are each two times the standard deviation away from the mean center of gravity line. These lines define the envelope which would contain 95 percent of all ship center of gravity tracks in the population of transits under the specific experimental condition given the actual sample transits performed by the subjects.

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[21] Ibid.

[22] R. B. Cooper and K. L. Marino, op. cit.

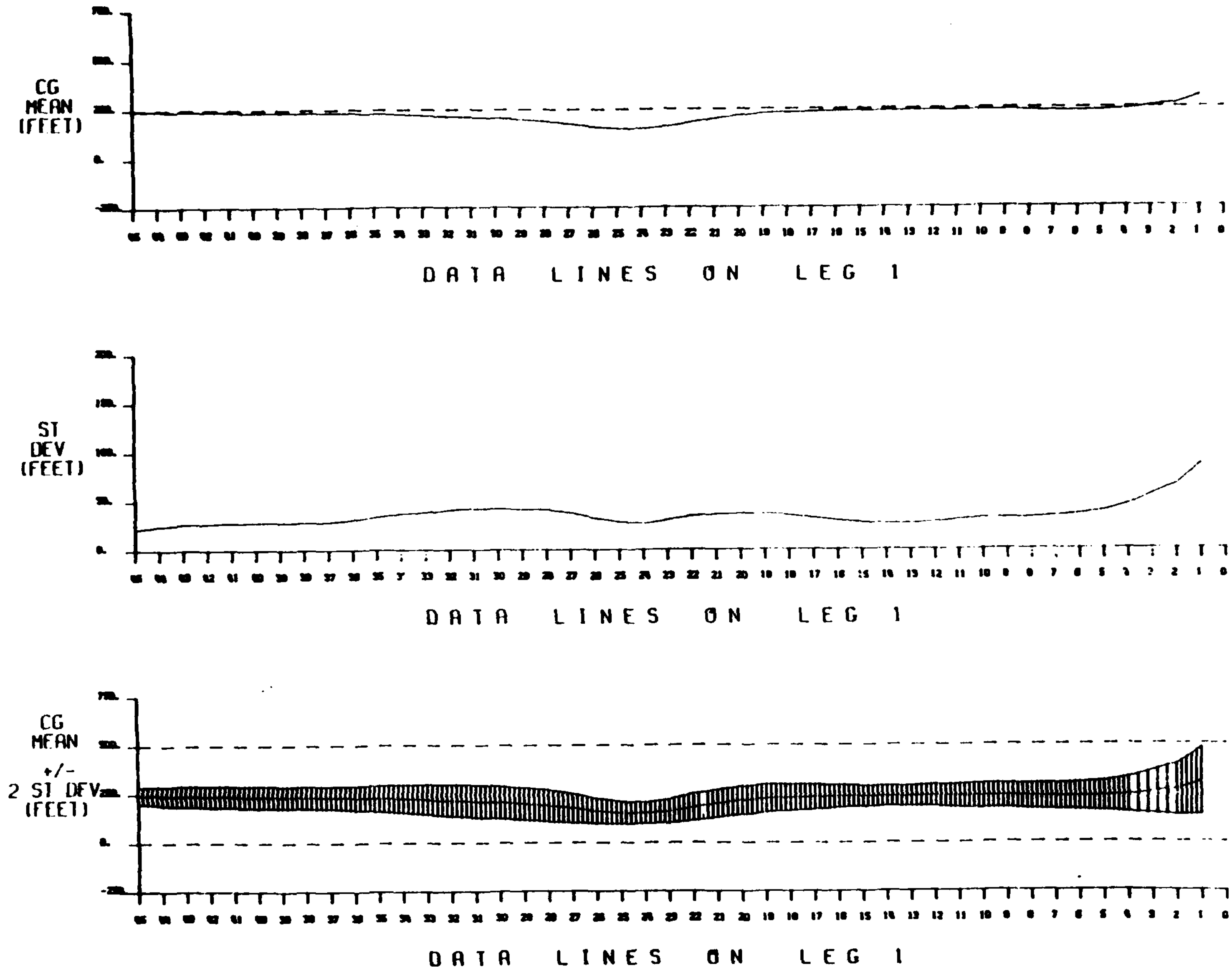

Figure 14. Example of Summary Plot Analysis

Appendix E contains the statistical analysis of track plots which were used to identify significant differences in trackkeeping performance as a result of the experimental variables. The figures were constructed as a result of statistically comparing, using the F-statistic at the $p \leq 0.10$ level of significance, one standard deviation of crosstrack variability between conditions at each data line. These figures illustrate the difference in variability which existed along the tracklines for each variable, and where it occurred. The data are used as statistical support for conclusions about the group mean track and crosstrack variability plots discussed in Section 4.

Additional plots were drawn which represented ownship's position as it was presented on the display. These plots were also drawn as mean, standard deviation and combined tracks so that they could be compared with the actual positions of the ship in each variable. While these plots are not published, they were helpful in enabling the analyst to determine whether differences in trackkeeping performance were due to perceptual problems or the fact that the display was exhibiting a large position error.

4.2 MANEUVERING PERFORMANCE

The maneuvering analysis was conducted for two major maneuvers, the transit of a straight leg with wind and current astern, and the transit of a straight leg with wind and current from the port quarter. The initial maneuver was to return to the centerline from a position 92 feet to the right of centerline. The second, was to negotiate a 35-degree left bend in the channel. To analyze maneuvering performance for the different variables, two analytical techniques were employed. The first was an analysis of the overall distribution and frequency of rudder commands, course commands and engine orders. The distribution of these control activities is illustrated graphically on the same page as the trackkeeping plots and in relatively the same format. All control activities were recorded at the time they actually occurred and were subsequently plotted at the position (crosstrack as well as along track) which ownship occupied when they occurred. This resulted in a tool which enabled the analyst to determine not only what control activities were used, but in many cases why they were used.

The second technique was a statistical analysis of the quantitative maneuvering data. A more detailed description of the individual measures which were analyzed is presented in Appendix D. Essentially they consisted of the following:

1. Return to and steady up on the channel centerline following the initial offset (wind and current astern)

   a. Along track distance required to return to the centerline

   b. Crosstrack overshoot of the centerline following the return to it

   c. Along track distance required to steady up on the centerline of the entrance leg

   d. Following negotiation of the bend (wind and current port quarter) — along track distance required to steady up on the centerline of the exit leg

2. Initial turn rudder applied before the bend

   a. Along track distance before the bend when the initial rudder was applied

   b. Magnitude of the initial turn rudder

   c. Maximum initial turn rudder that was applied

   d. Frequency of turn rudders which were applied

3. Check rudder applied beyond the bend

   a. Along track distance beyond the bend when the initial check rudder was applied

   b. Magnitude of the initial check rudder

Statistical differences as determined from the t-statistic at the 90 percent level of significance ($p \leq 0.10$) are indicated on the tables in which the measures are presented.

4.3 USER ACCEPTANCE

Structured interviews were administered by the test director at the end of each run. This enabled subjects to respond to questions about the run while it was fresh in their minds. The interviews were structured by use of questionnaires to be filled out jointly by the test director and subject. This ensured completeness and enabled the test director to clarify any questions which arose.

The questionnaires were brief (did not exceed five minutes for normal administration) and primarily addressed perceived individual performance (self-appraisal).

Questions were developed and arranged so that the subject could first give an appraisal of his performance in each segment of the waterway (i.e., poor, fair, good, or excellent); then he could choose from a number of potential deficiencies (e.g., rudder too early or rudder too late) to adequately describe his difficulty. The questionnaire is presented in Appendix C.

SECTION 5
RESULTS AND CONCLUSIONS

Results and conclusions of the RA-2 experiment are based upon both descriptive and statistical analysis of pilotage performance. As in the previous RA-1 and miniexperiment, trackkeeping and maneuvering performance as well as user acceptance are compared between experimental variables. In the case of the RA-2 experiment, these variables were system noise and tracker filter design characteristics.

To properly evaluate both the independent effects of these variables and their interaction effects, the analysis was conducted at two levels. First, all runs were divided into two groups; one in which 16 meter rms noise was simulated and one in which 32 meter rms noise was simulated. These two groups each with a sample size of 32 were graphically and statistically compared to determine the effect of the different noise levels on pilotage performance. All noise conditions were then combined and runs were divided into four groups by type of tracker. Comparisons in pilotage performance between these four groups determined the effect of filter rise times on pilotage performance. Sample sizes were 16 for each group.

The next analysis examined interaction effects. It specifically addressed the effect on pilotage performance of gyro aiding the tracker system. This analysis compared the unaided tracker with 24-second rise time against the gyro-aided tracker with 24-second rise time in each of the two, 16 meter rms and 32 meter rms, noise conditions. A final analysis compared pilotage performance of all subjects' initial runs with their final runs to identify the effect of learning on the overall experiment.

Of the 64 runs which were conducted during the RA-2 experiment, none produced effects considered serious enough to invalidate a run. Several excursions from the channel occurred as a result of overshooting or undershooting the bend. These, it will be shown, were attributed to the combination of display design and tracker design, not system noise. In general, the shiphandling characteristics of a relatively large, slow ship in a confined waterway and the environmental effects (i.e., wind and current) were considered by all subjects to be difficult but not unrealistic. Likewise, all subjects agreed the displayed information was sufficient to accomplish the pilotage in the given poor visibility; but they would never attempt such a transit without first "proving" the display during good visibility.

5.1 EFFECT OF NOISE ON PILOTAGE PERFORMANCE

The overall effect of noise alone on the radio aids to navigation display as it was simulated is best illustrated in Figures 15, 16, and 17. These plots show very little if any difference in trackkeeping performance as a result of noise alone. This conclusion is also supported in the statistical analysis of trackkeeping consistency, Figure E-1 of Appendix E. Further, Tables 7 and 8 which quantitatively describe the pilots' maneuvering performance show no significant differences for any of the measures analyzed.

It is the conclusion of this analysis that within the limits of noise which were simulated, and given all the display design characteristics present in the experiment, the pilot himself was a very adaptable filter. He was able to achieve good pilotage performance relatively independent of the effects of noise to which he was exposed.

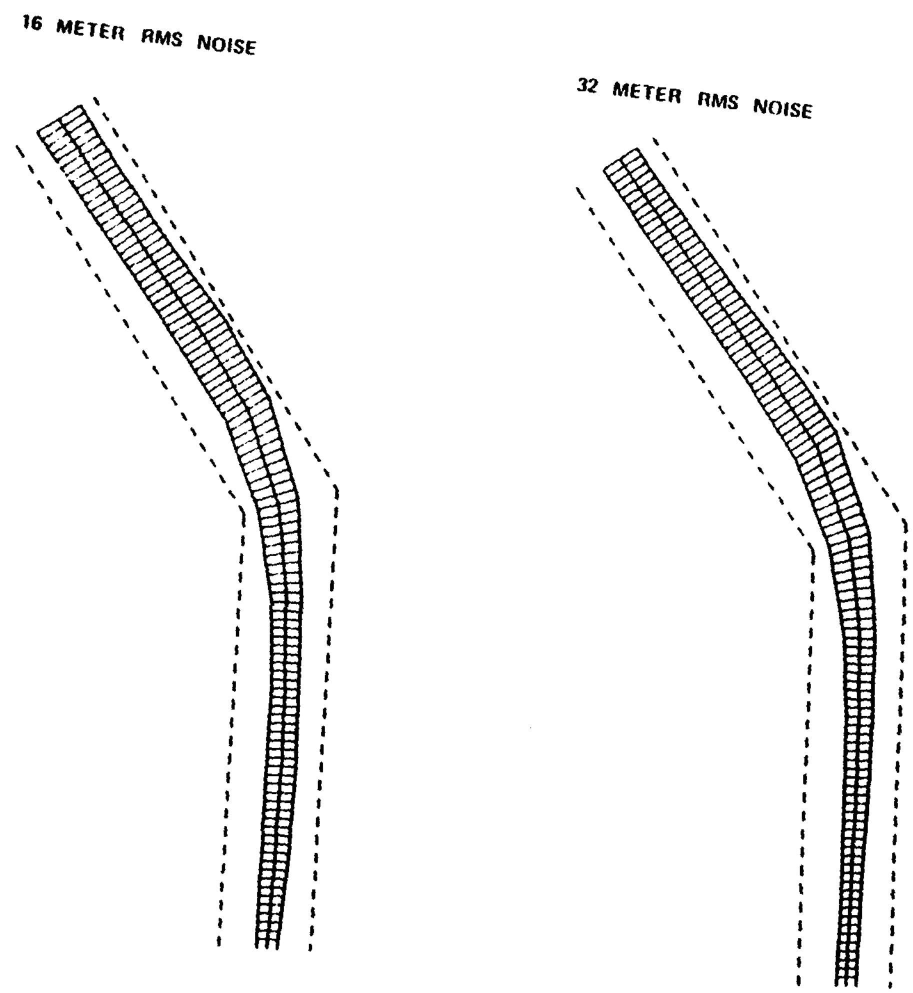

Figure 15. Effect of Noise with All Trackers

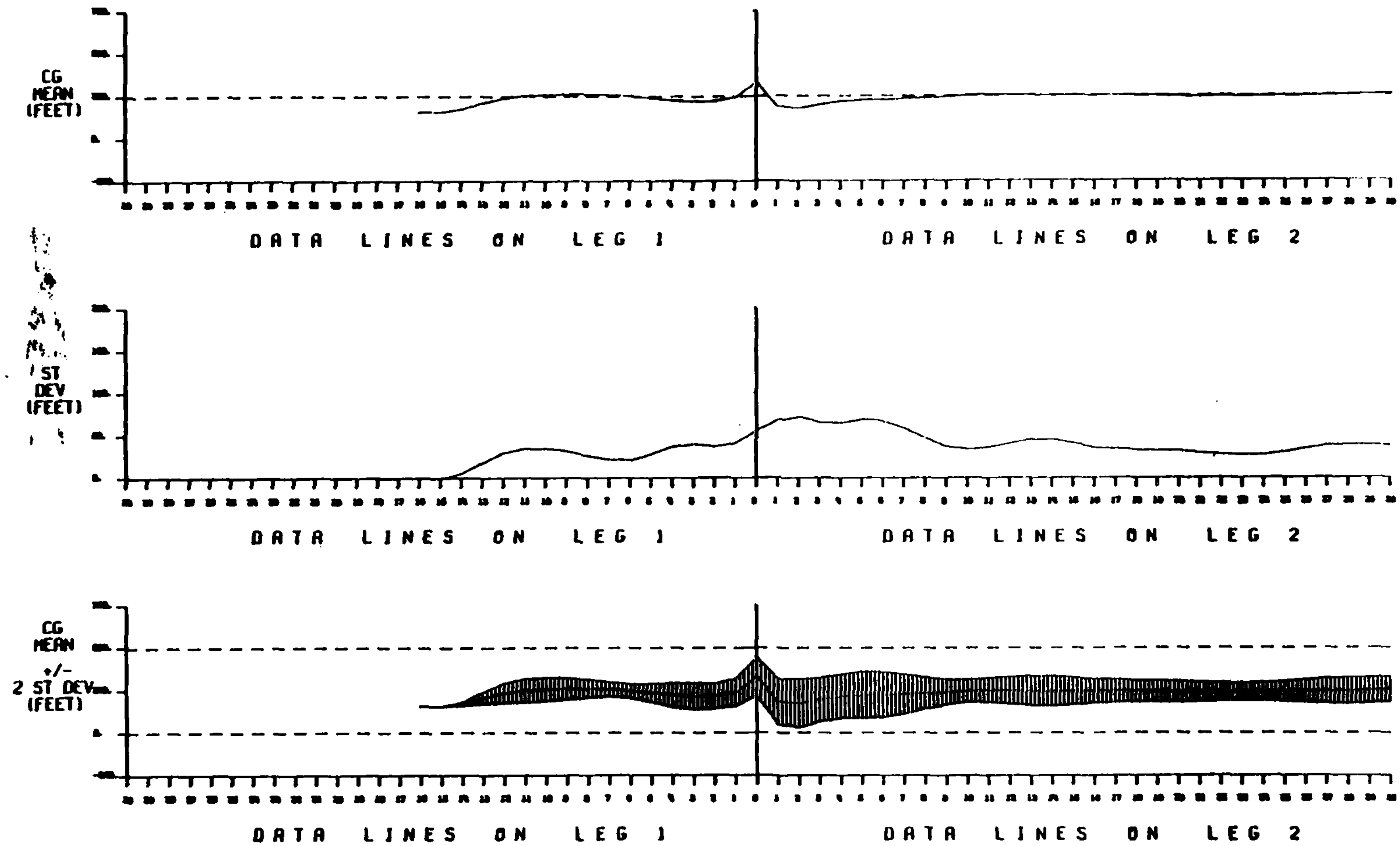

Figure 16. All Trackers in 16 Meter RMS Noise

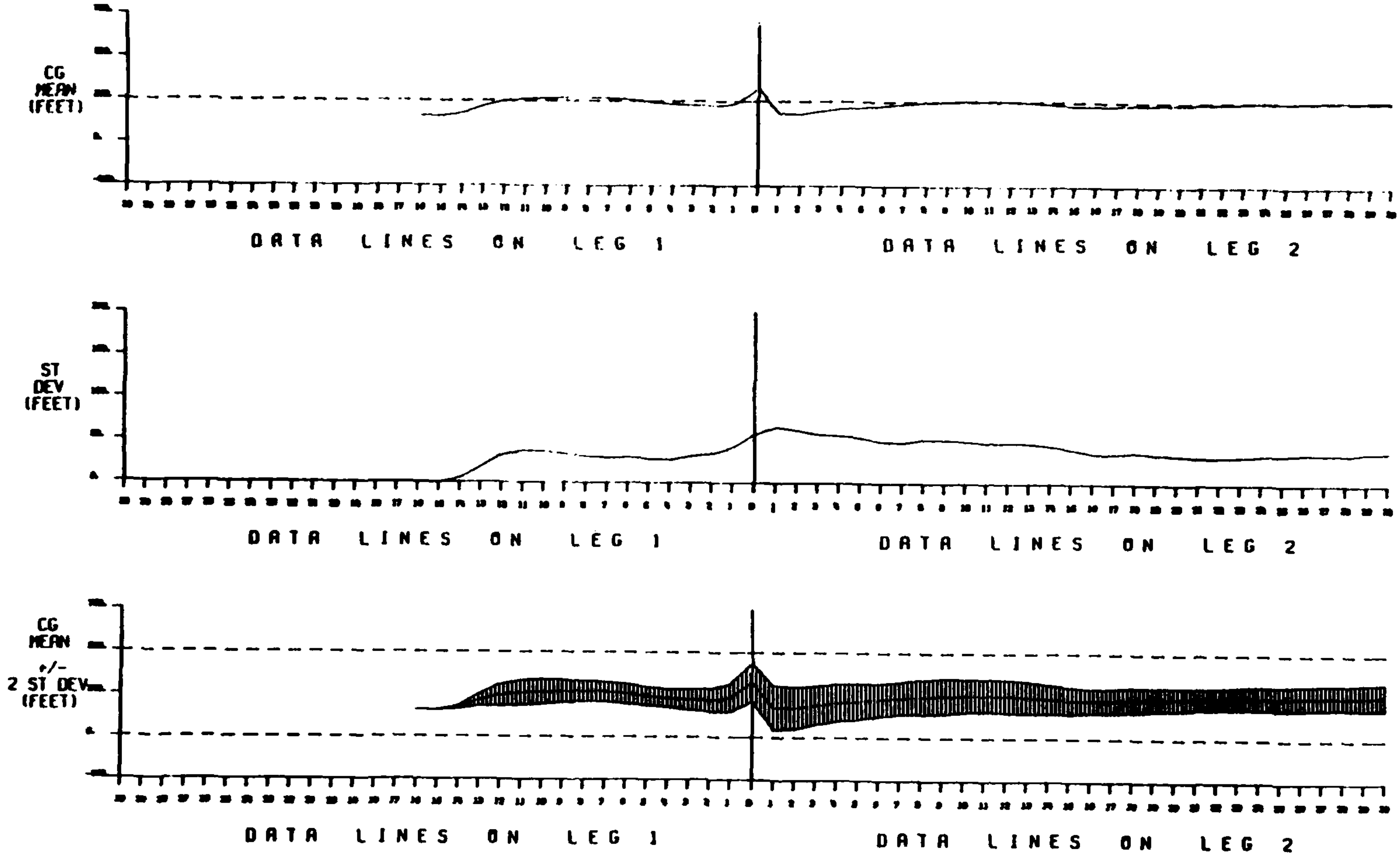

Figure 17. All Trackers in 32 Meter RMS Noise

TABLE 7. EFFECT OF NOISE ON MANEUVERING PERFORMANCE WITH ALL TRACKERS

Measure[1]	All Trackers In		Significant Difference[2]
	16 m rms Noise	32 m rms Noise	
Return to and Steady Up on Centerline			
1. Distance to return to centerline (nm)	0.388	0.348	None
2. Overshoot following return to centerline (ft left)	13	10	None
3. Distance to steady up in entrance leg (nm)	0.680	0.706	None
4. Distance to steady up in exit leg (nm)	0.795	0.925	None
Initial Turn Rudder Application			
1. Distance before bend at initial rudder (nm)	0.179	0.164	None
2. Magnitude of initial turn rudder (degrees)	10	15	None
3. Magnitude of subsequent turn rudder (degrees)	30	30	None
4. Frequency of turn rudder actuations	4	4	None
Check Rudder Application			
1. Distance beyond bend of initial check rudder (nm)	0.121	0.112	None
2. Magnitude of initial check rudder (degrees)	20	20	None

[1]Rationale for the derivation of these measures are presented in Appendix D.

[2]No statistical difference indicated at the $p \leq 0.10$ level of significance.

TABLE 8. MEAN FREQUENCY OF CONTROL ACTIVITIES

EXPERIMENTAL VARIABLES	RUDDER COMMANDS	COURSE COMMANDS	ENGINE ORDERS
Effect of Noise with All Trackers			
All trackers in			
- 16 meter RMS noise	21	11	3
- 32 meter RMS noise	20	14	2
Effect of Tracker Design			
In all noise conditions			
- tracker with 3-second rise time	21	12	2
- tracker with 12-second rise time	22	11	3
- tracker with 24-second rise time	21	13	2
- gyro-aided tracker	18	13	3
Tracker with 3-second rise time in			
- 16 meter RMS noise	26	10	2
- 32 meter RMS noise	16	14	2
Tracker with 12-second rise time in			
- 16 meter RMS noise	19	10	3
- 32 meter RMS noise	26	12	2
Tracker with 24-second rise time in			
- 16 meter RMS noise	23	10	2
- 32 meter RMS noise	19	15	2
Gyro-aided tracker in			
- 16 meter RMS noise	18	12	3
- 32 meter RMS noise	18	15	2
Effect of Learning			
Subjects' initial run	30*	11	3
Subjects' final run	16	13	4

*Statistically different at the $p \leq 0.10$ level of significance.

Because the analysis describes the average performance of all trackers under different noise conditions; the "better" trackers could have compensated for deleterious effects of "poorer" ones. For this reason the next analysis examined the effects of individual tracker design in all noise conditions.

5.2 EFFECT OF FILTER RISE TIME ON PILOTAGE PERFORMANCE

Obvious effects on pilotage performance, both in trackkeeping and maneuvering, were in evidence as the result of different tracker rise times and gyro aiding technique. These effects are shown graphically in Figures 18 through 22, but are most apparent in the statistical comparison of maneuvering performance, Table 9. When combining both noise levels (i.e., equal samples of 16 and 32 meter rms noise) as shown in Figure 18, there was little visible difference in trackkeeping performance among the unaided trackers, but a tendency to overshoot the bend with the gyro-aided tracker. Table 9 and Figures 19, 20, and 21, also show there were no significant differences in distance to return to the centerline or to steady up when noise conditions were combined.

Ownship jitter was most obvious with the short rise time trackers. It required pilots to consciously do their own filtering by estimating actual position somewhere between each consecutively displayed position. Results of the overall track plots indicate that this "visual filtering" was successful.

As tracker rise times lengthened, two additional factors began to influence the display. First, tracker positioning on the display became smoother, making ownship jitter less obvious. As a result, visual filtering became easier. Second, the longer rise time introduced lag into the system which introduced a bias error as soon as ownship began to maneuver. In other words, given a tracker with a lengthy rise time, jitter would be minimized, but ownship's along track and crosstrack position could be displayed with a large error depending upon ownship's speed and/or rate of turn.

The net effect on pilots' behavior resulting from the tradeoff between display jitter and lag are revealed in the analysis of pilotage performance with the different tracker designs. This comparison of performance between trackers with different rise times suggests that pilots are capable of "visual filtering" when the need to do so is obvious. However, in the absence of feedback as to ownship's actual position in the waterway, the existence of display lag and its effects on their pilotage will go undetected. What pilots saw on the display and the way the display portrayed their pilotage was the only feedback the pilots received. When a large bias error was present on the display as a result of filter lag, the pilots had no knowledge of it and maneuvered the ship as though it was presenting "perfect" position information. Unlike display jitter, the pilots could not compensate for lag.

For this reason, the effects of filter lag on pilotage performance were found to be large compared to the effects of jitter. This is best illustrated by a hypothetical scenario of a ship being piloted with a relatively long rise time filter. The scenario could be similar to that experienced by pilots when they used the unaided tracker with 24-second rise time in 32 meter rms noise to execute a 35-degree turn. The scenario is plotted in Figure A-6 of Appendix A which shows ownship's actual track and the position of ownship as it was presented on the display every second. The magnitude of display error, its direction from ownship's actual position and upon what occasion the error occurred is essential to understanding the pilots' behavior.

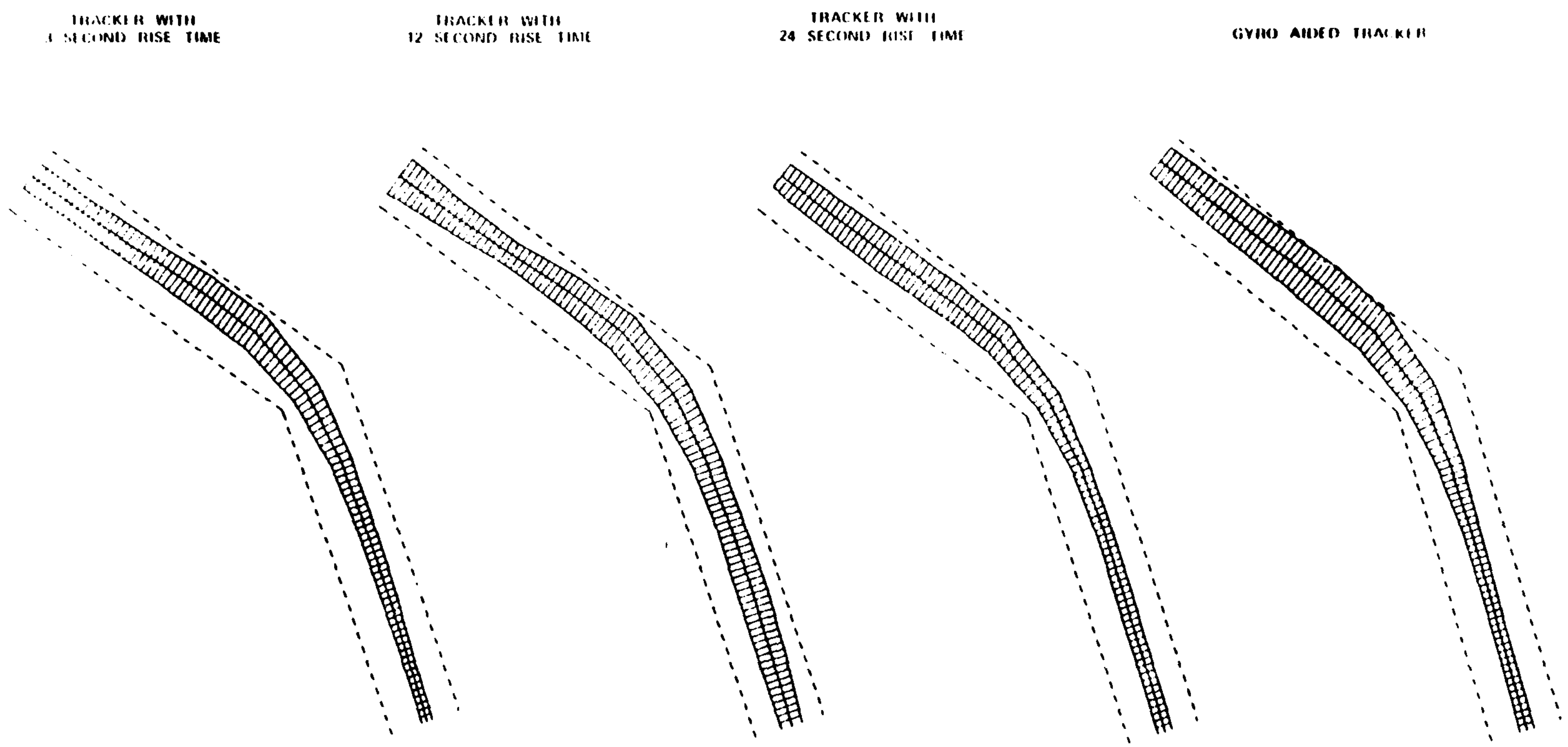

Figure 1[illegible]. Effect of Tracker Rise Time and Gyro-Aiding in All Noise Conditions

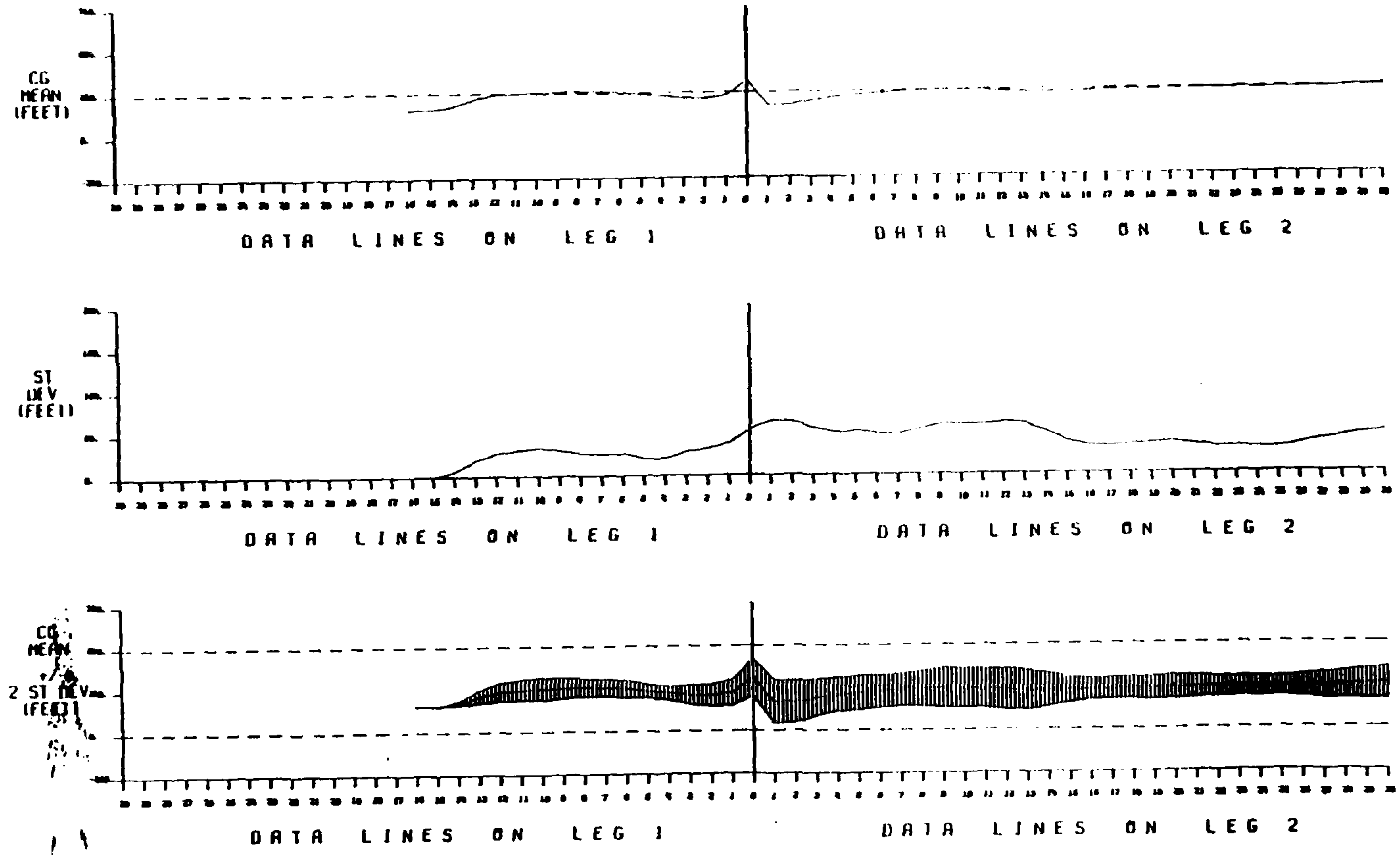

Figure 19. Tracker with 3-Second Rise Time in All Noise Conditions

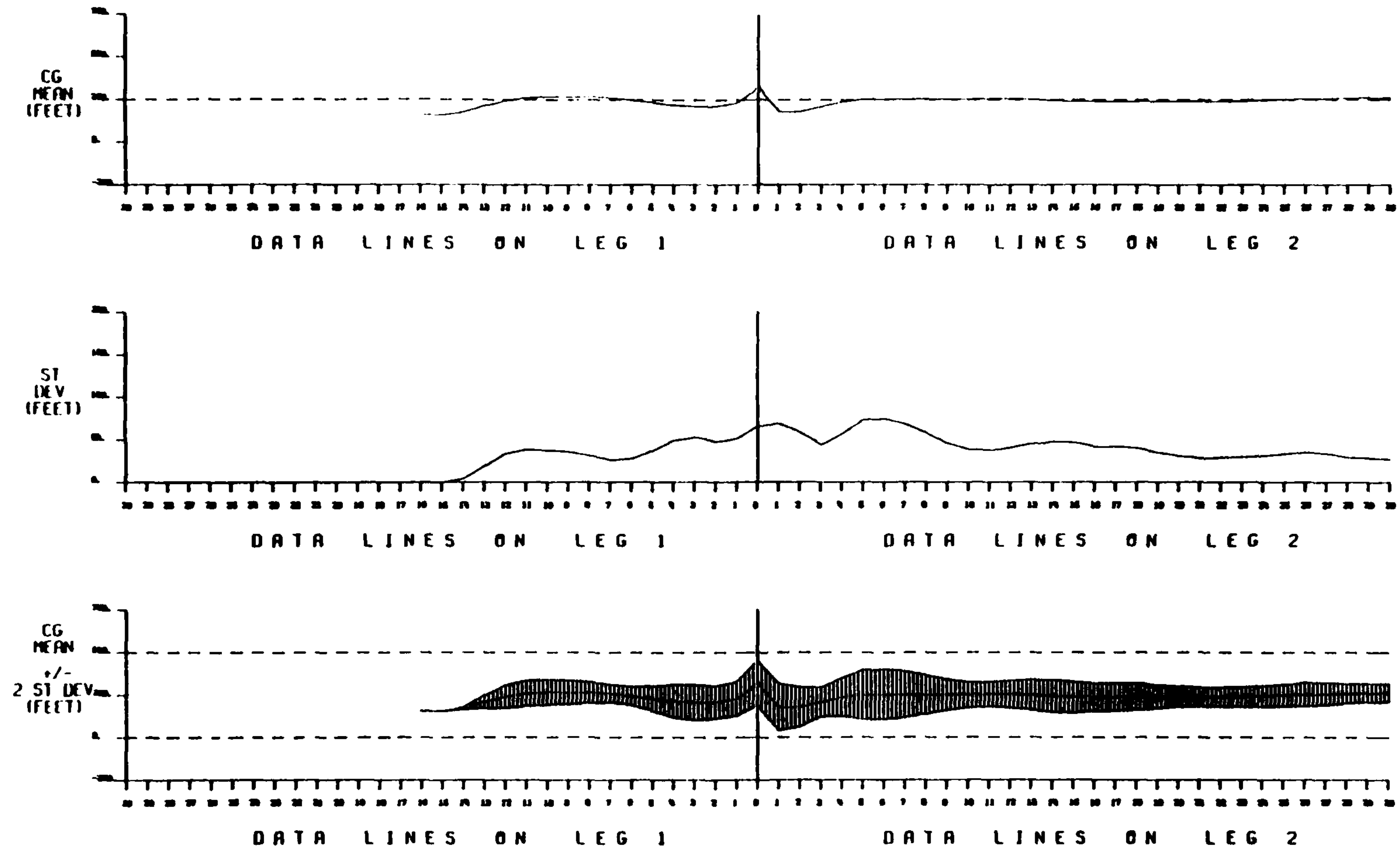

Figure 20. Tracker with 12-Second Rise Time in All Noise Conditions

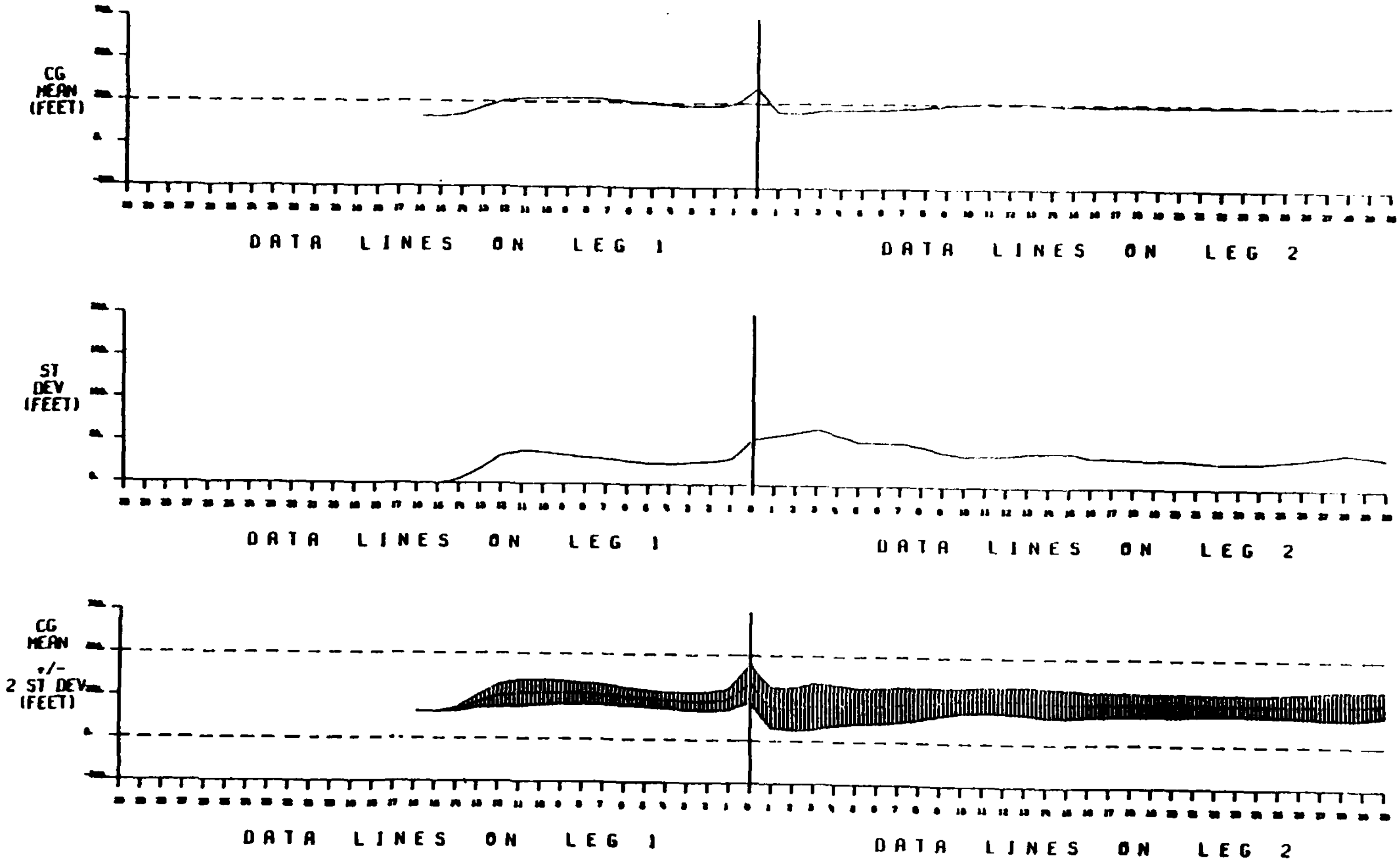

Figure 21. Tracker with 24-Second Rise Time in All Noise Conditions

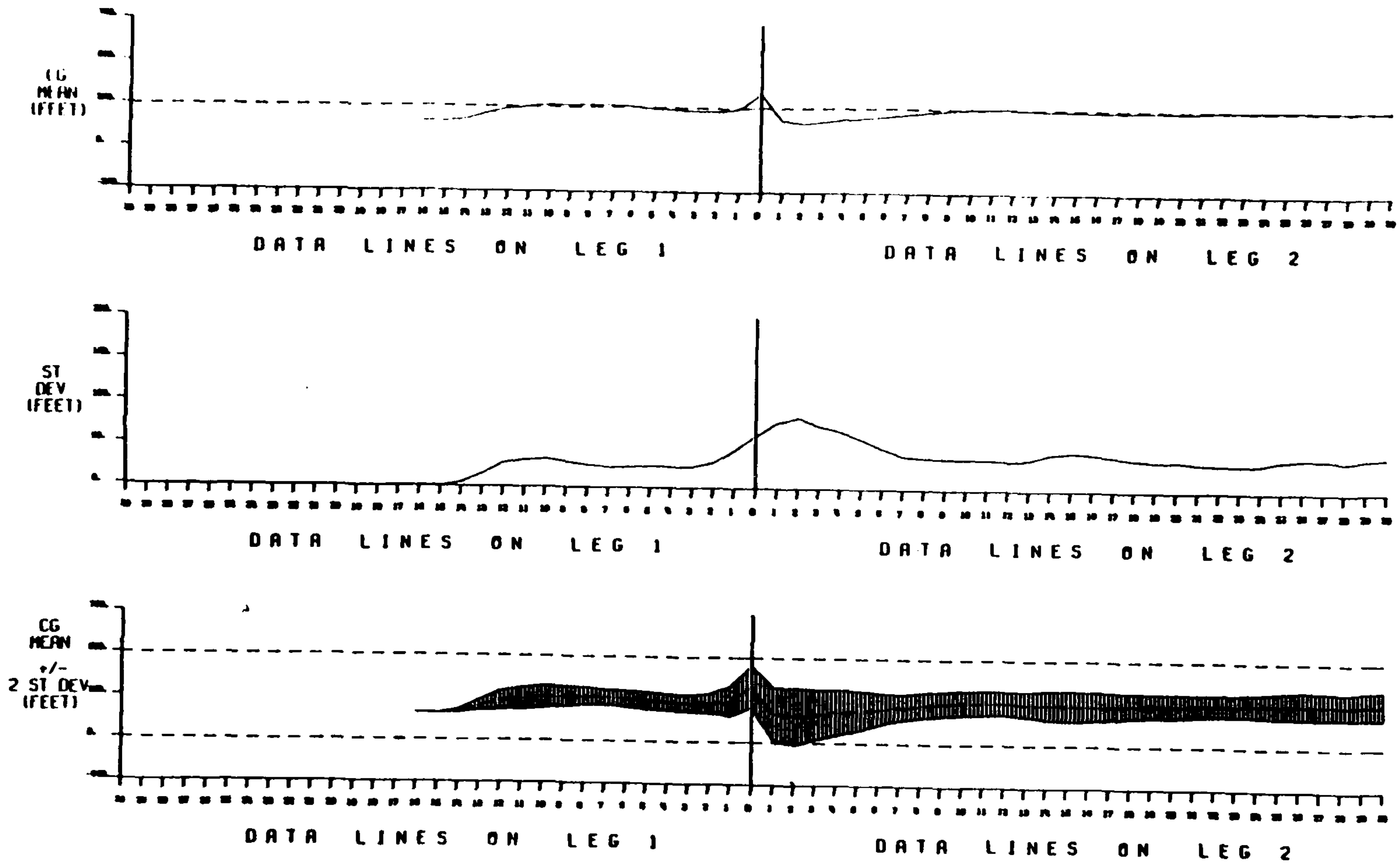

Figure 22. Gyro-Aided Tracker in All Noise Conditions

TABLE 9. EFFECT OF TRACKER DESIGN ON MANEUVERING PERFORMANCE IN ALL NOISE CONDITIONS

MEASURE[1]	In All Noise Conditions				SIGNIFICANT DIFFERENCE[2]
	Tracker with Rise Time				
	3 Sec.	12 Sec.	24 Sec.	Gyro-Aided	
Return to and Steady Up on Centerline					
1. Distance to return to centerline (nm)	0.365	0.337	0.390	0.379	None
2. Overshoot following return to centerline (ft left)	7	20	15	5	None
3. Distance to steady up in entrance leg (nm)	0.598	0.714	0.711	0.747	Shorter with 3-second rise time
4. Distance to steady up in exit leg (nm)	0.775	1.069	0.819	0.777	Shorter with 3-second rise time and when gyro aided.
Initial Turn Rudder Application					
1. Distance before bend at initial rudder (nm)	0.154	0.184	0.186	0.162	None
2. Magnitude of initial turn rudder (degrees)	10	15	15	15	None
3. Magnitude of subsequent turn rudder (degrees)	35	30	35	25	Smaller with gyro-aided tracker
4. Frequency of turn rudder actuations	3	4	5	5	None
Check Rudder Application					
1. Distance beyond bend of initial check rudder (nm)	0.113	0.120	0.118	0.117	None
2. Magnitude of initial check rudder (degrees)	20	20	20	20	None

[1]Rationale for the derivation of these measures are presented in Appendix D.

[2]Statistically different at $p \leq 0.10$ level of significance.

Hypothetical Scenario

The pilot is on a straight leg approaching a sharp 35-degree bend at a relatively slow speed of 6 knots. The long rise time tracker has stabilized from all previous maneuvers and is producing only slight jitter as a result of the well filtered noise. The errors indicated in the jitter are random all around ownship's actual position. The pilot is doing his own "visual filtering" between jitters to estimate actual position of ownship. Lag errors are almost non-existent.

As soon as the pilot initiates his turn maneuver and a rate of turn develops, the effect of lag begins to dominate. Since ownship is traveling slowly but the turn rate develops rapidly, the lag error transforms more into a crosstrack error than an along track error. Some along track lag, however, does exist. (See Figure A-6 in Appendix A.) As the turn rate of ownship increases and ownship actually begins to proceed around the bend, the lag error which is biased toward the outside of the turn also increases. The display thus indicates to the pilot that he is not moving into the bend as rapidly as he actually is, and, as a result, the pilot applies additional rudder to even further tighten his turn.

The pilot's perception of this maneuver is that ownship was extremely slow in responding to his initial turn rudder. If he had preconceived ideas of how the ship should handle whether from previous simulation runs or prior operational knowledge, he would be concerned about this inconsistency and would assume the ship will respond equally sluggishly to the check rudder.

Once ownship's turn rate is established and ownship is well into the bend, the lag error transforms even more into a crosstrack bias than before. This causes the display to show ownship as overshooting the new centerline and elicits additional measures, usually hard rudder, to be applied by the pilot.

As shown in the figure, the filter does not restabilize until well into the exit leg beyond the bend. This means that if ownship were actually on the centerline, for the beginning of the leg it would be presented on the display well to the right of center. Gradually, as the lag error reduces, ownship on the display would move toward the center. Pilots, without any external source of reference, would have no way of knowing this and would attempt to keep the displayed ownship in the center of the channel.

The result of this scenario, then, is that if a pilot were able to maintain ownship on the centerline of the display, he would surely undershoot the bend and end up to the left of center well into the exit leg.

Given the above scenario, it is possible to see the effects a long rise time tracker with long lag could have on pilotage performance. While these effects did occur to some degree in the RA-2 experiment, there is evidence to support the conclusion that they were not severely detrimental to the pilotage; and, in fact, appeared to improve it. An explanation for this is derived from the results of the previous RA-1 and miniexperiment. In none of these experiments which used displays with "perfect" position information was pilotage performance better or even comparable to visual runs (i.e., AN-CAORF and AN-VISUAL experiments).[23, 24] In all cases the displays led to at least some overshoot of the centerline, and occasionally an overshoot of the channel boundary. This effect, however, was minimal with the GRAPHIC and STEERING displays, and was one of the bases for selecting the GRAPHIC as the benchmark display[25].

The fact remains that there were tendencies of pilots to overshoot the bend when they used the benchmark display with "perfect" position information. If, as is suggested by the hypothetical scenario, the effect of tracker lag causes pilots to undershoot the bend, then a combination of the benchmark display with tracker lag should provide for "centerline" trackkeeping performance.

This irony, of course, is not the solution to either of the problems. In fact, it would probably not have occurred had pilots been more familiar with the use of a GRAPHIC display for piloting or had the scenario been different. For example, with a fast ship, the tracker lag would probably be transformed more into an along track error than a crosstrack error. The result would be that the actual ship would lead the displayed ship into the bend and the possibility of overshoot would be immense.

5.3 EFFECT OF GYRO-AIDING ON PILOTAGE PERFORMANCE

The potentially detrimental effects of tracker lag are well acknowledged by developers of tracker filters for navigation systems. As a result, some filters have been designed to "know" when an intentional maneuver is initiated, thus modifying the filter operation and eliminating much of the lag. Although there are several methods for signaling the initiation of a maneuver to the filter,the RA-2 experiments used a gyrocompass input. The results on display accuracy are shown in Figure A-8, Appendix A. Note that while noise error remains in the form of ownship jitter, once the maneuver is initiated there is little indication of bias error due to lag.

In summary, when pilots use the gyro-aided tracker, they see the same amount of jitter as on the unaided displays, but experience none of the effects of lag. Assuming, as this analysis has concluded, that pilots are able to "visually filter" out the jitter, then performance with the gyro-aided tracker should be very comparable to performance with the "perfect" position GRAPHIC display in the RA-1 experiment.

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[23] M. W. Smith and W. R. Bertsche, op. cit, January 1981.

[24] M. W. Smith and W. R. Bertsche, op. cit, February 1981.

[25] R. B. Cooper, K. L. Marino and W. R. Bertsche, op. cit.

Trackkeeping performance with the gyro-aided tracker, Figures 18 and 22, indicates the same moderate overshoot of the centerline and high crosstrack variability experienced in the RA-1 experiment.[26] It also suggests a somewhat less than favorable performance compared to the unaided trackers. The probable cause for this has been discussed. Further evidence to support the discussion is presented in Table 9. Note that for all trackers the average initial turn rudder was applied at approximately the same distance before the turn (0.154 to 0.162 nm), and approximately the same magnitude of initial turn rudder (30 to 35 degrees) was used between the unaided trackers and the gyro-aided trackers. However, in comparing subsequent rudders (i.e., those applied after the initial turn rudder), pilots used significantly more rudder with the unaided tracker (35 degrees) than the gyro-aided one (25 degrees). In other words, as suggested in the hypothetical scenario, pilots perceived themselves as entering the bend equally well with both trackers. Once into the turn, however, the unaided tracker made them perceive that they were going to overshoot the bend and they applied additional turn rudder. With the gyro-aided display they proceeded normally, maintaining much of the original rudder with which they originally initiated the turn.

This analysis describes the effects of each tracker design in the combined noise environment. The next analysis was conducted to identify the potential interactive effects of each tracker design with each noise level.

5.4 INTERACTIVE EFFECTS OF TRACKER DESIGNS AND NOISE LEVELS

Based upon the findings described in sections 5.2 and 5.3, the analysis of trackkeeping and maneuvering performance was interpreted using the following rationale:

1. An expedient return to, and steady up on the channel centerline following any maneuver was considered normal pilotage performance.

2. An overshoot of the exit leg centerline, but not an excursion from the channel was considered normal pilotage performance.

3. An undershoot of the bend was considered to result from tracker lag in the presentation of ownship's position on the display.

4. High pilot anxiety or excessive rudder application in the turn maneuver was considered to result from the effect of lag.

In light of this rationale, a review of Appendix E, which is the statistical analysis of trackkeeping performance, illustrates the effects of the various tracker designs and noise levels. In each figure, the upper plot shows mean track of all runs in each condition. The lower plot shows the variability of all runs as one standard deviation of crosstrack distance.

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[26] Ibid.

Figure E-2 shows no difference in mean tracks between 3- and 12-second rise time trackers in the low (16 meter rms) noise. Those differences in variability which are shown cannot be attributed to noise since the tracker with 3-second rise time showed the most jitter and in fact, has the significantly lower variability. The plot suggests that with jitter on the display pilots were conservative in their maneuvers to return to and steady up on the centerline. Figure E-3 shows the same two trackers in the higher (32 meter rms) noise. Here the tracker with 3-second rise time (i.e., the most jitter) shows a significantly more gradual return to the centerline and steady-up in the exit leg. There is relatively little difference in variability.

In the comparison between trackers with 12- and 24-second rise times (Figures E-4 and E-5), significant difficulty is indicated in steadying up with the 24-second tracker at both noise levels. Here,the tracker with minimal jitter (i.e., the 24-second tracker) produced minimal crosstrack variability.

Figures E-6 and E-7 compare the effects of large jitter from a 3-second tracker with minimal jitter but long lag from a 24-second tracker. In the lower (16 meter rms) noise where there is less jitter, the 3-second tracker permitted a relatively fast return to the centerline beyond the bend. In the higher 32 meter rms noise, this return to the centerline was much more gradual. With the 24-second tracker, performance was again affected by the difference in noise. In the lower noise, steadying up appeared to be difficult (see Figure E-6). The pilots saw no jitter on their display, but were deceived by the lag effect. At the higher noise level (see Figure E-7) both the 3-second and 24-second filters showed comparable tracks with a very gradual return to and steady up on the new centerline.

Figures E-8 and E-9 show the trackkeeping performance between 24-second trackers which were gyro-aided and those which were not. It is obvious from both figures that the gyro-aided tracker produced a greater overshoot beyond the bend which according to the analysis rationale is comparable to expected performance. The figures also show that with high (32 meter rms) noise the gyro-aided trackers produced a mean track comparable to the unaided trackers, but with significantly greater consistency (i.e., less crosstrack variability) among pilots.

5.4.1 Trackers with 3-Second Rise Time

In order to make recommendations on tracker design for use with the benchmark display, a determination of the causes for the effects revealed in the analysis is required. This is accomplished by comparing the pilotage performance for each tracker when it was used in each of the two different noise conditions. The analysis makes use of both descriptive track plots and a statistical comparison of quantitative measures.

Figures 23, 24, and 25 show the trackkeep..ıg performance which was achieved when the trackers with 3-second rise time were used. Very similar trackkeeping performance is in evidence regardless of noise. Table 10 shows no difference in maneuvering attributed to noise level, although there was a larger variability among pilots in steadying up initially with the higher noise. Overall, it is concluded that the tracker with 3-second rise time produced comparable, satisfactory pilotage performance in both noise levels. This performance is attributed primarily to the pilots' "visual filtering" ability.

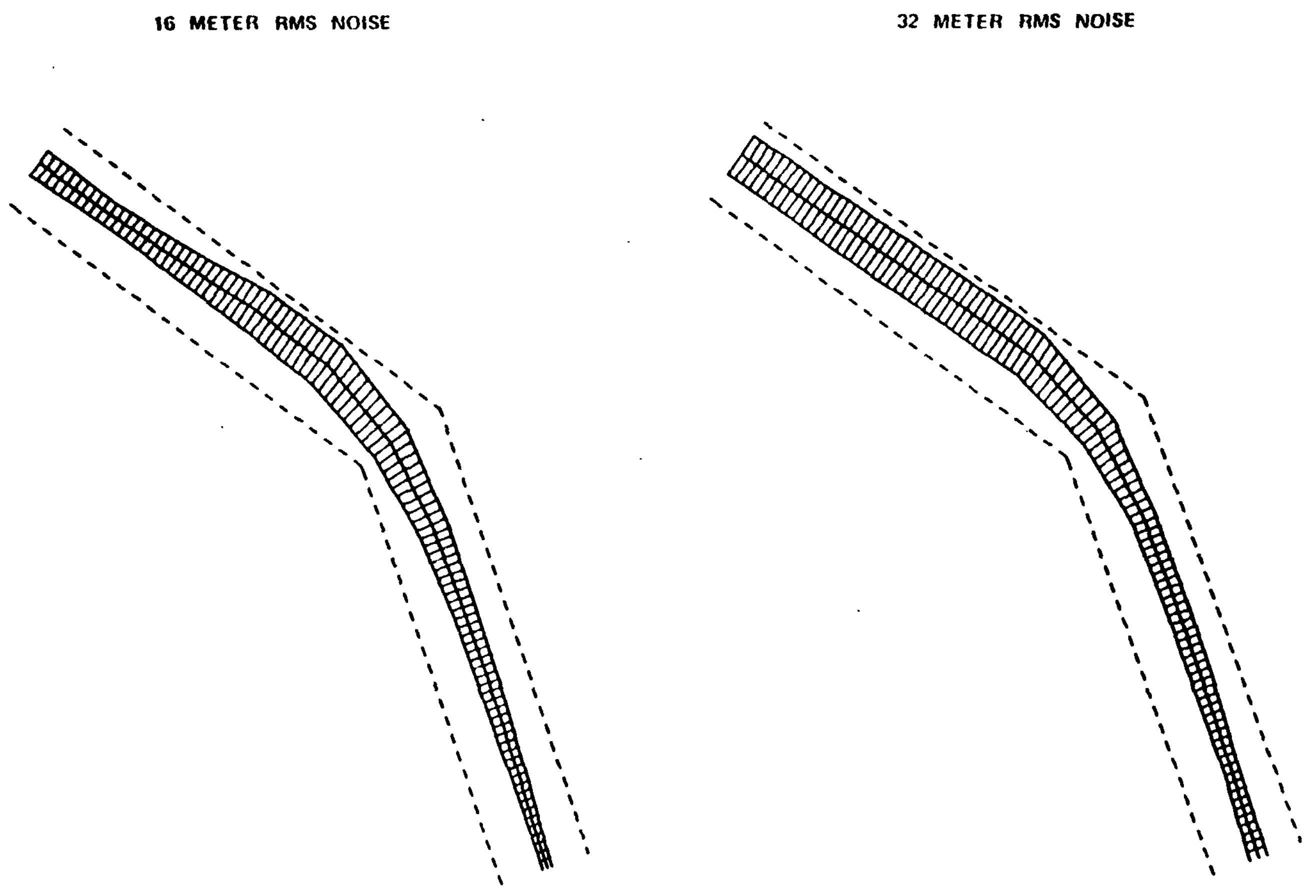


Figure 23. Effect of Noise on a Tracker with 3-Second Rise Time

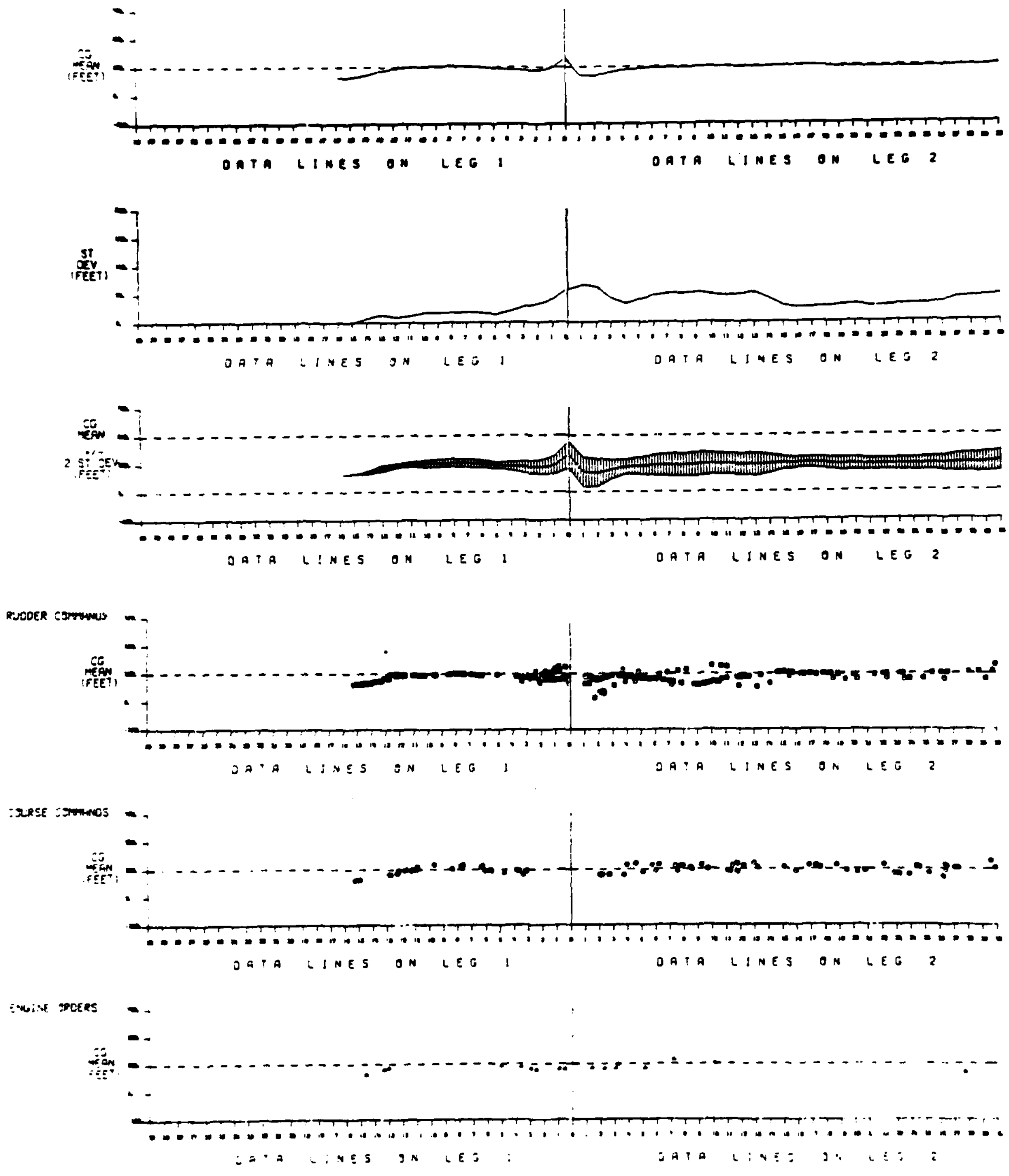


Figure 24. Tracker with 3-Second Rise Time in 16 Meter RMS Noise

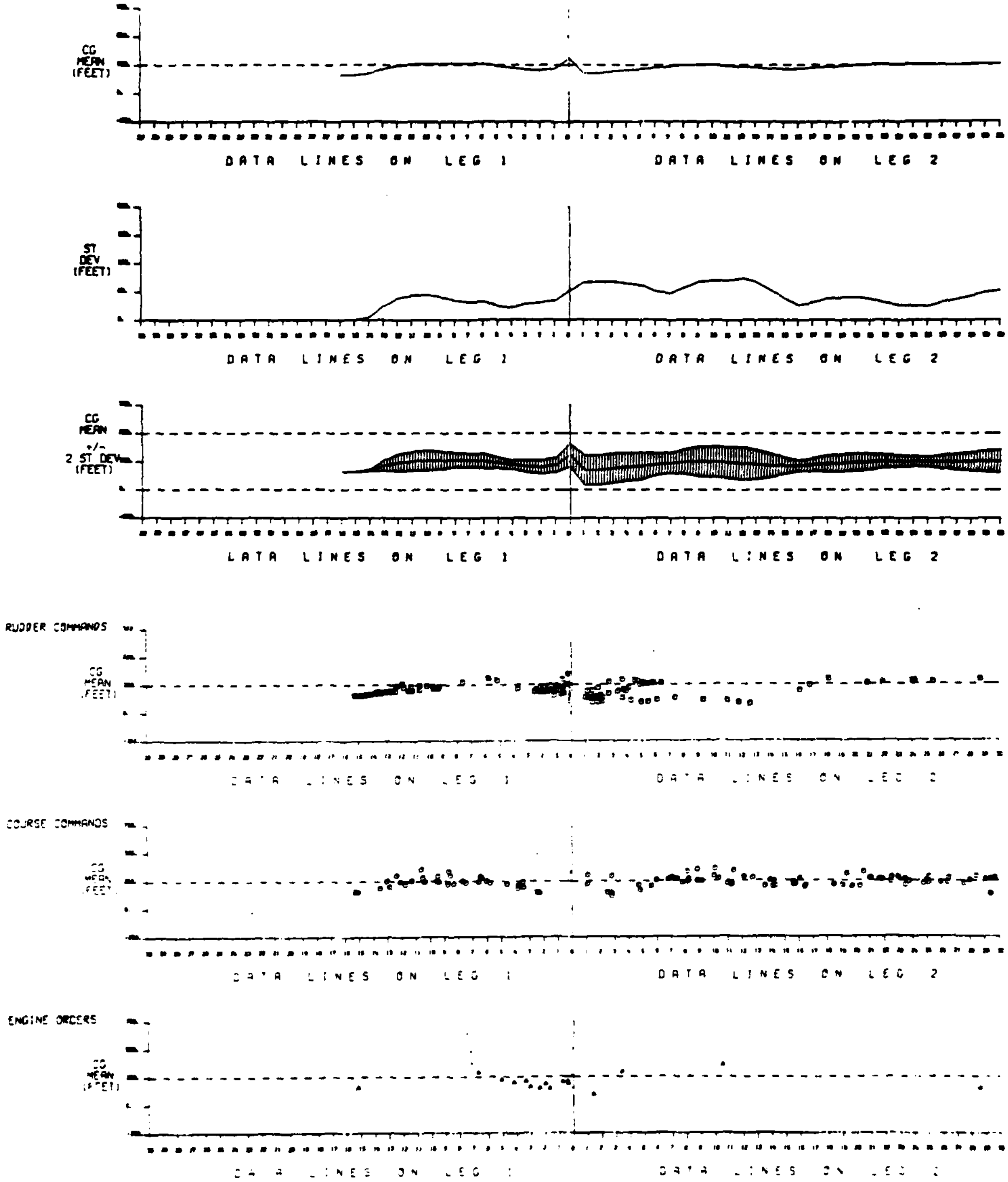


Figure 25. Tracker with 3-Second Rise Time in 32 Meter RMS Noise

TABLE 10. EFFECT OF TRACKER WITH 3-SECOND RISE TIME ON MANEUVERING PERFORMANCE

Measure[1]	Tracker with 3-Second Rise Time		Significant Difference[2]
	16 m rms Noise	32 m rms Noise	
Return to and Steady Up on Centerline			
1. Distance to return to centerline (nm)	0.371	0.360	None
2. Overshoot following return to centerline (ft left)	6	9	None
3. Distance to steady up in entrance leg (nm)	0.615	0.581	None
4. Distance to steady up in exit leg (nm)	0.773	0.776	None
Initial Turn Rudder Application			
1. Distance before bend at initial rudder (nm)	0.156	0.151	None
2. Magnitude of initial turn rudder (degrees)	10	10	None
3. Magnitude of subsequent turn rudder (degrees)	30	35	None
4. Frequency of turn rudder actuations	3	3	None
Check Rudder Application			
1. Distance beyond bend of initial check rudder (nm)	0.124	0.101	None
2. Magnitude of initial check rudder (degrees)	20	20	None

[1] Rationale for the derivation of these measures are presented in Appendix D.

[2] No statistical difference indicated at the $p \leq 0.10$ level of significance

5.4.2 Tracker with 12-Second Rise Time

Pilotage performance as indicated in Figures 26, 27 and 28 again shows more similar trackkeeping between the two noise levels when the tracker with 12-second rise time was used. There was a high variability among pilots in steadying up beyond the bend in the low noise condition. Table 11 shows a very gradual steady up in the high noise condition. Closer analysis of these measures revealed no particular detriment to maneuvering performance as a function of these effects. As reported in the statistical analysis of track plots, section 5.4 and Appendix E, the major difference in pilotage performance between the 3- and 12-second trackers was overall superior maneuvering to return to the centerline and steady up with the 12-second tracker.

5.4.3 Tracker with 24-Second Rise Time

Figures 29, 30 and 31 show the differences in trackkeeping performance resulting from noise for the tracker with 24-second rise time. While Table 12 shows no differences in maneuvering performance, differences are in evidence on the mean CG plots (Figures 30 and 31). They indicate considerable difficulty returning to the centerline beyond the bend for both noise conditions. Pilot variability also is large in this particular area with the higher noise.

The conclusion is that the noise variable did not significantly affect trackkeeping performance. The introduction of lag bias as a result of long rise time, however, produced difficulties in maneuvering, particularly returning to the centerline and steadying up.

5.4.4 Gyro-Aided Tracker with 24-Second Rise Time

A comparison of pilotage performance between when the gyro-aided tracker with 24-second rise time was used in the higher noise and when it was used in the lower noise is illustrated in Figures 32, 33 and 34; and Table 13. This tracker has minimal lag and minimal jitter, and is most similar to the "perfect" position display of the RA-1 experiment. It is, therefore, not surprising to find that pilots overshot the bend very much like they did in the RA-1 experiment. It is surprising,to find that they experienced larger crosstrack variability beyond the bend in the lower noise condition. No other indications point to noise level as having an effect on the gyro-aided tracker's performance.

5.5 LEARNING EFFECTS

Although certain interactions of the experimental variables were shown to have some effect on pilotage performance, none are believed to have as great an effect on overall safety of the transit as the design of the display format itself. Ability to stay within the channel was not impaired by noise. Tracker lag, on the other hand, went undetected by the subjects. It resulted in a biased trackkeeping performance which, because of original inadequacies in the display, caused pilotage performance to appear better than it actually was. Although all pilots were familiar with the use of the benchmark display, none had ever been given the opportunity to "prove" its use in good visibility. As a result, the pilots were "blindly" following the display, assuming its representation of ownship in the channel was accurate. This decision to test the benchmark display without allowing pilots to "prove" its accuracy probably resulted in experimental results that are less optimistic than would otherwise have been achieved.

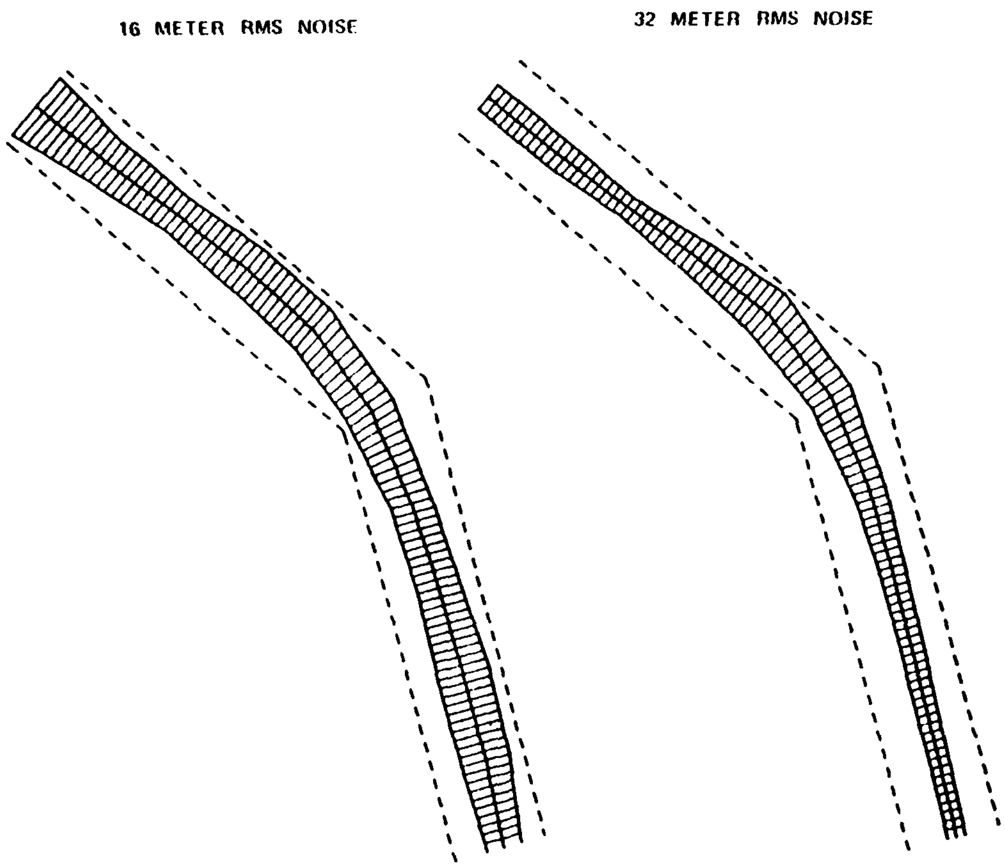


Figure 26. Effect of Noise on Tracker with 12-Second Rise Time

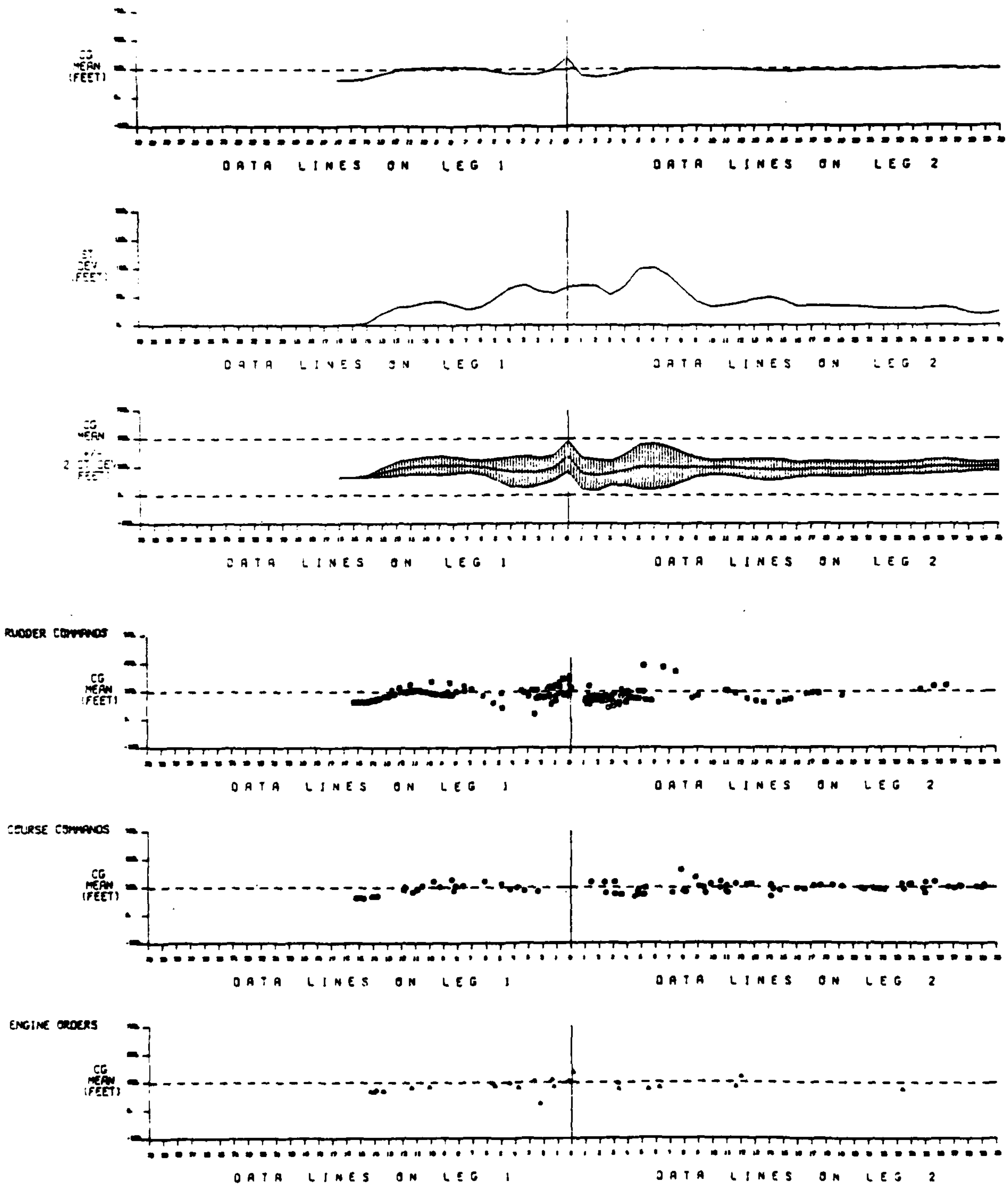


Figure 27. Tracker with 12-Second Rise Time in 16 Meter RMS Noise

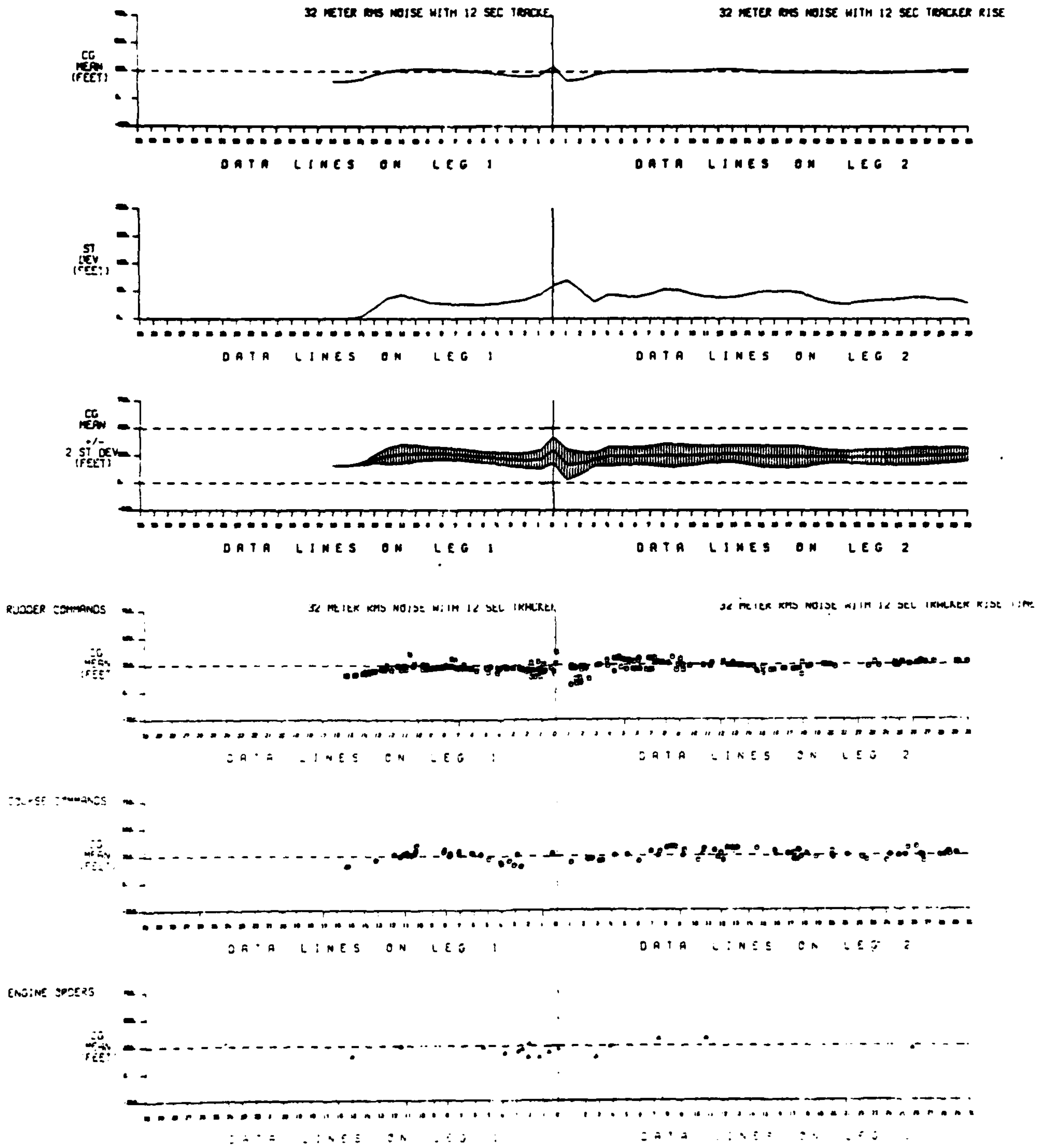


Figure 28. Tracker with 12-Second Rise Time in 32 Meter RMS Noise

TABLE 11. EFFECT OF TRACKER WITH 12-SECOND RISE TIME ON MANEUVERING PERFORMANCE

MEASURE[1]	Tracker with 12-Second Rise Time		SIGNIFICANT DIFFERENCE[2]
	16 meter	32 meter	
Return to and Steady Up on Centerline			
1. Distance to return to centerline (nm)	0.353	0.319	None
2. Overshoot following return to centerline (ft left)	24	15	None
3. Distance to steady up in entrance leg (nm)	0.667	0.761	None
4. Distance to steady up in exit leg (nm)	0.906	1.232	Longer with higher noise level
Initial Turn Rudder Application			
1. Distance before bend at initial rudder (nm)	0.188	0.179	None
2. Magnitude of initial turn rudder (degrees)	15	10	None
3. Magnitude of subsequent turn rudder (degrees)	30	30	None
4. Frequency of turn rudder actuations	4	3	None
Check Rudder Application			
1. Distance beyond bend of initial check rudder (nm)	0.131	0.109	None
2. Magnitude of initial check rudder (degrees)	20	25	None

[1]Rationale for the derivation of these measures are presented in Appendix D.

[2]Statistically different at $p \leq 0.10$ level of significance.

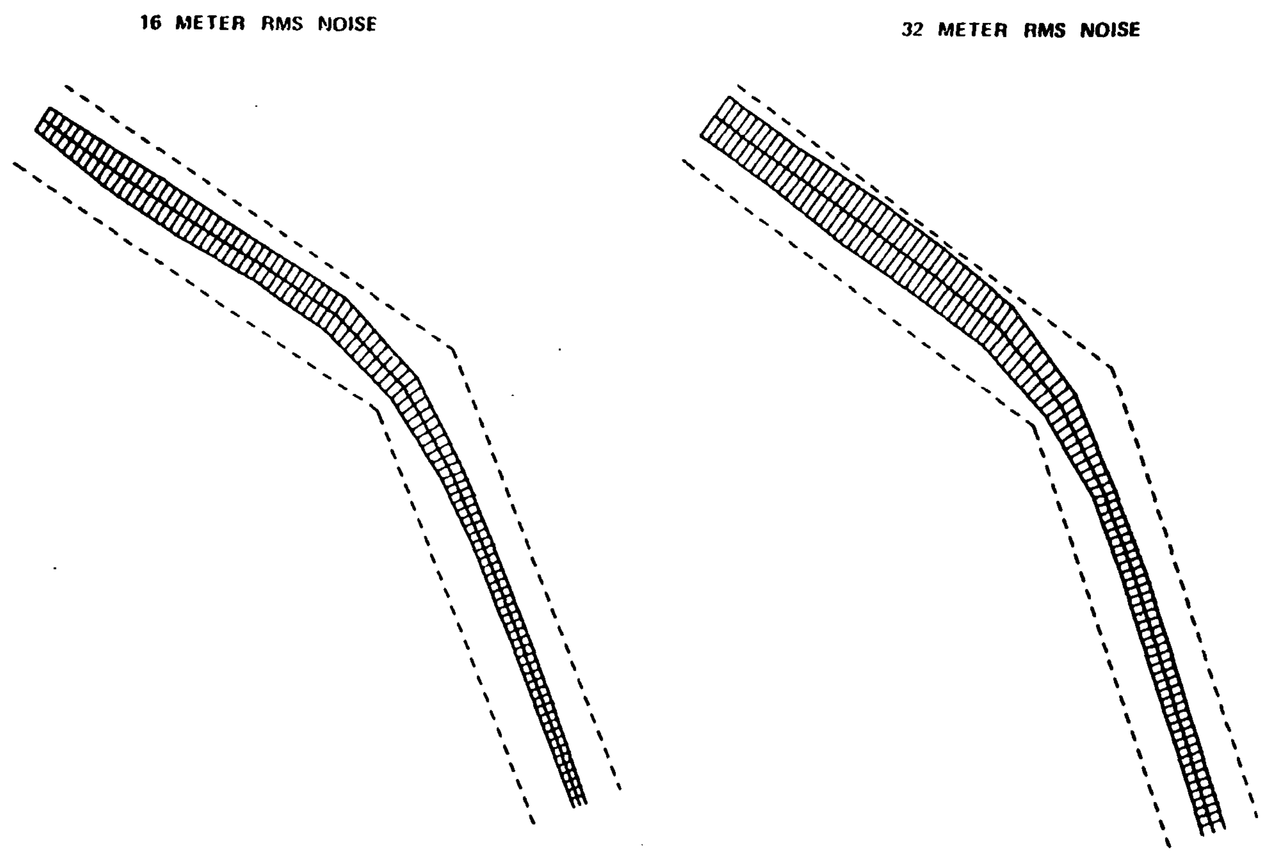


Figure 29. Effect of Noise on a Tracker with 24-Second Rise Time

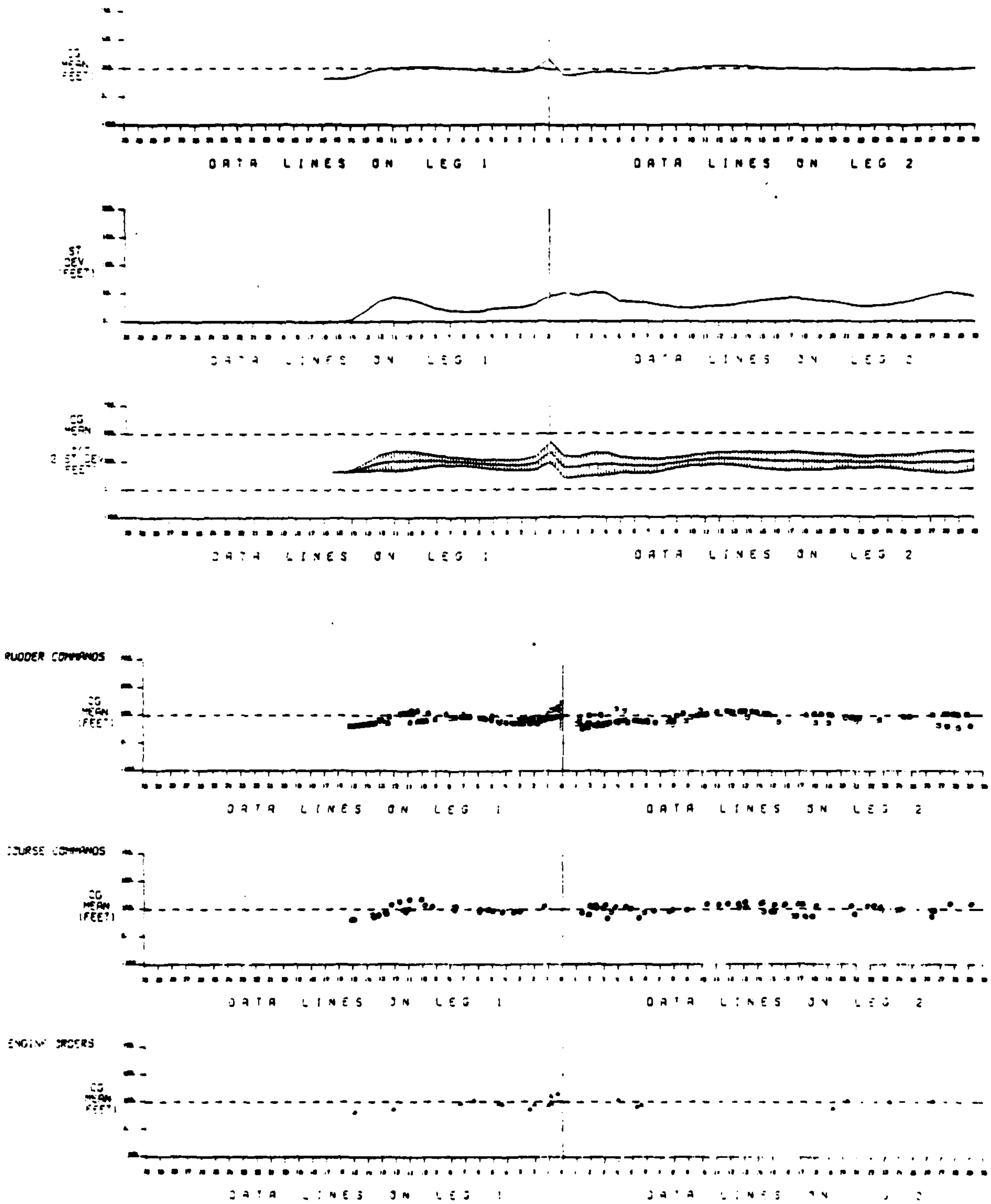


Figure 30: Tracker with 24-Second Rise Time in 16 Meter RMS Noise

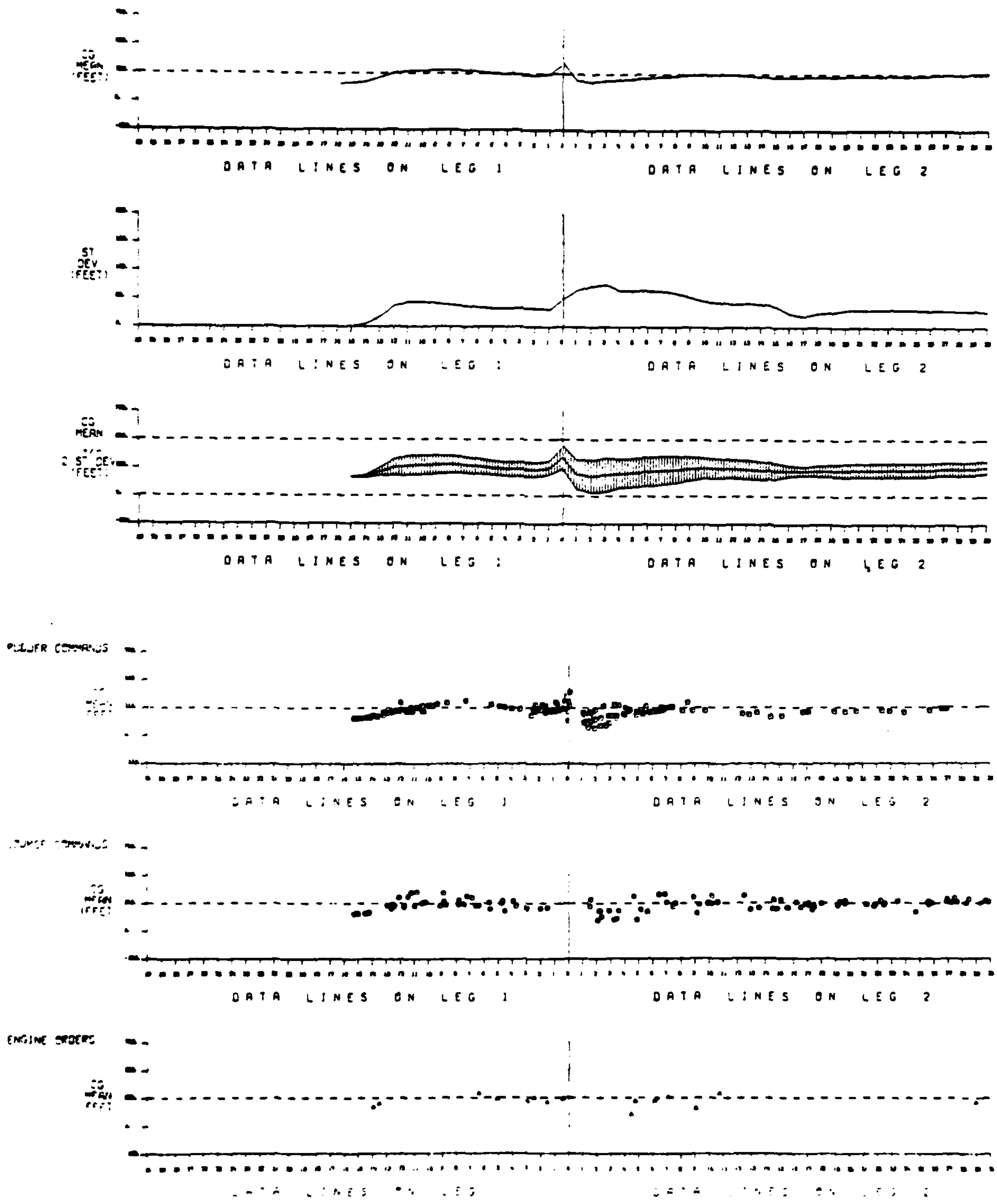


Figure 31. Tracker with 24-Second Rise Time in 32 Meter RMS Noise

TABLE 12. EFFECT OF TRACKER WITH 24-SECOND RISE TIME ON MANEUVERING PERFORMANCE

MEASURE[1]	Tracker with 24-Second Rise Time In-		SIGNIFICANT DIFFERENCE[2]
	16 meter rms noise	32 meter rms noise	
Return to and Steady Up on Centerline			
1. Distance to return to centerline (nm)	0.419	0.362	None
2. Overshoot following return to centerline (ft left)	12	17	None
3. Distance to steady up in entrance leg (nm)	0.716	0.706	Longer with higher noise level
4. Distance to steady up in exit leg (nm)	0.726	0.912	None
Initial Turn Rudder Application			
1. Distance before bend at initial rudder (nm)	0.207	0.165	None
2. Magnitude of initial turn rudder (degrees)	10	15	None
3. Magnitude of subsequent turn rudder (degrees)	35	30	None
4. Frequency of turn rudder actuations	4	5	None
Check Rudder Application			
1. Distance beyond bend of initial check rudder (nm)	0.108	0.127	None
2. Magnitude of initial check rudder (degrees)	20	20	None

[1] Rationale for the deriviation of these measures are presented in Appendix D.

[2] Statistically different $p \leq 0.10$ level of significance.

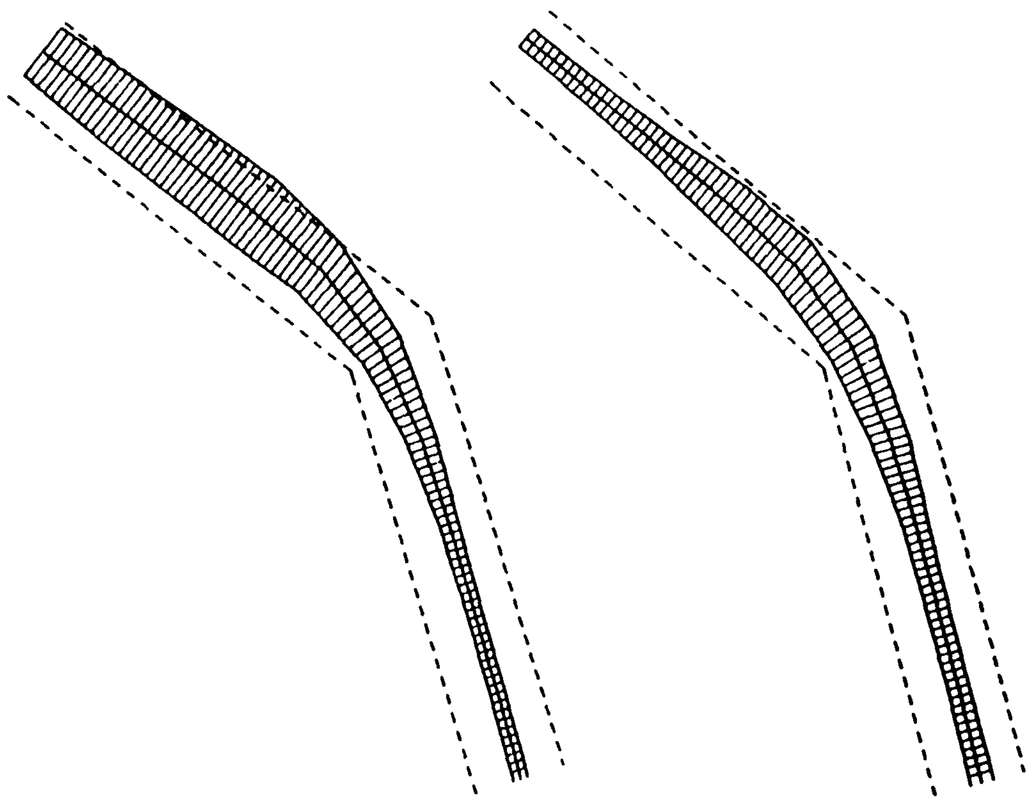


Figure 32. Effect of Noise on a Gyro-Aided Tracker

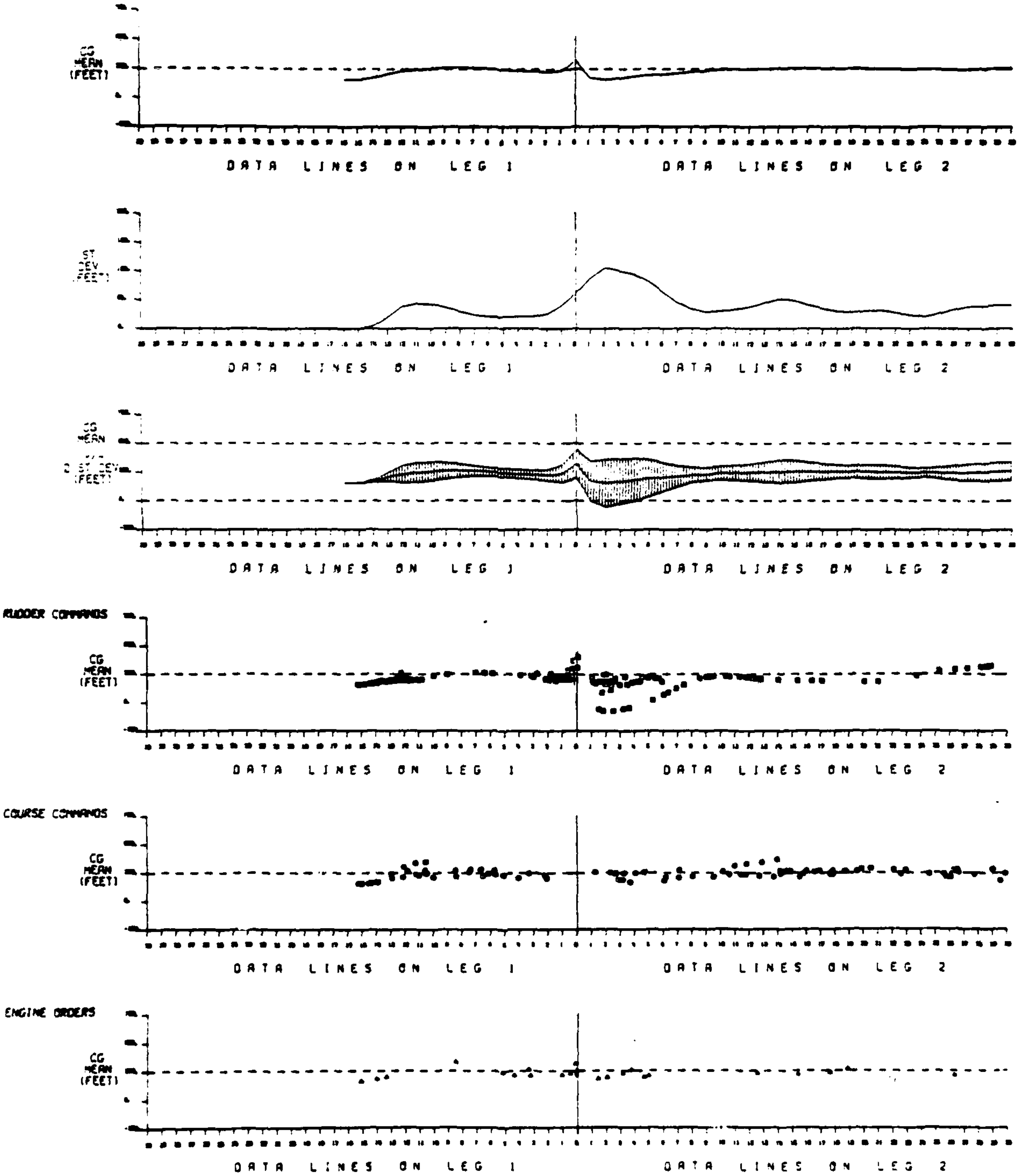


Figure 33. Gyro-Aided Tracker in 16 Meter RMS Noise

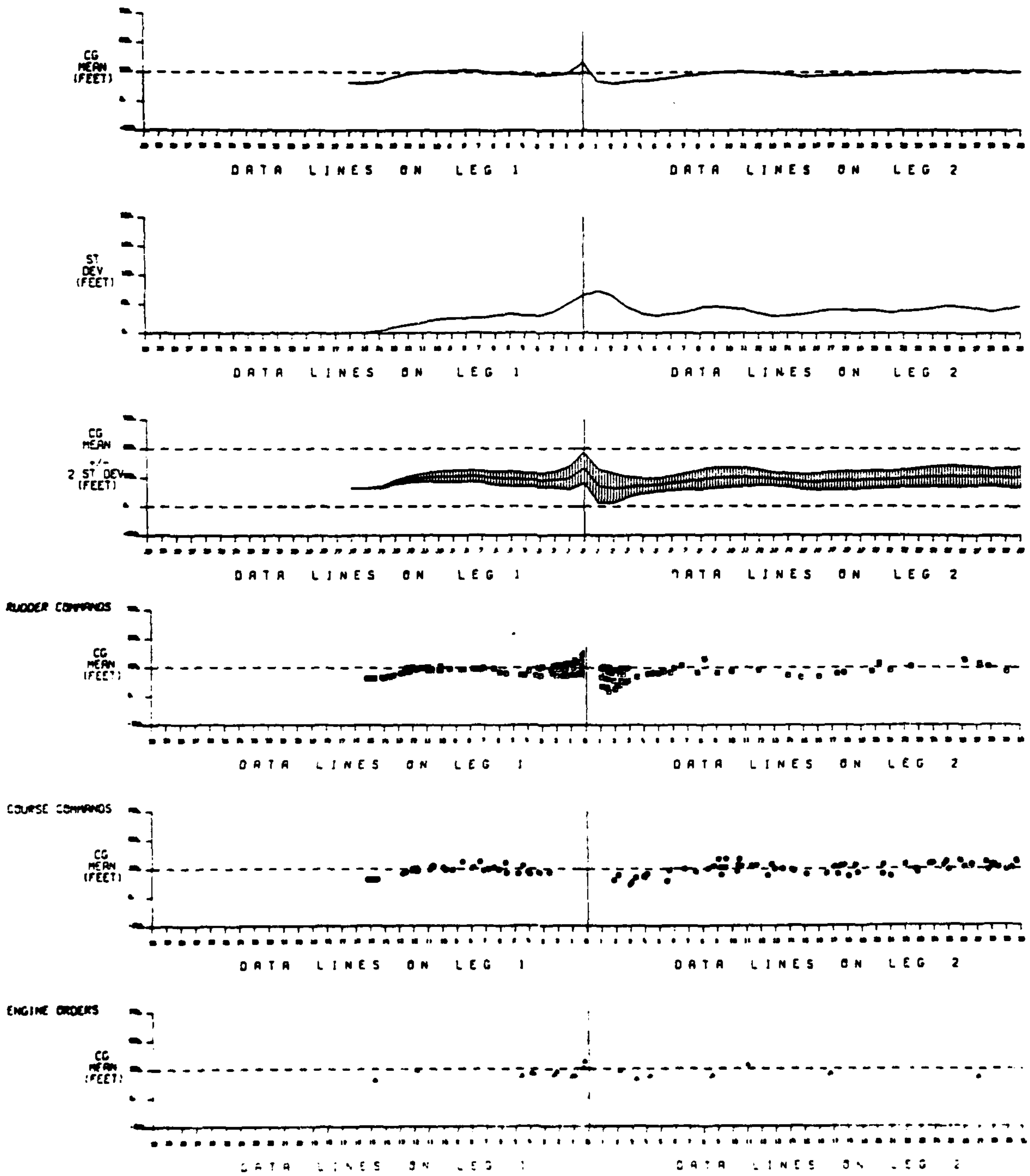


Figure 34 Gyro-Aided Tracker in 32 Meter RMS Noise

TABLE 13. EFFECT OF GYRO-AIDED TRACKER ON MANEUVERING PERFORMANCE

MEASURE[1]	Gyro-Aided Tracker In -		SIGNIFICANT DIFFERENCE[2]
	16 meter rms noise	32 meter rms noise	
Return to and steady Up on Centerline			
1. Distance to return to centerline (nm)	0.408	0.351	None
2. Overshoot following return to centerline (ft left)	10	0	None
3. Distance to steady up in entrance leg (nm)	0.722	0.773	None
4. Distance to steady up in exit leg (nm)	0.773	0.780	None
Initial Turn Rudder Application			
1. Distance before bend at initial rudder (nm)	0.161	0.163	None
2. Magnitude of initial turn rudder (degrees)	15	15	None
3. Magnitude of subsequent turn rudder (degrees)	25	25	None
4. Frequency of turn rudder actuations	4	5	None
Check Rudder Application			
1. Distance beyond bend of initial check rudder (nm)	0.122	0.112	None
2. Magnitude of initial check rudder (degrees)	15	25	Larger with higher noise level

[1] Rationale for the derivation of these measures are presented in Appendix D.

[2] Statistically different at $p \leq 0.10$ level of significance.

Pilots participating in the RA-2 experiment had used the benchmark display in previous experiments. Nevertheless, they had never used it with jitter or lag present. In order to determine what effects, if any, learning to use the display with jitter and lag had upon the experiment, an analysis comparing subjects' performance during their initial runs with performance in their final runs was conducted. These runs contained a balancedmmixture of experimental variables.

Figures 35, 36 and 37 show some improvement in trackkeeping performance among pilots as a function of learning the display, waterway, and ship characteristics. A review of the bend (Figure 35) shows high crosstrack variability among pilots when recovering from their maneuvers in the initial runs. Final runs, on the other hand, were marked by bolder maneuvers to return to the channel centerline following the initial maneuver and steadying up beyond the bend. This conclusion is illustrated by the mean CG tracks in Figures 36 and 37 and supported statistically in Table 14. Although the bolder maneuvers occurred during the final runs with a relatively high variability among pilots, it suggests that whatever learning did occur was manifested by the unique behavior of individual pilots, i.e., some felt confident enough to make bolder maneuvers, while others chose to continue their original strategies which had proven successful. Table 8 shows significantly fewer rudder commands during the final runs than the initial runs. This is a characteristic behavior of pilots which results when they become confident of the operation.

5.6 User Acceptance of the System

The appraisal of how potential users would accept the electronic radio aids to navigation display was based on (1) experimenter observations, (2) informal subject comments during the experiment, and (3) responses to a self-appraisal questionnaire administered at the end of each run. The questionnaire supplied pilots' opinions of the displays and an assessment of their own performance in each segment of the waterway. The questionnaire and resulting responses is presented in Appendix C.

Table 15 shows a summary of questionnaire responses. In general, the pilots believed they adapted to all variations of noise and tracker characteristics, and they were satisfied with their overall performance. The pilots stated that the display with the most jitter which was the tracker with 3-second rise time in 32 meter rms noise, was least accurate. They assessed their overall performance with it to be "fair to poor." This was the worst subjective rating for any of the displays.

The pilots gauged most of their display preference in the straight legs because this is where jitter was most obvious. In the bend, they showed significant dissatisfaction with their own performance whenever they used a long rise time tracker. The pilots, themselves, had no way of knowing that tracker lag was causing their maneuvering difficulties. As a result they tended to blame themselves for the maneuvering difficulty.

Pilots stated that the information update rate was acceptable. They believed a consistent rate of about once every second was better than a slower or inconsistent one. There was further indication that if the update rate were increased, with conditions of large jitter there might be a temptation to interpolate every update of ownship's position and thus increase the annoyance factor. Pilots were more concerned about consistency of the update rate than its absolute frequency. Consistency allowed them to pace their vigilance and monitoring tasks.

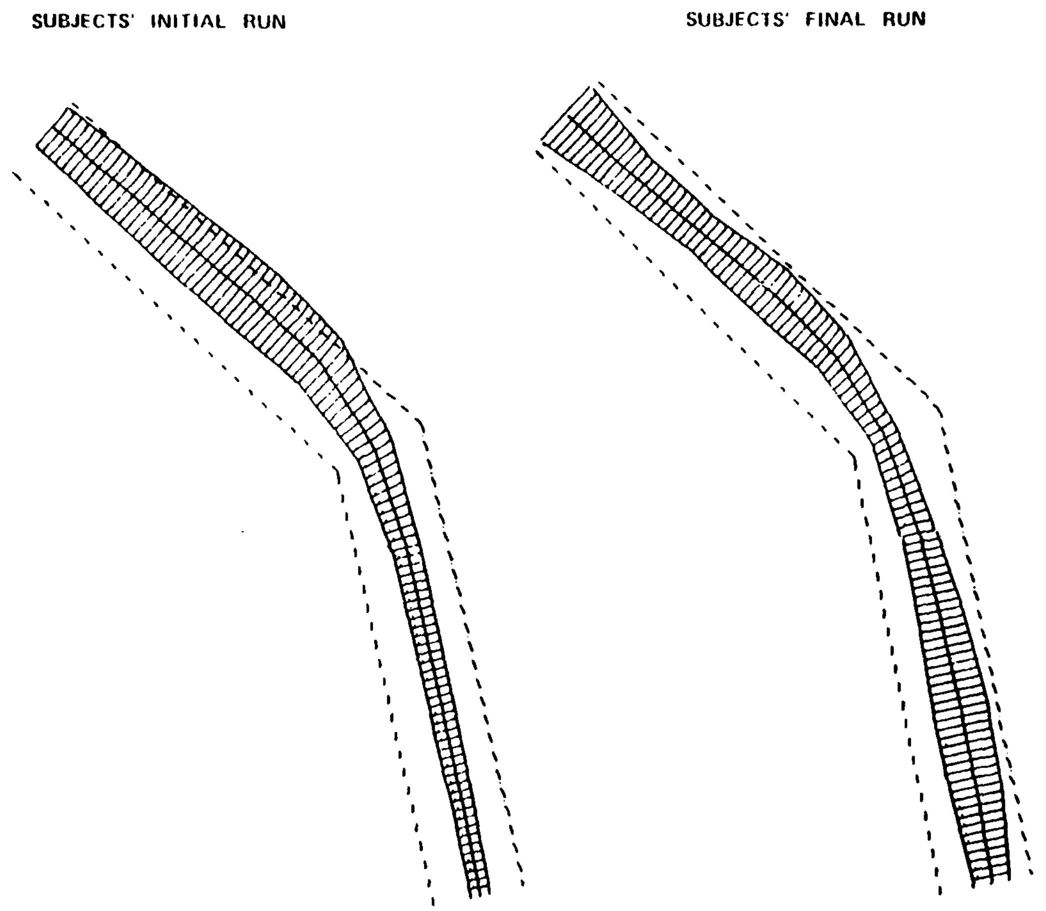


Figure 35. Overall Turning Performance as a Function of Learning

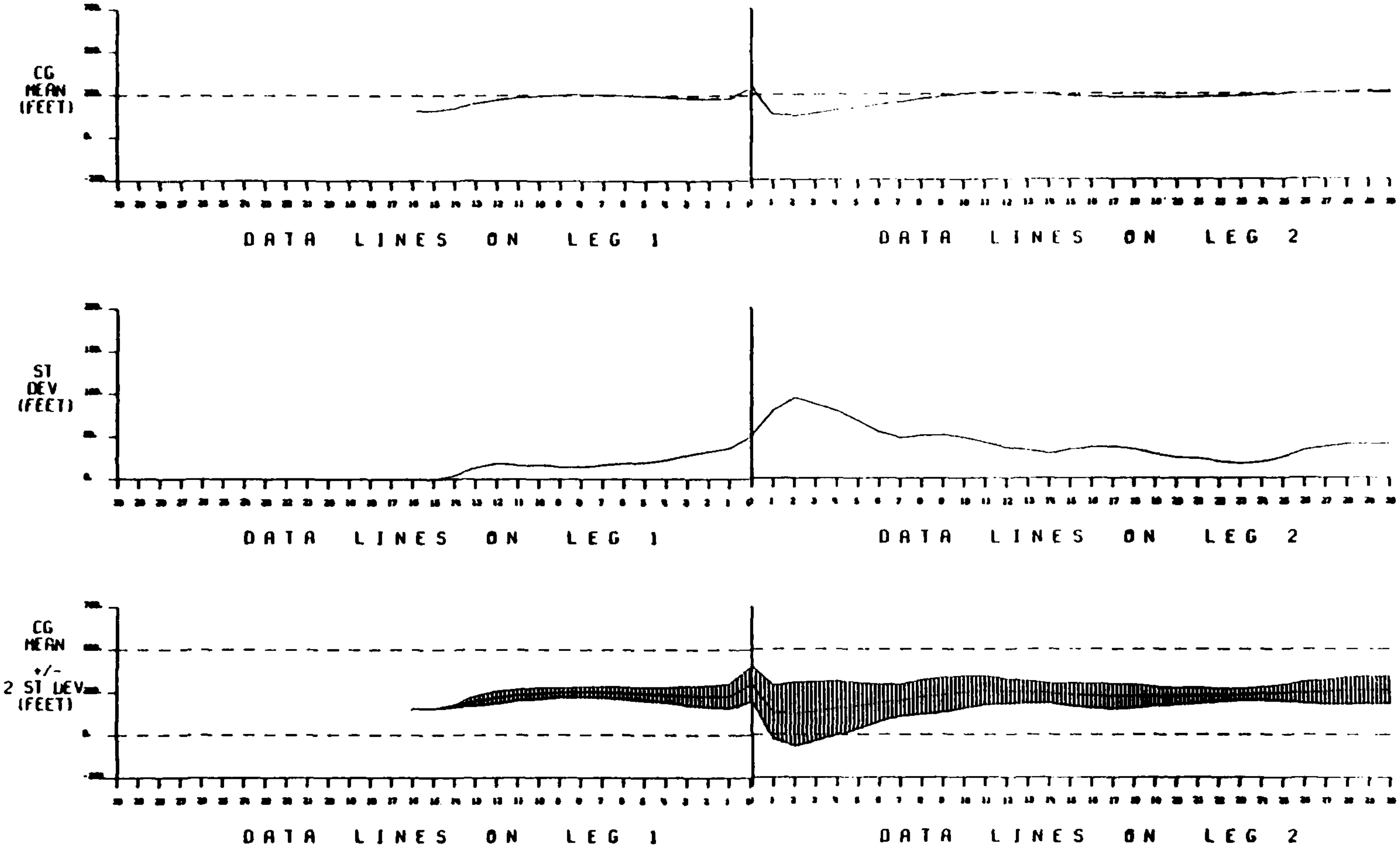


Figure 36. Overall Trackkeeping Performance during Subjects' Initial Run

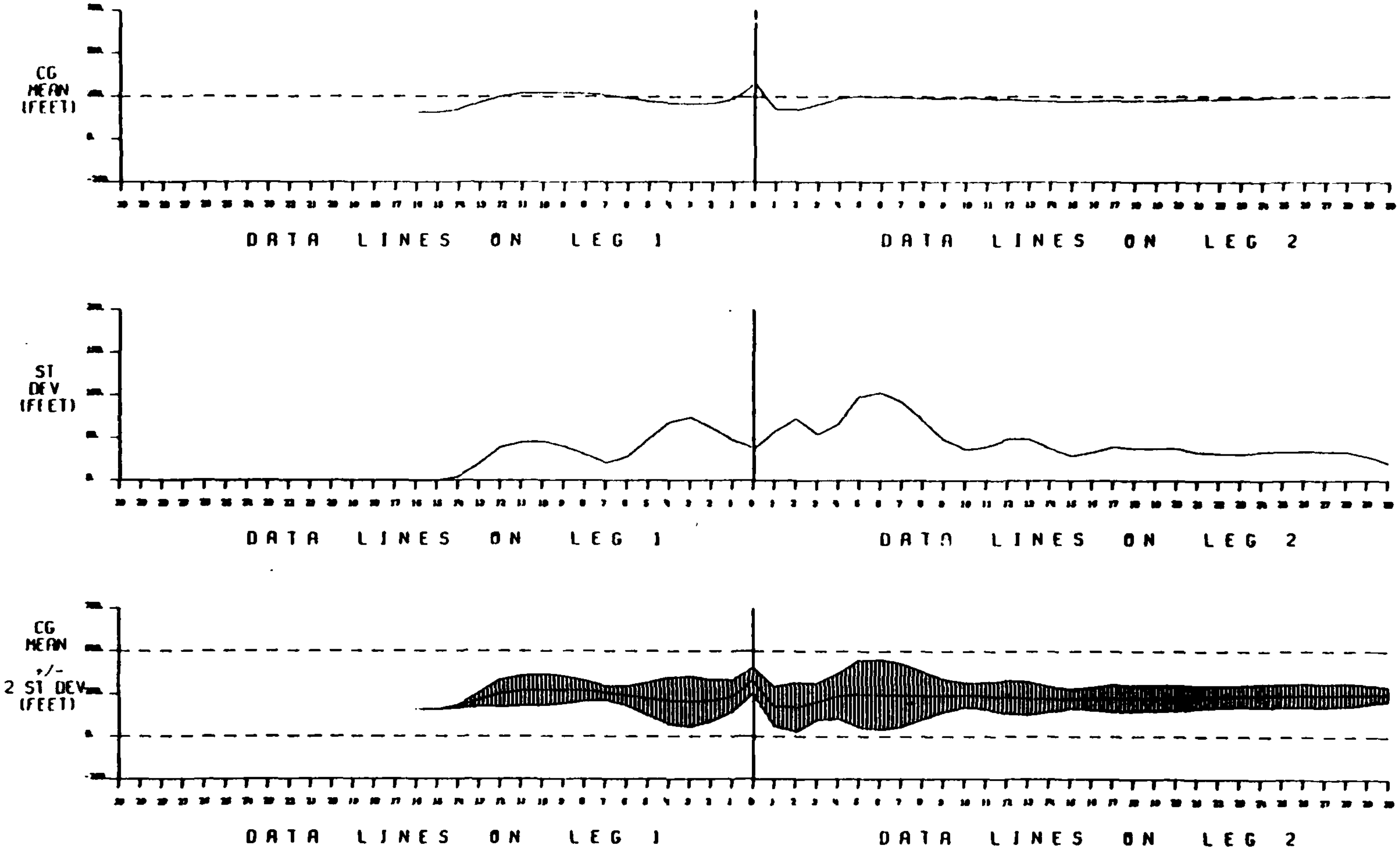


Figure 37. Overall Trackkeeping Performance during Subjects' Final Run

TABLE 14. EFFECT OF LEARNING ON MANEUVERING PERFORMANCE

MEASURE[1]	Initial Run	Final Run	SIGNIFICANT DIFFERENCE[2]
<u>Return to and Steady Up on Centerline</u>			
1. Distance to return to centerline (nm)	0.420	0.327	Longer during initial runs
2. Overshoot following return to centerline (ft left)	9	15	None
3. Distance to steady up in entrance leg (nm)	0.675	0.653	None
4. Distance to steady up in exit leg (nm)	0.965	0.788	Longer during initial runs
<u>Initial Turn Rudder Application</u>			
1. Distance before bend at initial rudder (nm)	0.127	0.146	None
2. Magnitude of initial turn rudder (deg)	15	15	None
3. Magnitude of subsequent turn rudder (deg)	30	30	None
4. Frequency of turn rudder actuations	4	3	None
<u>Check Rudder Application</u>			
1. Distance beyond bend of initial check rudder (nm)	0.116	0.131	None
2. Magnitude of initial check rudder (deg)	25	20	Nome

[1]Rationale for the derivation of these measures are presented in Appendix D.

[2]Statistically different at $p \leq 0.10$ level of significance.

TABLE 15. SUMMARY OF QUESTIONNAIRE RESPONSES

	NOISE (meter rms)		TRACKER DESIGN (rise time in seconds)			
	16	32	3	12	24	Gyro-Aided
Trackkeeping Appraisal						
After I steadied up, my transit of the first straight leg was:	good	fair to good	fair to good	good	good	good
Except for my initial offset, in the first straight leg I was on the centerline:	usually	occasionally	occasionally	usually	usually	usually
After I steadied up, my transit of the second straight leg was:	fair to good	fair to good	fair to good	fair to good	fair to good	fair to good
In the second straight leg, I was on the centerline:	usually	occasionally	occasionally	usually	usually	usually
Maneuvering Appraisal						
My initial return to and steady-up on the channel centerline was:	good	fair to good	good	fair to good	fair to good	good
During this initial maneuver, I overshot the centerline:	seldom	frequently	seldom	frequently	frequently	seldom
My overall turn at the bend was:	good	fair	fair	fair	fair	fair to good
Following the bend, my steady-up on the second leg was	good	good	fair to good	fair to good	good	good
In steadying up beyond the bend, I overshot the centerline:	seldom	occasionally	occasionally	seldom	seldom	frequently
In general, my overall pilotage was:	good	fair	fair	good	fair	good
On the display, ownship's jitter was:	minimal to moderate	minimal to extreme	moderate to extreme	moderate	minimal	minimal

Throughout the straight legs, pilots' trackkeeping performance was considered by them to be better when they used displays with least jitter. These were indicated to be the trackers with 12- and 24-second rise time in either noise condition and the 3-second trackers in the lower level noise. With the 3-second tracker in higher noise, pilots were uncertain of their ability to maneuver or maintain a steady track on the centerline.

In maneuvering through the bend, pilots continued to be aware of jitter, mostly with the 3-second tracker, but somewhat with the 12-second tracker in the higher noise. With the 24-second tracker, however, all subjects perceived extreme difficulties in shiphandling. This difficulty, unbeknownst to them, was the effect of tracker lag. As shown on Table 15 initial maneuvers with the 24-second tracker were perceived as worse than the steady-up maneuvers. This was probably due to the filter stabilizing by the time steadying up was begun.

The major complaint was that with the 24-second tracker the ship initially responded very sluggishly, but then checked up quickly. The result was that pilots subsequently took extreme measures to prevent what looked like a large overshoot of the bend; then blamed themselves for not starting with a larger or earlier turn rudder. For the most part, pilots were very displeased with their performance when they maneuvered with the 24-second trackers, and with the system's performance when they maneuvered with the 3-second trackers. Ironically, all the way through the exit leg, pilots were relatively satisfied with their performance regardless of which display they used. This suggests that the pilots did, in fact, adapt well to the jitter and had begun to treat it as a normal characteristic by the end of the run.

The conclusion is that pilots perceived themselves as being able to handle both jitter and the effects of tracker lag. That they would fully "trust" or appreciate a display with characteristics similar to the 3- and 24-second tracker is doubtful. From all indications of the user acceptance analysis, it appears that the 12-second tracker would be the best of the unaided trackers, but that the gyro-aided tracker would be most preferred for pilotage.

Appendix A

TRACKER PERFORMANCE DATA ON THE RA-2 VARIABLES

The performance of the $\alpha - \beta$ trackers was evaluated for a 30,000 dwt tanker executing a 35-degree turn at 8 knots.* This appendix contains the individual track plots from which performance data was derived and discussed in Section 2. Position tracker rise times of 3, 12, and 24 seconds are shown for each condition. The individual track plots appear in the designated figures. Tracker sample time was T = 1 second.

α-β Trackers Without Gyro Aiding

rms noise = 16 m (52.8 ft) Figures A-1 through A-3
rms noise = 32 m (105.6 ft) Figures A-4 through A-6

α-β Trackers With Gyro Aiding (Gyro tracker rise time 3 seconds; $\Delta\hat{X}_{n+1} = -0.85\hat{\theta}_{n+1} T \hat{V}_n \sin\hat{\theta}_{n+1}$

$\Delta\hat{Y}_{n+1} = 0.85\hat{\theta}_{n+1} T \hat{V}_n \cos\hat{\theta}_{n+1}$

rms noise = 16 m (52.8 ft) Figure A-7
rms noise = 32 m (105.6 ft) Figure A-8

*R.B. Cooper, K.L. Marino, and W.R. Bertsche. "Simulator Evaluation of Electronic Radio Aids to Navigation Displays, The RA-1 Experiment." Washington, D.C., U.S. Coast Guard, August 1980.

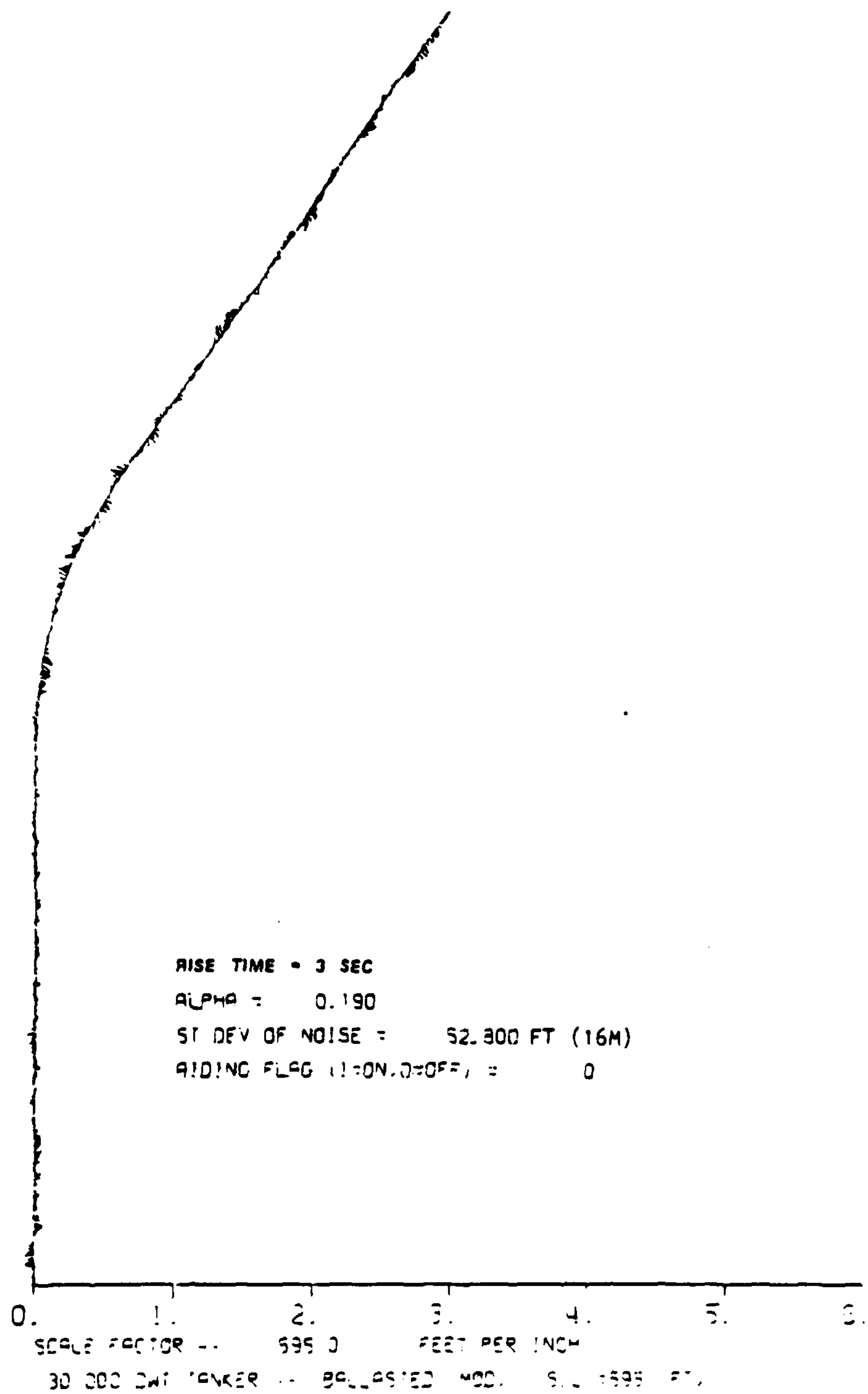

RISE TIME = 3 SEC
ALPHA = 0.190
ST DEV OF NOISE = 52.800 FT (16M)
AIDING FLAG (1=ON,0=OFF) = 0
0.
1.
2.
3.
4.
5.
6.
SCALE FACTOR -- 595.0 FEET PER INCH
30 000 DWT TANKER -- BALLASTED MOD.

Figure A-1.

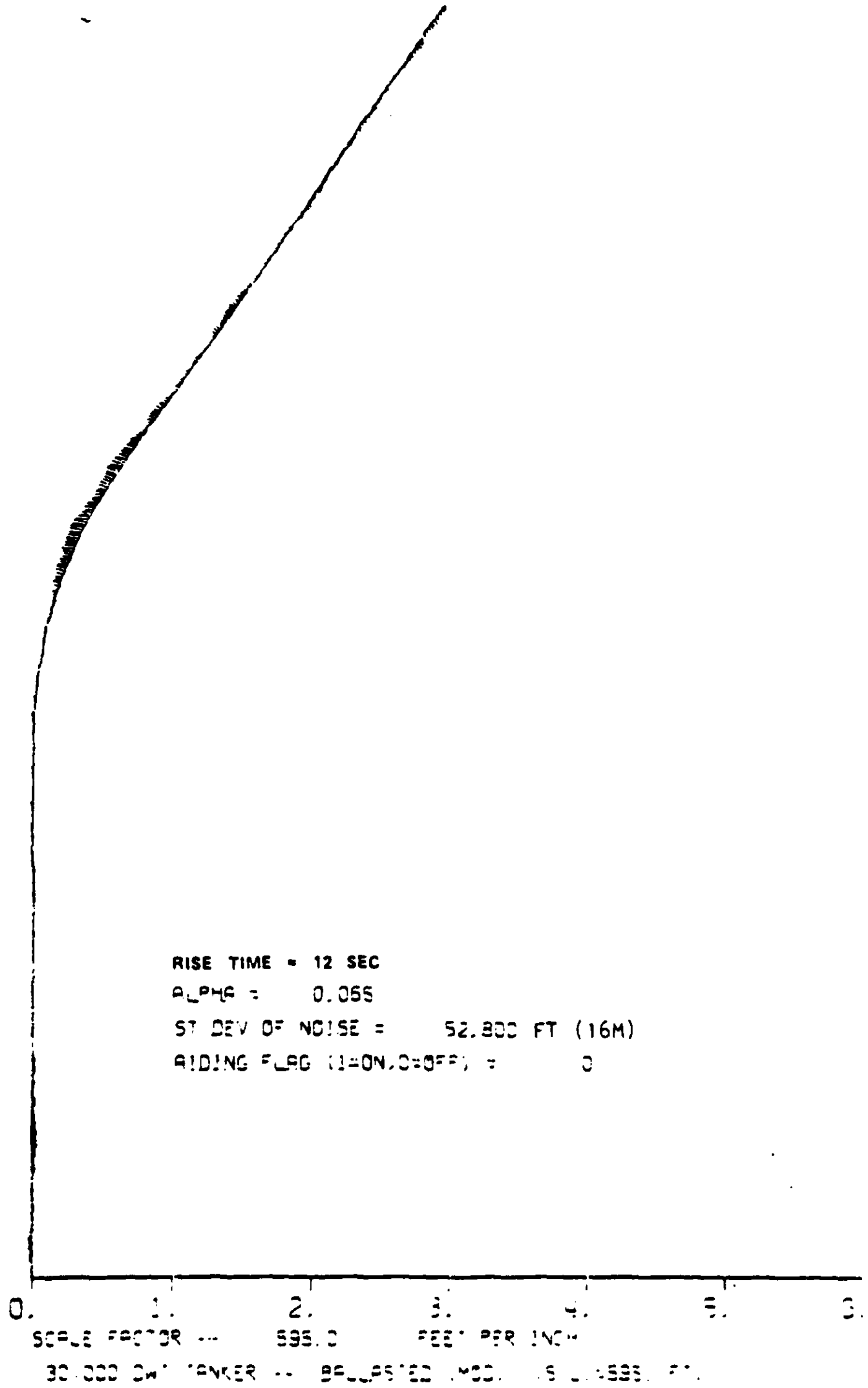

RISE TIME = 12 SEC
ALPHA = 0.065
ST DEV OF NOISE = 52.800 FT (16M)
RIDING FLAG (1=ON,0=OFF) = 0
0.
1.
2.
3.
4.
SCALE FACTOR -- 595.0 FEET PER INCH

Figure A-2.

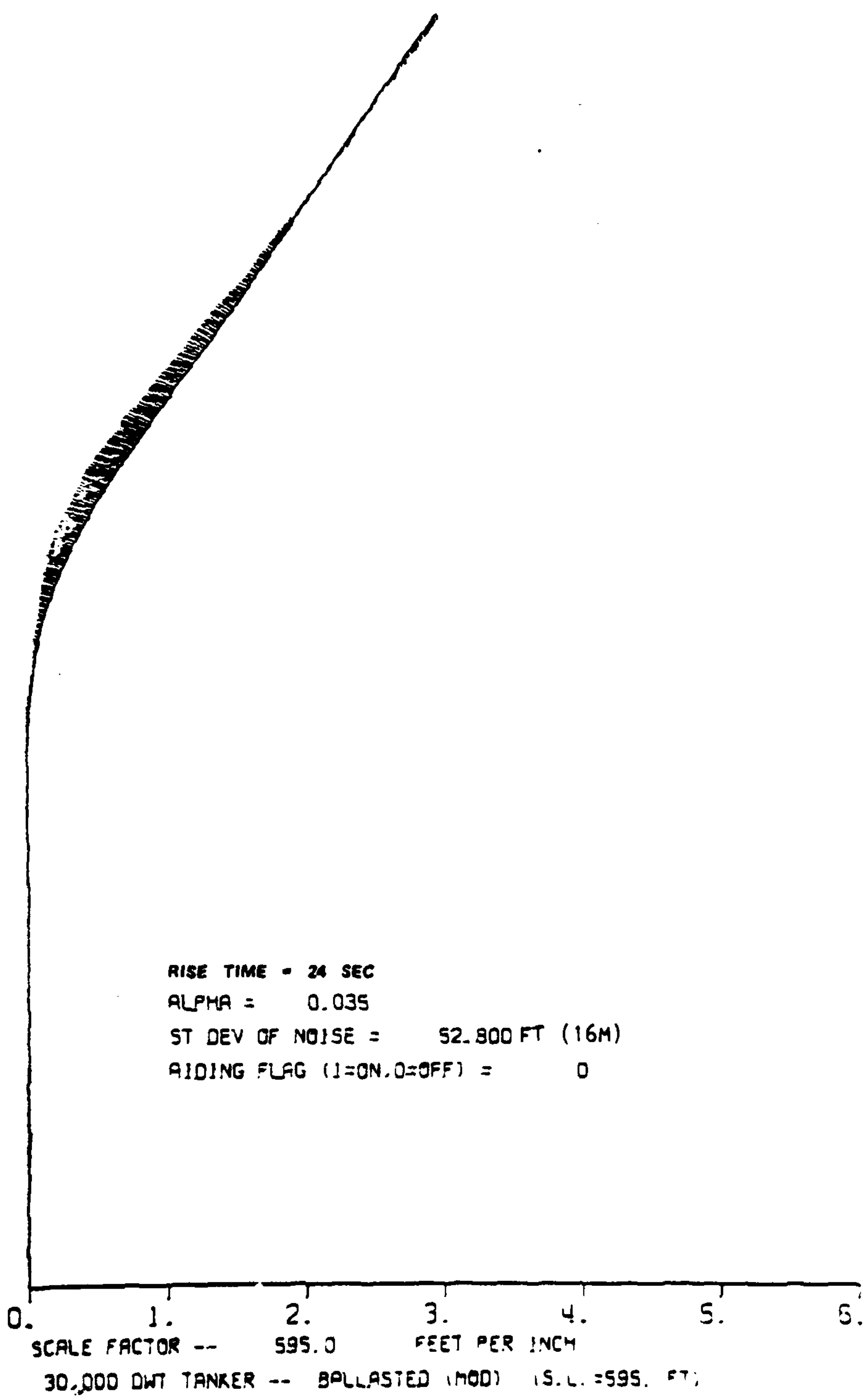

RISE TIME = 24 SEC
ALPHA = 0.035
ST DEV OF NOISE = 52.800 FT (16M)
AIDING FLAG (1=ON,0=OFF) = 0
0. 1. 2. 3. 4. 5. 6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure A-3.

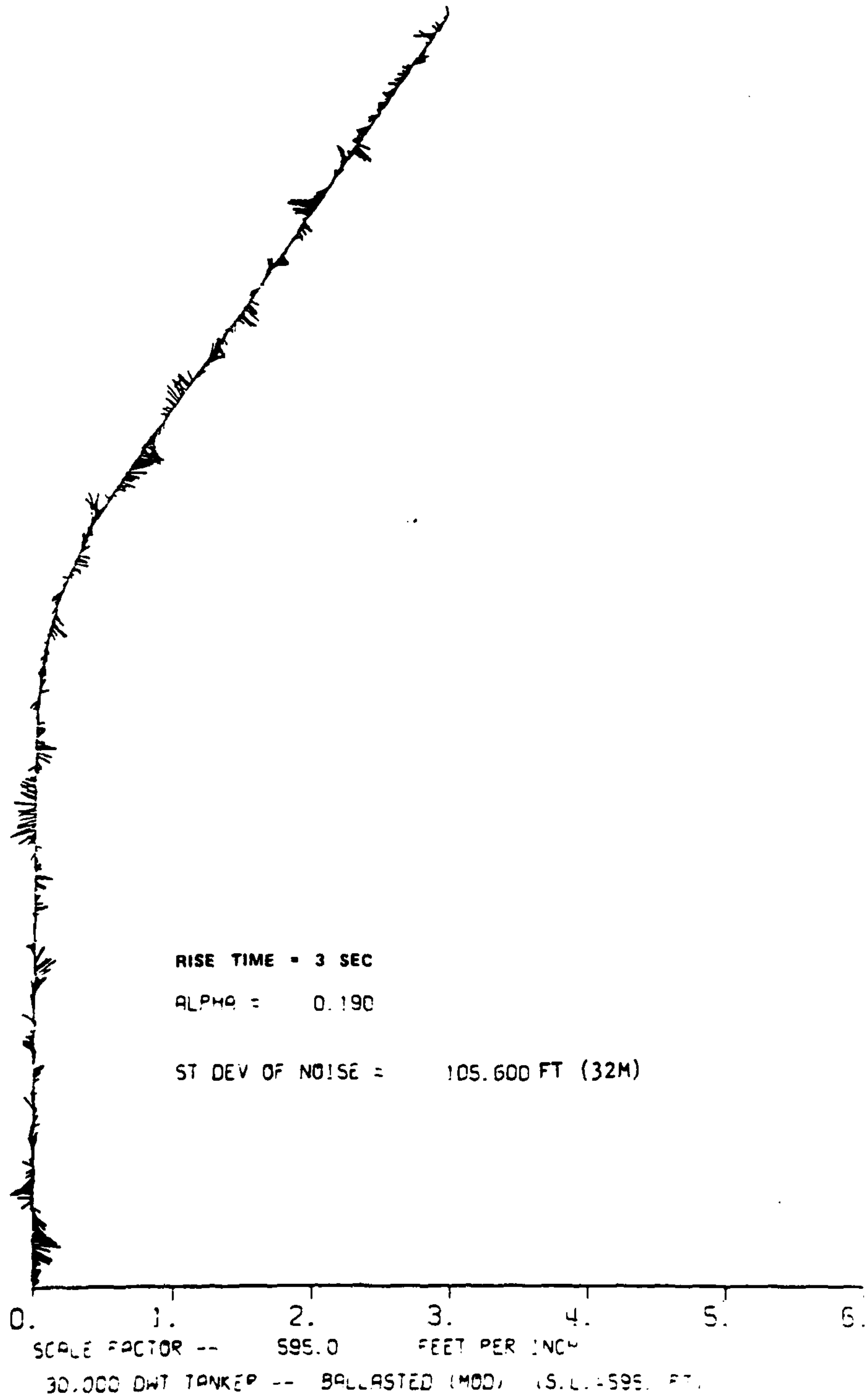
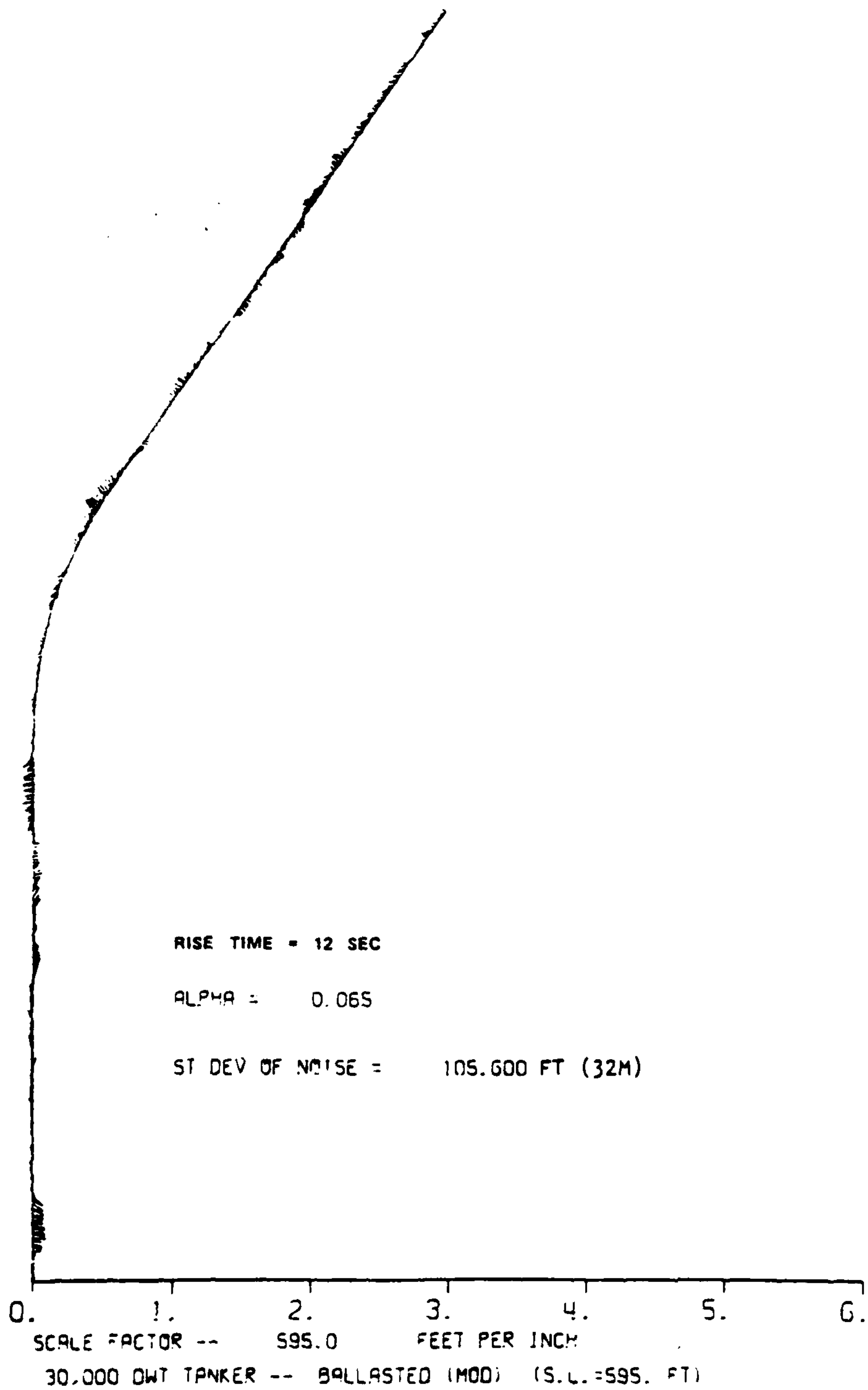

RISE TIME = 3 SEC
ALPHA = 0.190
ST DEV OF NOISE = 105.600 FT (32M)
0.
1.
2.
3.
4.
5.
6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT.)

Figure A-4



RISE TIME = 12 SEC
ALPHA = 0.065
ST DEV OF NOISE = 105.600 FT (32M)
0.
1.
2.
3.
4.
5.
6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure A-5

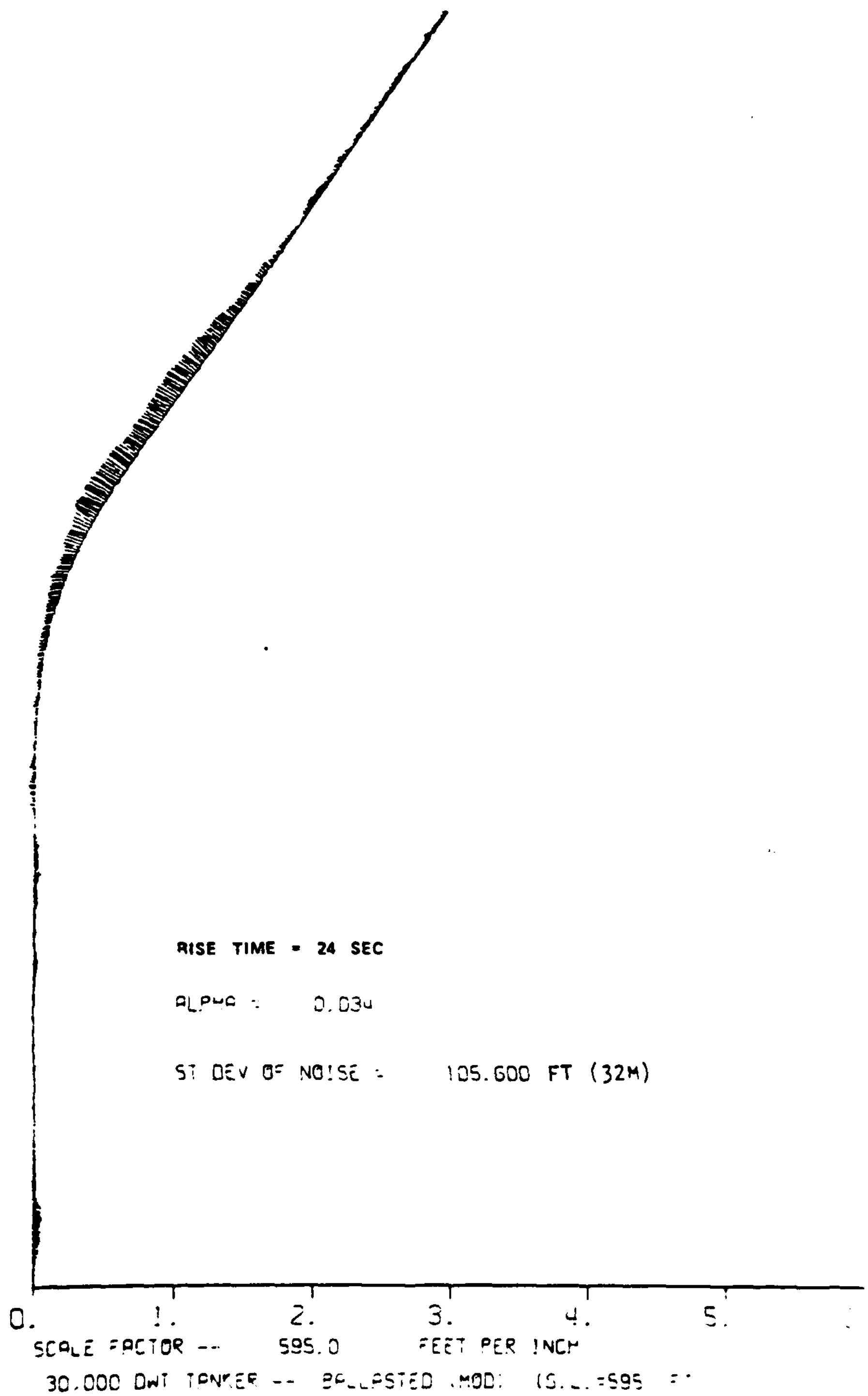

RISE TIME = 24 SEC
ALPHA = 0.034
ST DEV OF NOISE = 105.600 FT (32M)
0.
1.
2.
3.
4.
5.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD)

Figure A-6.

AD-A106 672 ECLECTECH ASSOCIATES INC NORTH STONINGTON CT F/G 17/7
SIMULATOR EVALUATION OF ELECTRONIC RADIO AIDS TO NAVIGATION DIS--ETC(U)
JUL 81 R B COOPER, K L MARINO, W R BERTSCHE DOT-CG-835285-A
UNCLASSIFIED EA-81-U-009 USCG-D-50-81 NL

2 of 2

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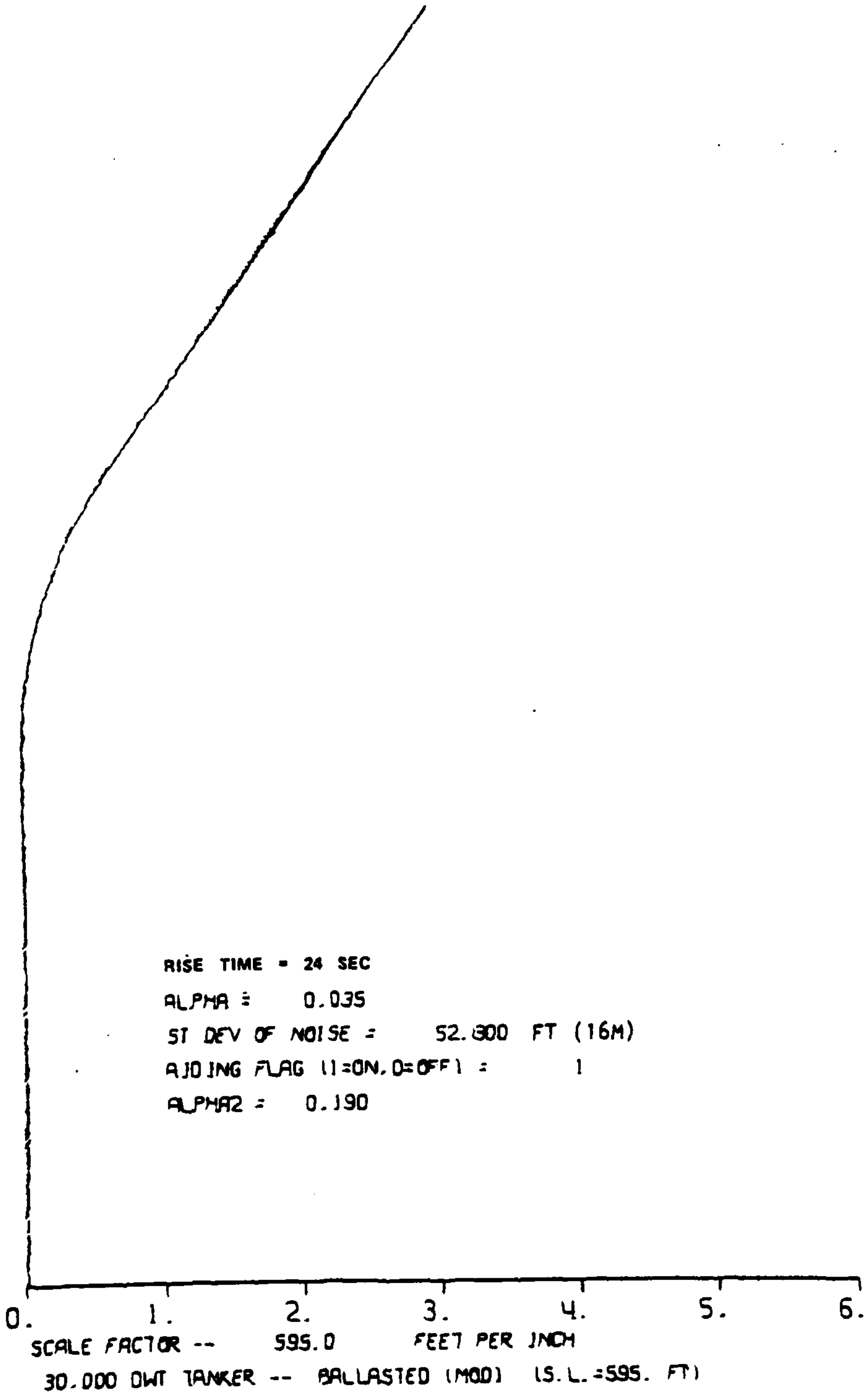
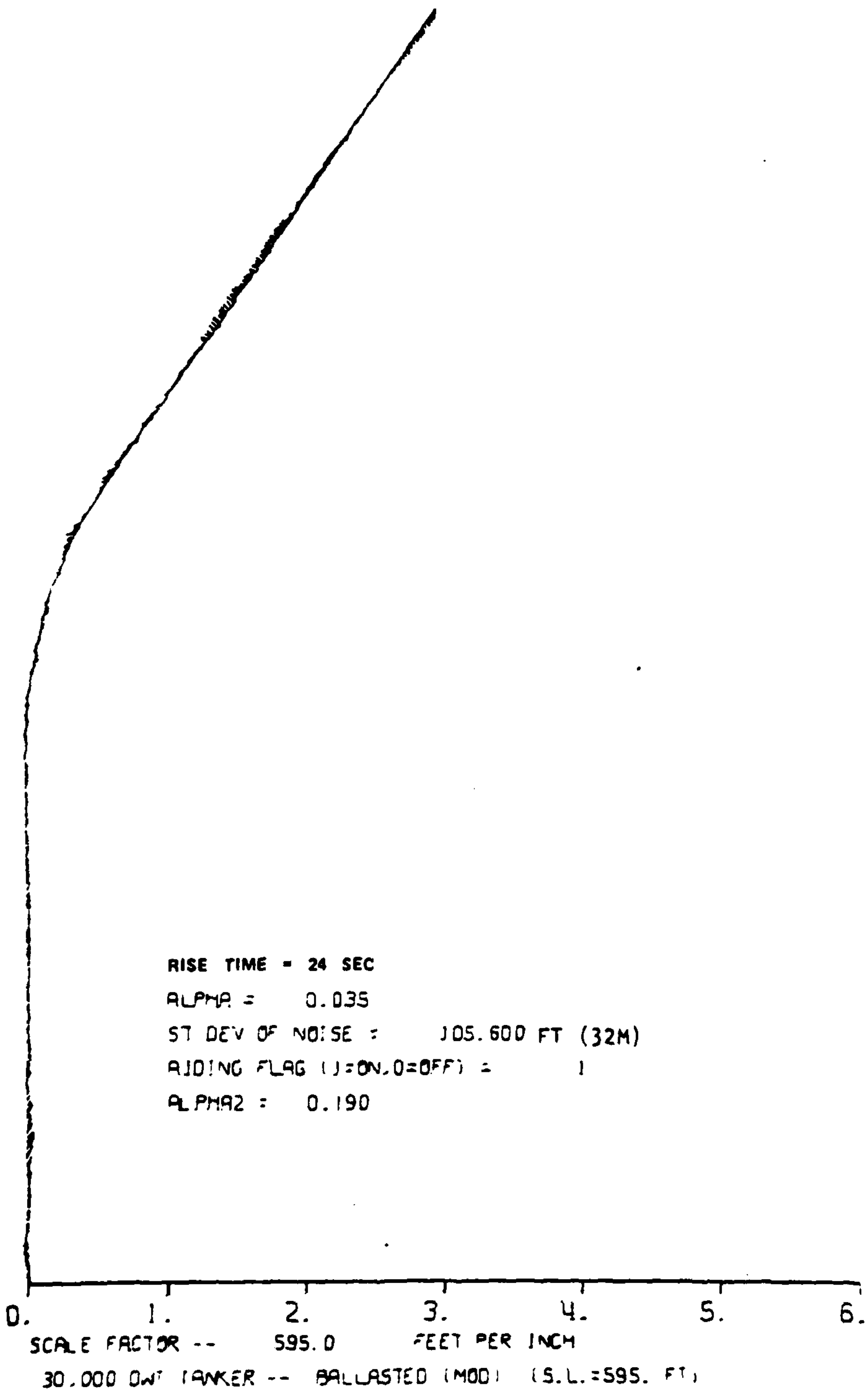

RISE TIME = 24 SEC
ALPHA = 0.035
ST DEV OF NOISE = 52.800 FT (16M)
AIDING FLAG (1=ON, 0=OFF) = 1
ALPHA2 = 0.190
0.
1.
2.
3.
4.
5.
6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure A-7



RISE TIME = 24 SEC
ALPHA = 0.035
ST DEV OF NOISE = 105.600 FT (32M)
AIDING FLAG (1=ON,0=OFF) = 1
ALPHA2 = 0.190
0.
1.
2.
3.
4.
5.
6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure A-8.

Appendix B

INSTRUCTIONS TO SUBJECTS

Introduction. We have asked you to participate in this experiment to evaluate the effectiveness of a navigation display for piloting a ship through a restricted waterway in limited visibility. You will use the display eight times to determine its usefulness in navigating the ship for 5 miles through a 500-foot wide channel. The display will be described in detail when you are ready to use it.

For the next 10 minutes you may familiarize yourself with the response characteristics of the ship and the proficiency of your helmsman. Using the gyrocompass, which is initially set at 341 degrees true, we'd suggest you make several large course changes to determine the amount of rudder needed to initiate and check the ship's swing, and the effect of rpm on turning maneuvers. Ownship is a 30,000 dwt tanker in ballast with a 28-foot draft. It has a 595-foot length overall, and an 84-foot beam. You will begin half ahead at about 7 knots, with a 1-1/2 knot following current. You may ask any questions and try any maneuvers during this time.

Scenario. During this experiment, we will be measuring how well you keep to the center of the channel. Your goal, therefore, is to keep on the channel centerline as much as possible from your starting position up to the second waypoint (reference chart). The channel is 500 feet wide and 36 feet deep.

Your starting position will be 1.2 nm from a 35-degree left bend in the channel. Ownship is 92 feet to the right of the channel centerline, and you should return to the centerline as soon as practical. Your head is steady on 341 degrees true, and the ship's speed is 8 knots over ground at the beginning of the run. The engine order telegraph (EOT) is set at half ahead, 40 rpm, to make 6.5 knots through the water. RPM changes are permitted; however, we would like you to maintain about 8 knots overall transit speed. Use of speed variations are limited to full ahead, half ahead, slow ahead, dead slow ahead, and stop. No astern bells are available.

There will be a following current of 1.5 knots at the beginning of the run. This current will decrease steadily while approaching the turn. After the turn, the current will be 3/4 knot broad on the port quarter. It will return gradually to aft (reference chart). There will be a wind of 30 knots. The wind direction is from aft during the first leg and from broad on the port quarter during the second leg.

Display. The display that you will use is a graphic display showing ownship's position in the channel. The display will be true motion oriented track-up. With the true motion display, ownship comes on at the bottom of the screen and resets after it has traveled three-fourths of the distance across the screen. In the track-up mode, the picture comes on with the channel centerline oriented up, and ownship moves through it. Once you have completed the turn, the display will automatically change to the new track-up, and ownship will reset to the bottom of the screen.

The display is provided with a heading vector which corresponds to gyro heading and is drawn to the edge of the screen. Ship image is the actual shape and size of ownship scaled to the display. You will be on heading of 341 degrees in the first leg, half ahead, 1.2 nautical miles from the turn. Ownship is 92 feet to the right of the channel centerline. Please return to the centerline as soon as practical.

<u>Questionnaire</u>. At the end of each run, we will ask you "20 questions" about how well you think you piloted different segments of the waterway. As you transit the waterway, you might try to think of how your pilotage could have been better or worse, according to your own criteria. Are there any questions?

Appendix C

C.1 INTERVIEW QUESTIONNAIRE

Subject: ____________

Run: ______________

1. My initial return to and steady-up on the channel centerline was: (check one)

    ____ poor
    ____ fair
    ____ good
    ____ excellent

2. During this initial maneuver, I: (check any)

    ____ overshot the centerline
    ____ never reached the centerline
    ____ maneuvered too severely
    ____ maneuvered too gradually

3. After I steadied up, my transit of the first straight leg was: (check one)

    ____ poor
    ____ fair
    ____ good
    ____ excellent

4. Except for my initial offset, in the first straight leg I was: (check one)

    ____ never on the centerline
    ____ seldom on the centerline
    ____ usually on the centerline
    ____ always on the centerline

5. In the first straight leg, I had difficulty: (check any)

    ____ determining a proper course
    ____ maintaining a steady course
    ____ keeping on the centerline
    ____ judging my speed

6. My overall turn at the bend was: (check one)

    ____ poor
    ____ fair
    ____ good
    ____ excellent

7. My turn rudder before the bend should have been: (check any)

    ____ earlier
    ____ later

____ larger
____ smaller

8. I entered the bend: (check any)

____ too fast
____ too slow
____ too far to the right side of the channel
____ too far to the left side of the channel

9. My turn through the bend resulted in: (check any)

____ an overshoot of the bend
____ an undershoot of the bend
____ excessive rate of turn into the bend
____ excessive drift angle (crabbing) through the bend

10. Following the bend, my steady-up on the second leg was

____ poor
____ fair
____ good
____ excellent

11. My check rudder after the bend should have been: (check any)

____ earlier
____ later
____ larger
____ smaller

12. In steadying up beyond the bend, I: (check any)

____ overshot the centerline
____ never reached the centerline
____ may have gone outside the channel
____ definitely went outside the channel

13. After I steadied up, my transit of the second straight leg was: (check <u>one</u>)

____ poor
____ fair
____ good
____ excellent

14. In the second straight leg, I was: (check <u>one</u>)

____ never on the centerline
____ seldom on the centerline
____ usually on the centerline
____ always on the centerline

15. In the second straight leg, I had difficulty: (check any)

____ determining a proper course

____ maintaining a steady course
____ keeping on the centerline
____ judging my speed

16. In this run, the displayed information was: (check one)

____ never accurate
____ sometimes accurate
____ usually accurate
____ always accurate

17. The rate of speed at which the information on the display was updated was: (check one)

____ too slow
____ slow but acceptable
____ fast but acceptable
____ too fast

18. In this run, the navigation display: (check any)

____ flickered
____ jittered
____ drifted
____ was cluttered
____ was erratic or unreliable
____ should have been on a different range scale
____ was difficult to understand

19. In general, the overall pilotage was: (check one)

____ poor
____ fair
____ good
____ excellent

20. Given another opportunity with this same display, ship, and waterway, I could do an even better job of staying in the channel centerline: (check one)

____ yes
____ no

C.2 QUESTIONNAIRE RESULTS BY PERCENTAGE OF RESPONSES

	16 meter rms noise Tracker Rise Time (Sec.)				32 meter rms noise Tracker Rise Time (Sec.)			
	3	12	24	24*	3	12	24	24*
My initial return to and steady-up on the channel centerline was:								
poor			25.0		12.5			
fair		37.0	12.5	12.0	25.0	**50.0**	**50.0**	38.0
good	**62.0**	**63.0**	**50.0**	**63.0**	**38.0**	**50.0**	**50.0**	**50.0**
excellent	38.0		12.5	25.0	25.0			12.0
During this initial maneuver, I:								
maneuvered correctly	**62.0**	12.5	25.0	**63.0**	**50.0**	25.0	**50.0**	25.0
overshot the centerline		**63.0**	**63.0**	12.0	25.0	25.0	38.0	**63.0**
never reached the centerline				19.0		12.0		
maneuvered too severely		12.5	6.0		12.5			
maneuvered too gradually	38.0	12.5	6.0	6.0		**38.0**	12.0	12.0
did not know					12.5			
After I steadied up, my transit of the first straight leg was:								
poor		12.5						
fair		12.5	25.0		**50.0**	25.0	38.0	50.0
good	**88.0**	**75.0**	**63.0**	**88.0**	38.0	**75.0**	50.0	50.0
excellent	12.0		12.0	12.0	12.0		12.0	
Except for my initial offset, in the first straight leg I was:								
never on the centerline								
seldom on the centerline		12.0	25.0	12.0	**50.0**	25.0		12.5
usually on the centerline	**88.0**	**88.0**	**63.0**	**88.0**	**50.0**	**75.0**	**100.0**	**75.0**
always on the centerline	12.0		12.0					12.5
In the first straight leg, I had difficulty:								
none	**50.0**	**50.0**	**50.0**	**75.0**	**38.0**	25.0	**38.0**	25.0
determining a proper course	12.5				4.0	12.5		12.0
maintaining a steady course	31.0	38.0	25.0		24.0	12.5	25.0	**44.0**
keeping on the centerline		12.0	25.0	25.0	34.0	**50.0**	31.0	19.0
judging my speed	6.5						6.0	
My overall turn at the bend was:								
poor	25.0	**50.0**	38.0	12.0	**38.0**	**37.5**	**63.0**	25.0
fair	25.0			**50.0**	25.0	25.0	12.5	**38.0**
good	**38.0**	**50.0**	**62.0**	38.0	25.0	**37.5**	12.5	25.0
excellent	12.0				12.0		12.5	12.0

*Gyro-aided

C.2 (con't)

16 meter rms noise Tracker Rise Time (Sec.)				32 meter rms noise Tracker Rise Time (Sec.)				
3	12	24	24*	3	12	24	24*	
								My turn rudder before the bend should have been:
12.5		12.5	25.0	25.0	38.0	12.5	12.0	none (was appropriate)
50.0	31.0	50.0	38.0	31.0	25.0	44.0	25.0	earlier
12.5	12.5	12.5	25.0		6.0		31.5	later
25.0	44.0	25.0	12.0	38.0	31.0	31.0	31.5	larger
	12.5			6.0		12.5		smaller
								I entered the bend:
50.0	63.0	63.0	63.0	63.0	75.0	38.0	38.0	appropriately
	12.0	12.5	12.5	12.0	12.5	12.0	12.0	too fast
44.0			12.5		12.5	25.0	31.0	too slow
	25.0	12.5	12.0					too far to the right side of the channel
6.0		12.5		25.0		25.0	19.0	too far to the left side of the channel
								My turn through the bend resulted in:
12.5		38.0	25.0	12.0	25.0	12.0	44.0	none (was appropriate)
56.0	50.0	44.0	56.0	38.0	50.0	56.0	31.0	an overshoot of the bend
	38.0	12.0	12.5	12.0	12.5			an undershoot of the bend
						12.5		excessive rate of turn into the bend
31.5	12.0	6.0	6.5	38.0	12.5	19.0	25.0	excessive drift angle (crabbing) through the bend)
								Following the bend, my steady-up on the second leg was
12.0		25.0	12.0	25.0	25.0	25.0	25.0	poor
25.0	37.0	12.0	38.0	50.0	12.0	12.5		fair
63.0	63.0	63.0	38.0	25.0	63.0	50.0	75.0	good
			12.0			12.5		excellent
								My check rudder after the bend should have been:
50.0	38.0	38.0	50.0	12.0	38.0	25.0	12.0	none (was appropriate)
6.5	25.0	31.0	25.0	38.0	31.0		19.0	earlier
25.0	18.5		12.5	19.0	12.5	38.0	50.0	later
6.5	18.5	31.0		25.0	6.0	12.0	19.0	larger
12.0			12.5	6.0	12.5	25.0		smaller

*Gyro-aided

C.2 (con't)

16 meter rms noise Tracker Rise Time (Sec.)				32 meter rms noise Tracker Rise Time (sec.)				
3	12	24	24*	3	12	24	24*	
								In steadying up beyond the bend, I:
38.0	38.0	50.0	38.0	12.5	25.0	38.0		none (was on the centerline)
44.0	38.0	25.0	38.0	25.0	50.0	31.0	63.0	overshot the centerline
	12.0	12.5	12.0	38.0	25.0		25.0	never reached the centerline
6.0	12.0			12.5		19.0	12.0	may have gone outside the channel
12.0		12.5	12.0	12.5		12.0		definitely went outside the channel
								After I steadied up, my transit of the second straight leg was:
				12.0	12.0		25.0	poor
37.5	38.0	25.0	38.0	50.0	25.0	38.0	25.0	fair
37.5	50.0	63.0	50.0	38.0	63.0	50.0	38.0	good
25.0	12.0	12.0	12.0			12.0	12.0	excellent
								In the second straight leg, I was:
								never on the centerline
12.0		12.0	25.0	50.0	25.0	50.0	25.0	seldom on the centerline
88.0	100.0	88.0	63.0	50.0	75.0	50.0	63.0	usually on the centerline
			12.0				12.0	always on the centerline
								In the second straight leg, I had difficulty:
25.0	38.0	38.0	50.0		38.0	25.0		none
12.5		12.0	12.0	6.0	19.0	25.0		determining a proper course
31.0	31.0			30.0	31.0	6.0	44.0	maintaining a steady course
25.0	31.0	44.0	38.0	60.0	6.0	44.0	56.0	keeping on the centerline
6.5		6.0		4.0	6.0			judging my speed
								In this run, the displayed information was:
				25.0				never accurate
25.0		12.0		37.5		12.0	25.0	sometimes accurate
75.0	100.0	63.0	75.0	37.5	100.0	88.0	75.0	usually accurate
		25.0	25.0					always accurate
								The rate of speed at which the information on the display was updated was:
	12.5	40.0	38.0	12.0	12.0		25.0	acceptable
12.5	12.5	12.5	12.0	38.0	25.0	25.0	37.5	too slow
75.0	75.0	25.0	38.0	50.0	63.0	63.0	37.5	slow but acceptable
12.5		12.5	12.0			12.0		fast but acceptable
								too fast

*Gyro-aided

C.2 (con't)

	16 meter rms Tracker Rise Time (Sec.)				32 meter rms noise Tracker Rise Time (sec.)			
	3	12	24	24*	3	12	24	24*
In this run, the navigation display:								
erratic	**12.0**				12.5		12.5	
flickered		**25.0**	6.0		12.5	6.0	6.0	19.5
jittered	**46.0**	**25.0**	12.5	12.0	**25.0**	**38.0**	11.0	6.0
drifted	17.0	19.0	25.0	6.0	17.0	25.0	23.0	**31.0**
was cluttered								
was erratic or unreliable	4.0		6.0		23.0		6.0	19.5
should have been on a different range scale	21.0	19.0	12.5	**44.0**	5.0	**31.0**	**29.0**	12.0
was difficult to understand					5.0			
acceptable		12.0	**38.0**	38.0			12.5	12.0
In general, the overall pilotage was:								
poor	12.0	12.0	12.0	12.5	**37.5**	38.0		**25.0**
fair	25.0	38.0	38.0	12.5	**37.5**		**62.0**	**25.0**
good	**63.0**	**50.0**	**50.0**	**75.0**	25.0	**62.0**	38.0	**25.0**
excellent								**25.0**
Given another opportunity with this same display, ship, and waterway, I could do an even better job of staying in the channel centerline:								
yes	**100.0**	**100.0**	**88.0**	**88.0**	**88.0**	**100.0**	**100.0**	**62.0**
no			12.0	12.0	12.0			38.0

*Gyro-aided

APPENDIX D

MANEUVERING ANALYSIS RATIONALE

Appendix D contains the rationale and methodology for determining the measures shown on the "Effect on Maneuvering Performance" tables presented in Section 5.

MANEUVERING ANALYSIS

CRITERIA FOR DETERMINING:

1. Distance to return to centerline

a. Alongtrack distance (ATD) from the start of the run until ownship crosses the centerline

or in the event ownship does not cross centerline

b. ATD from the start of the run until ownship makes its first closest approach to the centerline

or in the event ownship closest approach to centerline occurs more than 1 nm from the start — i.e., a very gradual return to the centerline

c. ATD from the start of the run to the first course command 340 degrees or larger

or in the event no course command 340 degrees or larger is given

d. ATD from the start of the run to the first time three similar crosstrack distances occur consecutively ($\pm$ 2 feet)

2. Overshoot following return to centerline

a. Largest crosstrack distance (CTD) immediately following when ownship crosses the centerline

or in the event ownship does not cross the centerline

b. Largest CTD immediately following when ownship makes its first closest approach to the centerline

or in the event a 340-degree or larger course command or three consecutive similar crosstrack distances are used to establish the return to centerline

c. CTD at the time of "return to the centerline"

3. Distance to steady up in entrance leg

a. ATD from the start of the run when crosstrack distance first becomes 25 feet or less beyond the established "overshoot" *or in the event crosstrack distance following the overshoot does not become 25 feet or less within 1 nm from the start, i.e., a very gradual return to the centerline*

b. ATD from the start of the run to the first time three similar crosstrack distances occur consecutively ($\pm$2 feet)

or in the event three similar crosstrack distances do not occur consecutively

c. ATD from the start of the run but beyond 1 nm from the start when crosstrack distance first becomes 25 feet or less

4. <u>Distance to steady up in exit leg</u>

a. ATD from the waypoint (center of the bend) when crosstrack distance is less than 25 feet and proceeded by three consecutive course errors less than 5 degrees, within 1 nm from the waypoint

or in the event crosstrack distance does not become 25 feet or less within 1 nm from the waypoint

b. ATD from the waypoint (center of the bend) for the third of three consecutive course errors less than 5 degrees after the closest approach to the centerline, excluding the initial crossing if an overshoot

or in the event there are no three consecutive course errors less than 5 degrees

c. The third of the three smallest consecutive course errors beyond 1 nm from the waypoint

5. <u>Distance before bend at inital rudder</u>

a. Distance before the waypoint (center of the bend) at which the initial turn rudder was applied.

6. <u>Magnitude of initial turn rudder</u>

a. The amount of rudder initially applied to execute the turn.

7. <u>Maximum initial turn rudder</u>

a. The largest rudder applied at any time to increase the swing

8. <u>Frequency of turn rudder actuations</u>

a. Total number of rudder actuations prior to check rudder

9. Distance beyond bend of initial check rudder

a. Distance beyond the waypoint (center of the bend) at which the initial turn rudder was applied.

10. Magnitude of initial check rudder

a. The amount of rudder initially applied to execute the turn.

APPENDIX E

STATISTICAL COMPARISON OF TRACKKEEPING PERFORMANCE

Appendix E contains the statistical comparison of mean tracks and trackkeeping variability at each data line of the waterway between display design variables. This analysis forms the basis for the interpretations of pilotage performance of Section 5 and is frequently referenced in that section.

The figures presented herein were derived as a result of statistical tests on the means and standard deviations of crosstrack distances for all runs conducted within each experimental condition. The T-test was used to test for differences in group means and the F-statistic for differences in group variability. Differences greater than or equal to the 0.10 level of significance are indicated by arrows along the trackline. The data are used as statistical support in Section 5. Data lines are numbered in both directions from the center of the bend along the entrance leg 1 and exit leg 2. They represent discrete measurement points 474 feet apart to which each statistical test was applied.

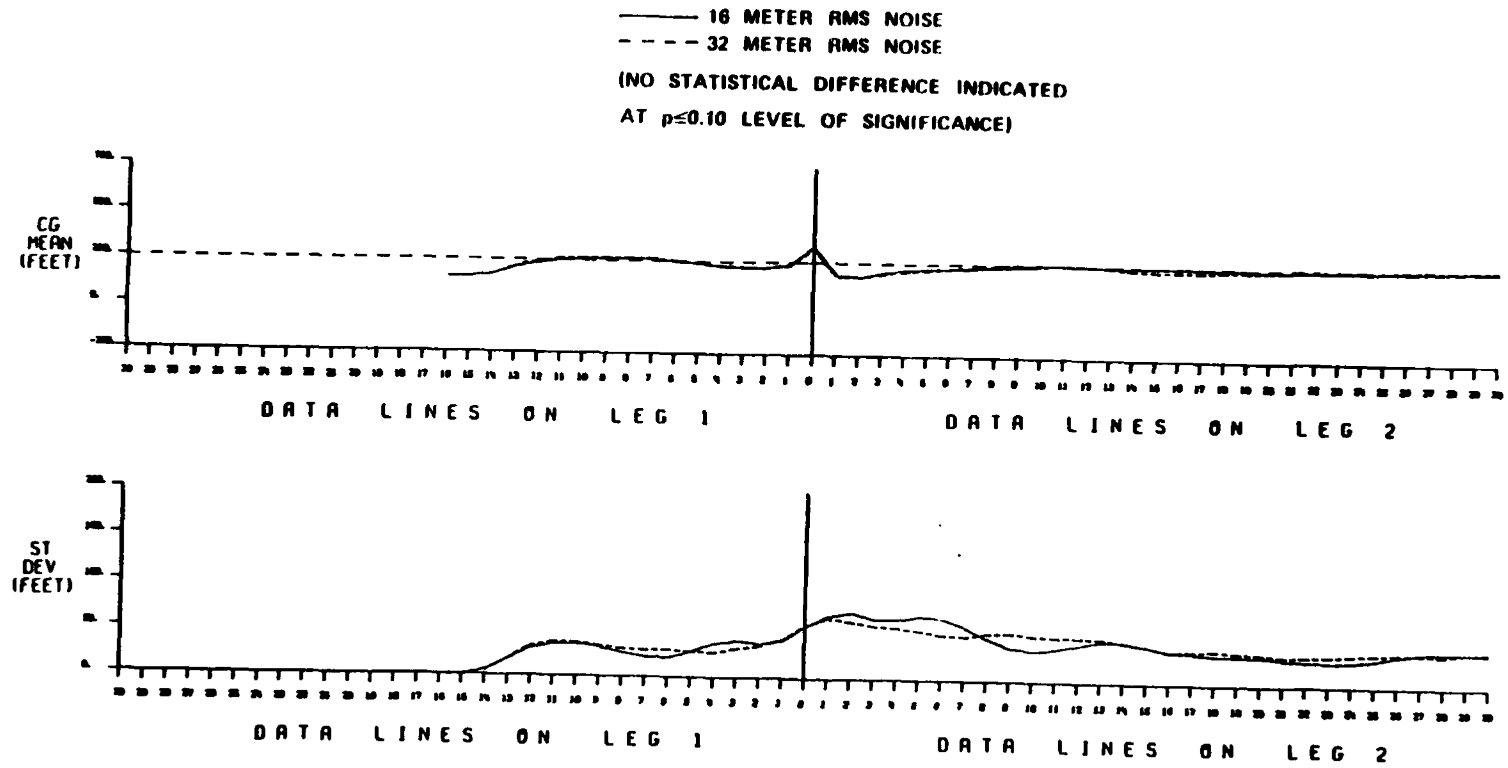


Figure E-1. Statistical Comparison on the Effects of Noise with all Trackers

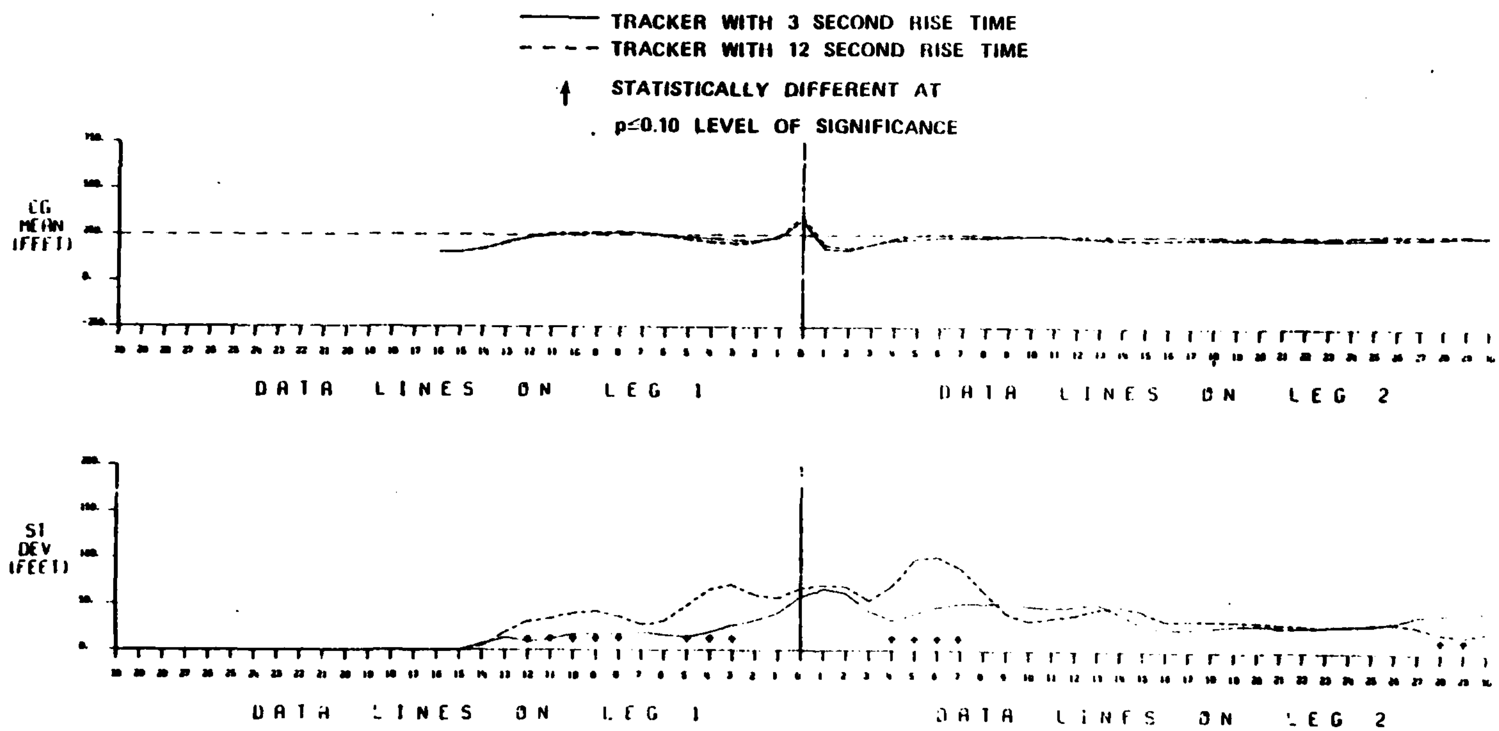


Figure E-2. Statistical Comparison between Trackers with 3-Second and 12-Second Rise Time in 16 Meter RMS Noise

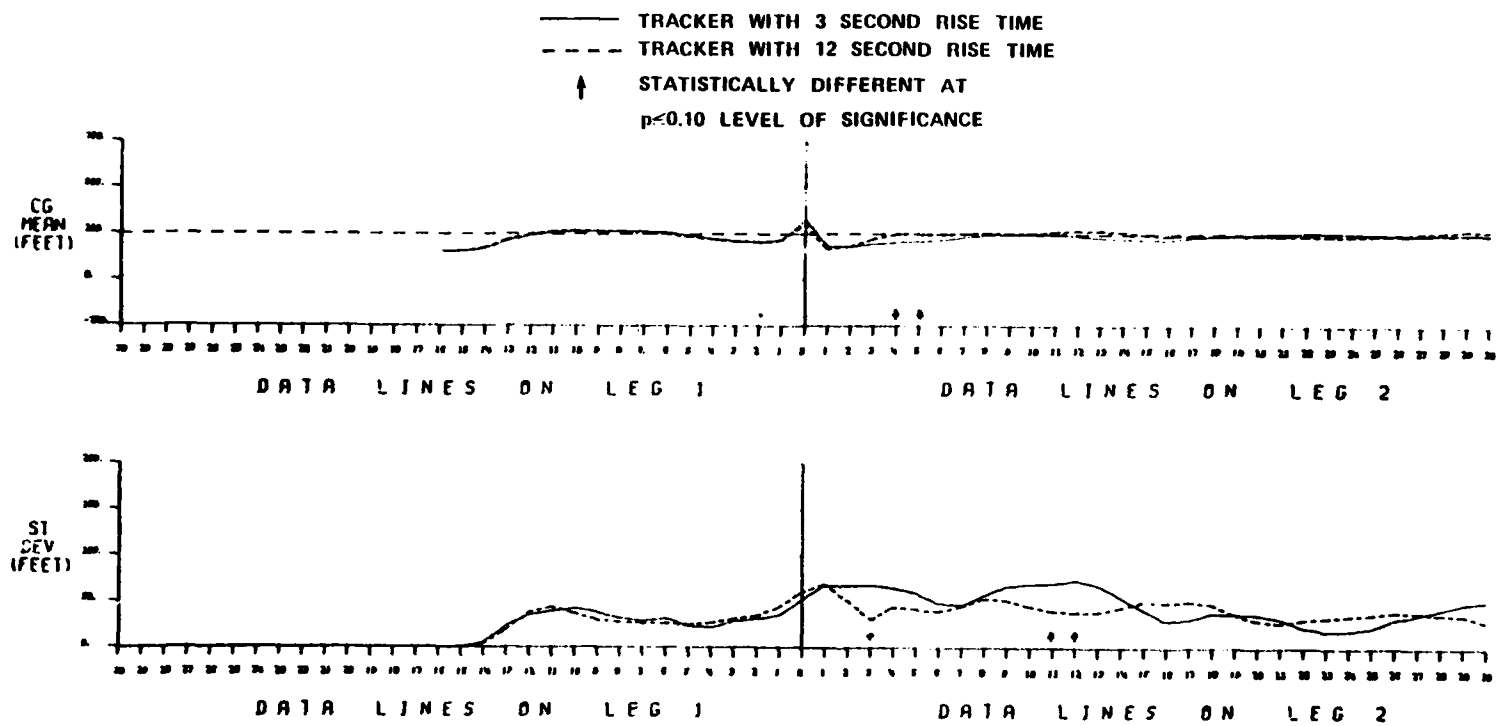


Figure E-3. Statistical Comparison between Trackers with 3-Second and 12-Second Rise Time in 32 Meter RMS Noise

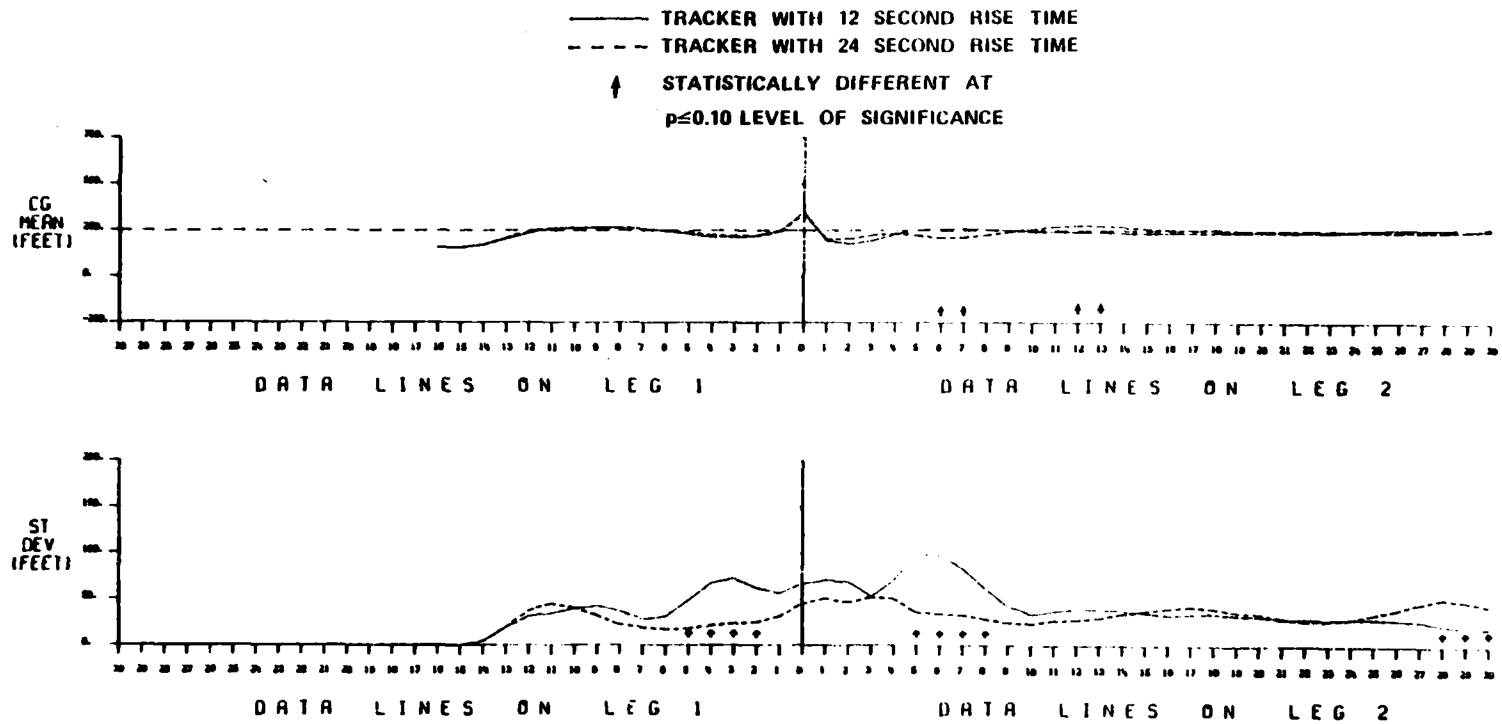


Figure E-4. Statistical Comparison between Trackers with 12-Second and 24-Second Rise Time in 16 Meter RMS Noise

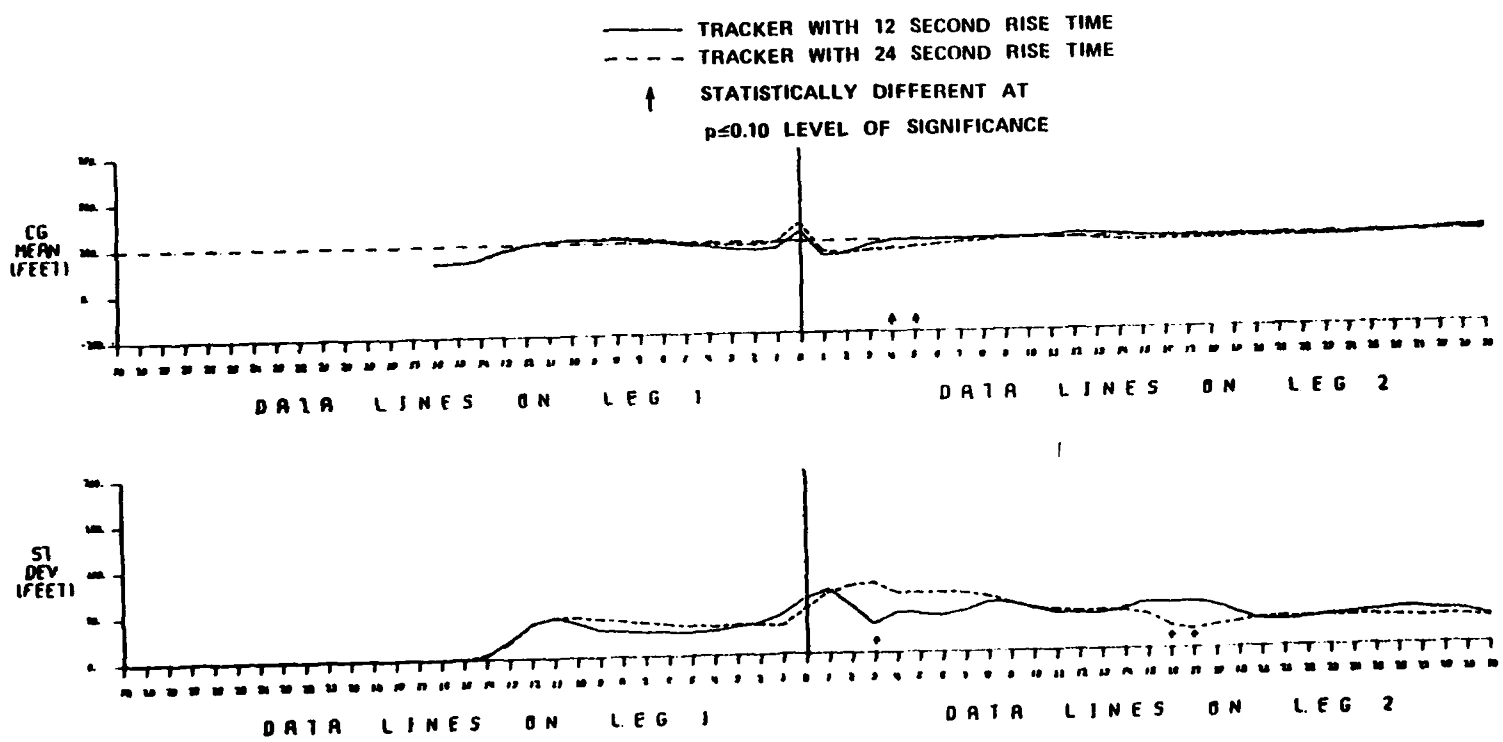


Figure E-5. Statistical Comparison between Trackers with 12-Second and 24-Second Rise Time in 32 Meter RMS Noise

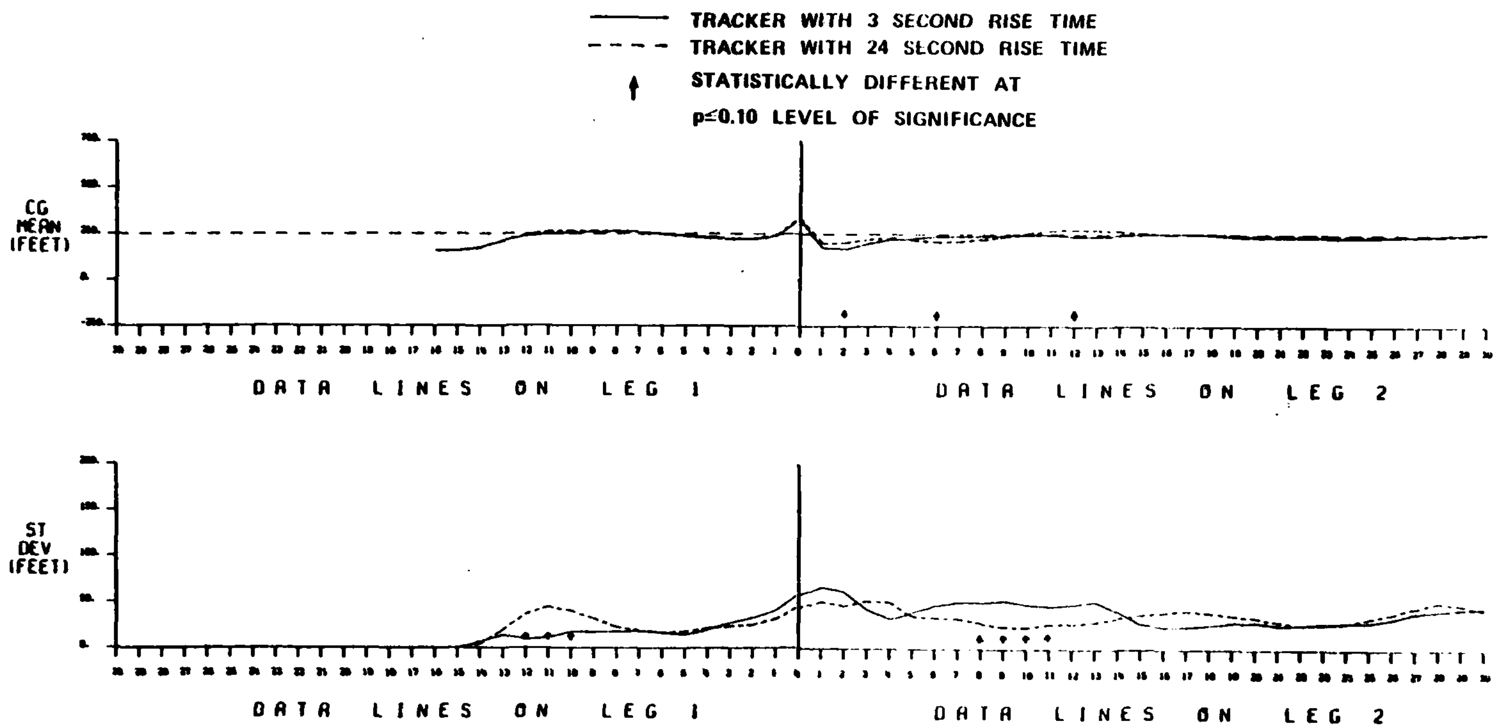


Figure E-6. Statistical Comparison between Trackers with 3-Second and 24-Second Rise Time in 16 Meter RMS Noise

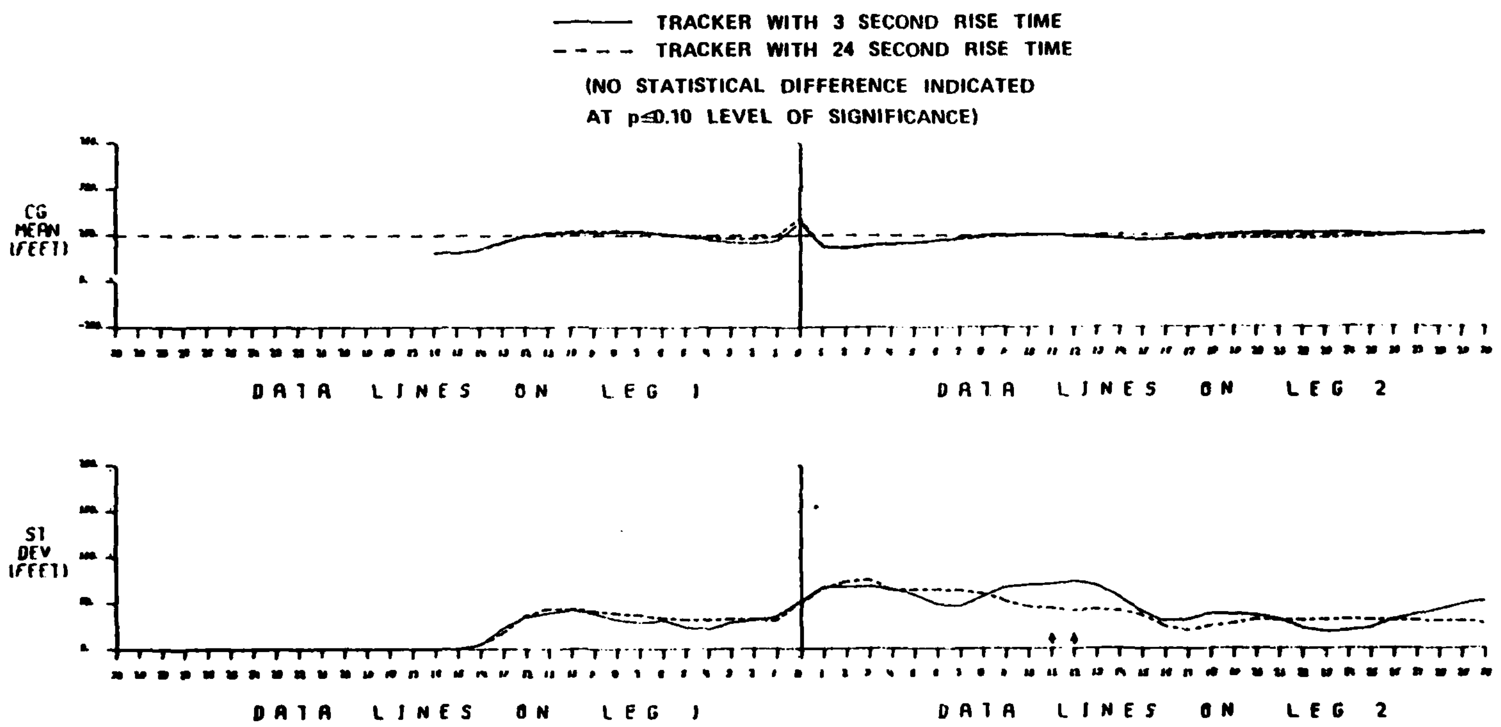


Figure E-7. Statistical Comparison between Trackers with 3-Second and 24-Second Rise Time in 32 Meter RMS Noise

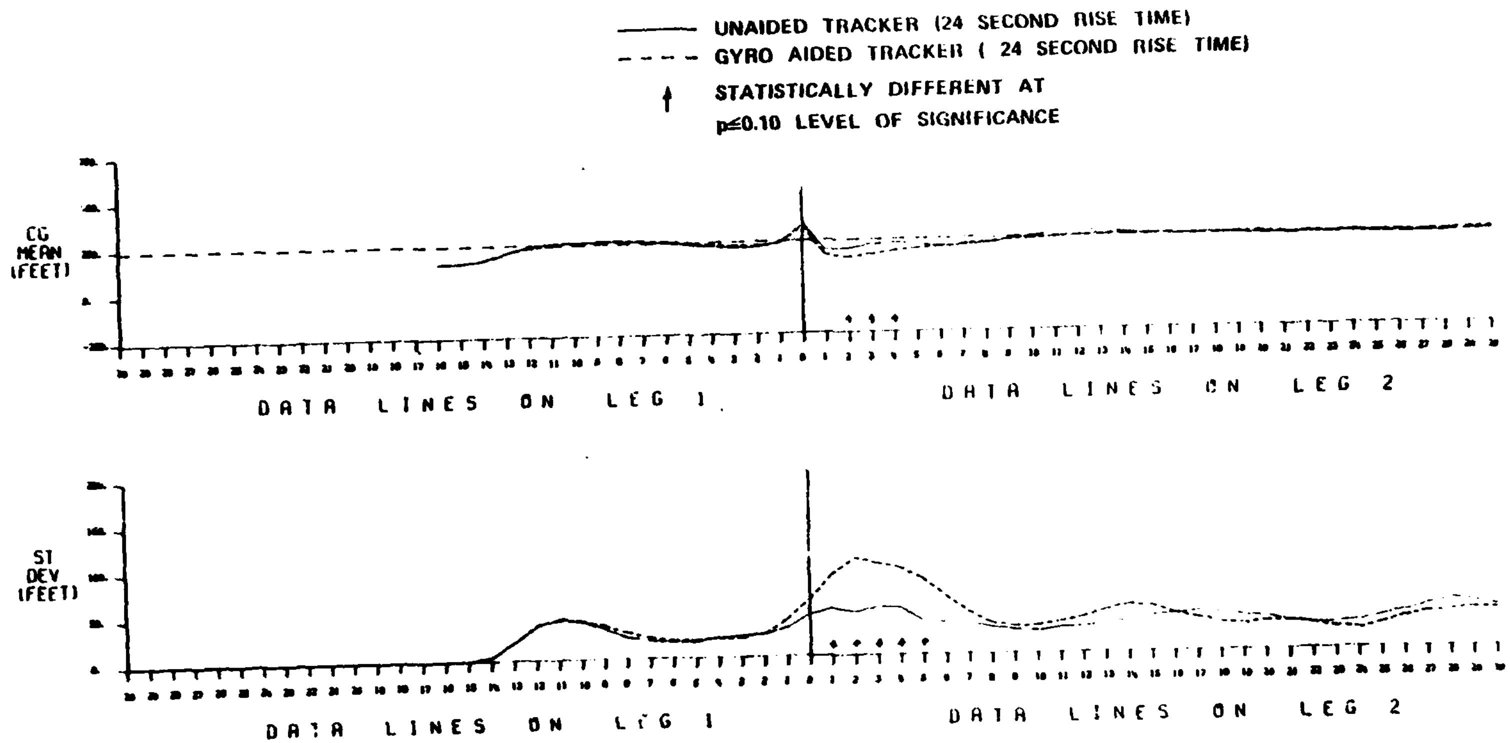


Figure E-8. Statistical Comparison between Unaided and Gyro-Aided Trackers in 16 Meter RMS Nois

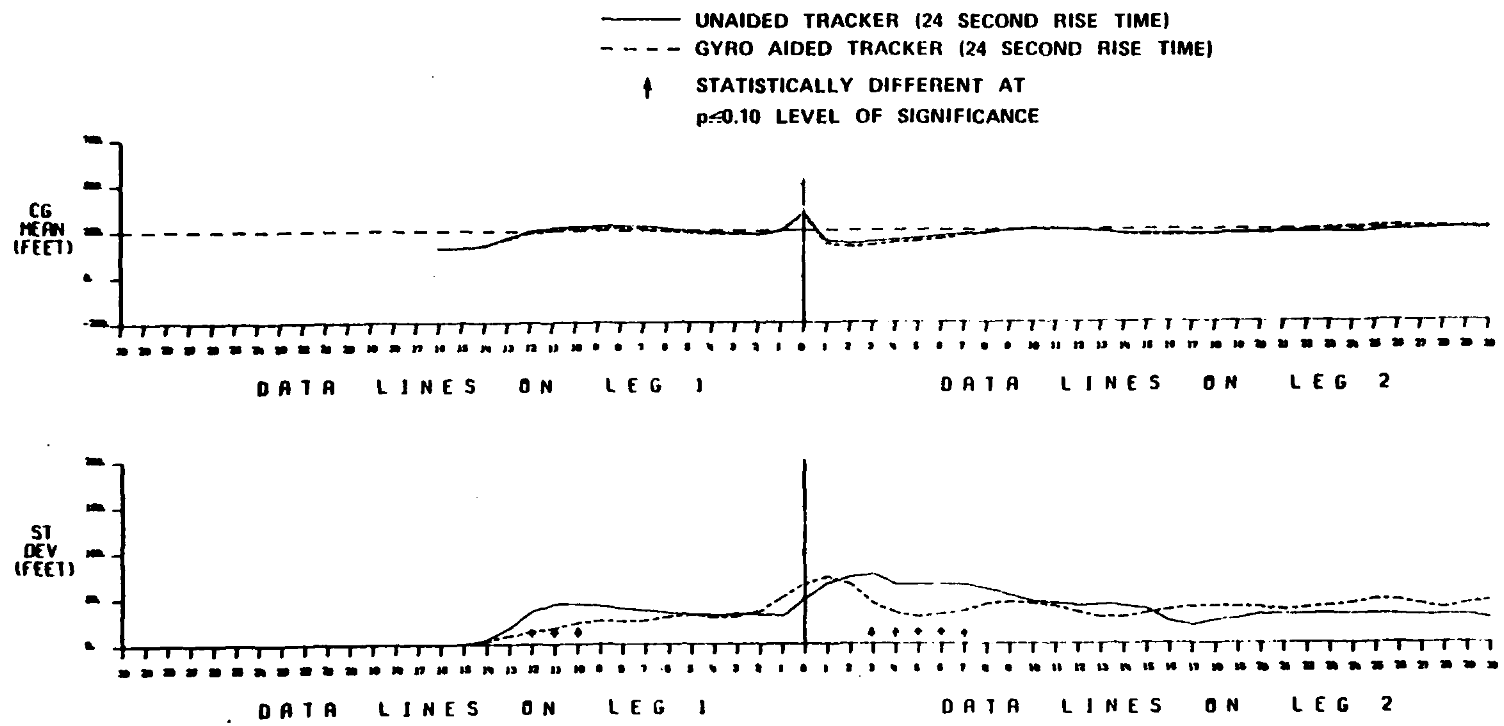


Figure E-9. Statistical Comparison between Unaided and Gyro-Aided Trackers in 32 Meter RMS Noise

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