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JAN 81 R . COOPER, K L MARINO, W R BERTSCHE DOT-CG-835285-A
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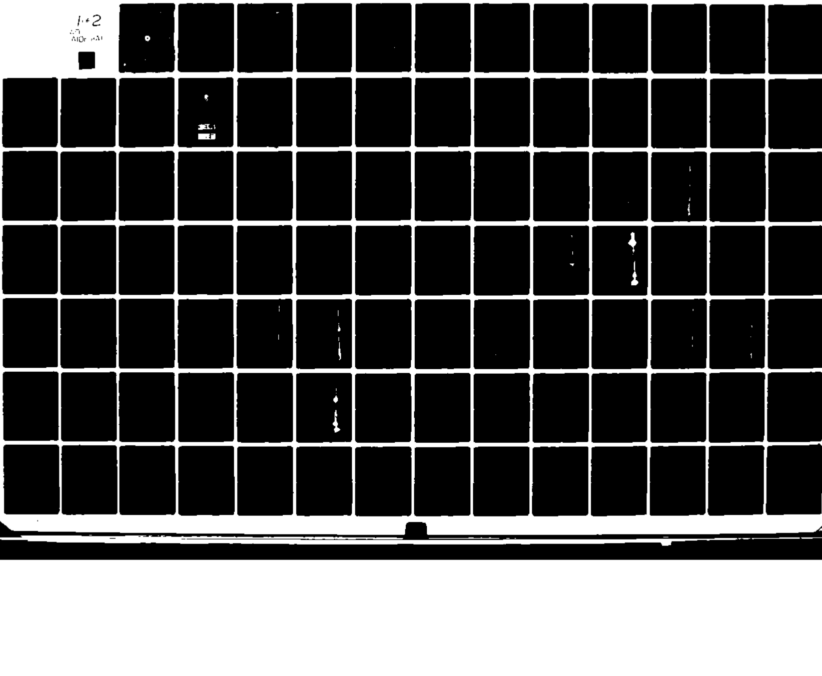

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SIMULATOR EVALUATION OF ELECTRONIC RADIO AIDS TO NAVIGATION DISPLAYS
THE RA-1 EXPERIMENT

Eclectech Associates, Incorporated
North Stonington Professional Center
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January 1981

Interim Report

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16. Abstract

This report describes a ship's bridge simulation evaluation of electronic radio aids to navigation displays conducted for the purpose of trading off display information effectiveness with operational requirements and shipboard system cost. The experiment known as RA-1 is the second of a series of experiments which are addressing DIGITAL, GRAPHIC, PERSPECTIVE and STEERING display formats with various noise and filter characteristics. The first, a miniexperiment of abbreviated length, selected five of the most operationally effective display designs from among 18 original display formats. To these were added two predictor steering displays for a total of seven displays; all to be evaluated in the more stringent, full-length RA-1 simulation. As the result of superior pilotage performance shown in this experiment, a true motion, trackup GRAPHIC display with either course or heading vectors is recommended as the "benchmark" display for inclusion in a future RA-2 simulation. The RA-2 experiment will evaluate the "benchmark" display's effectiveness in a radio aids to navigation noise environment and as a function of system filtering characteristics and the implementation of gyro aiding. The simulation of the noise environment and system filtering characteristics is evaluated in this report.

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)	18. Distribution Statement: Document is available to the public through the National Technical Information Service, Springfield, VA 22161

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17. KEY WORDS (CONTINUED)

perspective navigation display
shiphandling
trackkeeping
crosstrack variability
crosstrack distance
rudder actuations
magnitude of rudder
turning cues
steering cues
motion 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 second 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 describes a full length simulator evaluation consisting of fifty-two 45-minute runs for the purpose of selecting the one or two most effective displays from among seven alternate designs selected during the first phase miniexperiment. The full length evaluation, known as the radio aids experiment 1 (RA-1), was conducted using "perfect position" information for displaying ownship in the world. The display(s) selected by the RA-1 experiment will again be reevaluated using full-length scenarios, only this time in a noise environment of known proportions and using specified tracking filter characteristics and filter aiding techniques. This, the RA-2 experiment, will be designed both from the RA-1 recommendations on display design and as a result of findings revealed during the development of the radio aids to navigation system noise simulation model described in this report. The RA-2 experiment will be presented in subsequent documentation.

"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]

---

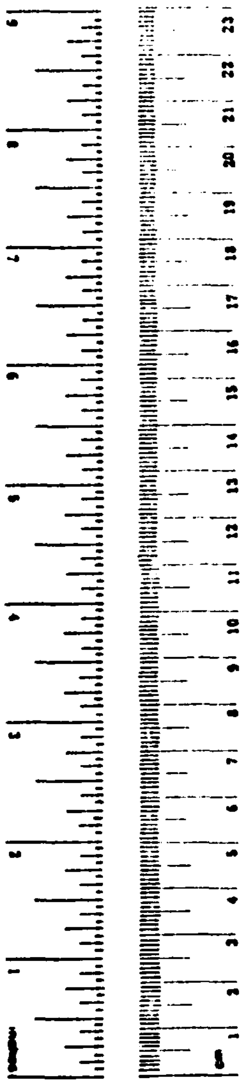
[1] United States Coast Guard, An Approach to the Study of Electronic Displays for Use in Restricted Waterways, a Position Paper, December 1979.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

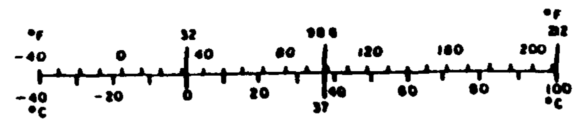
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2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

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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Section 1

SUMMARY OF CONCLUSIONS

The predominant conclusion of the RA-1 experiment is that for conditions comparable to those simulated only some display formats could be expected to produce safe shiphandling performance. The other displays would require additional operator instruction and/or display modification for safe shiphandling. Of the four display concepts examined, the GRAPHIC and STEERING displays produced the most satisfactory results. This was evident in all major measures of trackkeeping performance, maneuvering performance and user acceptance. Table 1 shows a summary of these metrics as interpreted from the statistical analysis of Section 5.

The Simplified Digital Display (D-1) without turnmaking recommendations appears to be the most difficult for pilots to use. With the exception of Leg 1 in which a 92-foot return to the centerline was required, all other trackkeeping performance was severely deficient. Large track variability among pilots as well as inconsistency in control activities (steering and propulsion commands) suggest that the D-1 display could, perhaps, be made effective either through design modification or operator training. It was indicated, however, (Table 1) that the digital format and particularly the lack of turnmaking information in the bend would render the display relatively unacceptable to potential users.

The D-1 display is not recommended for inclusion in the RA-2 experiment, but due to its potential low-cost should be considered for future experimental consideration or in the development of a combination or hybrid display.

The Digital Display with Turn Recommendations (D-2) produced comparable results in the first leg, a well executed but unnecessarily early turn and extreme difficulty steadying up in Leg 2. Causes of this are again believed to be a lack of experience using the display and particularly the subjects' inability to adequately recover from the turn. A high variability in selecting the turn point was in evidence (i.e., the turn point had to be manually selected by the operator), although this could be expected to diminish once operators became familiar with the device, waterway and shiphandling characteristics.

The D-2 display is also not recommended for inclusion in the RA-2 experiment; however, like the D-1 display its development and evaluation should be pursued independently. Most subjects stated that they thought the DIGITAL concept could be made workable, but only after extensive testing, critique and refinement.

The PERSPECTIVE display was found to be easily understood and potentially readily accepted by the subjects. It did not, however, produce the level of performance which subjects had anticipated. The major difficulties with the PERSPECTIVE display are illustrated in Table 1. While the first leg and turn were well executed, subjects were never able to align on the Leg 2 centerline. Also, there are indications from the maneuvering measures that subjects were required to use erratic and uncharacteristic rudder actuations to achieve the turn. Apparently, the perceptual image is deficient with regard to the way pilots normally view their visual scene. Most subjects blamed their difficulty on the lack of a velocity cue (i.e., the channel boundary lines did not indicate the ship's forward motion). Others acknowledged that because they could not see abeam and because the centerline was

TABLE 1. SUMMARY OF CONCLUSIONS

● INDICATES SUPERIOR DISPLAY EFFECTIVENESS AS INTERPRETED FROM –

(1) SUMMARY TRACK PLOT ANALYSES
(2) MANEUVERING PERFORMANCE
(3) ANALYSIS OF CONTROL ACTIVITIES
(4) POST RUN AND POST SIMULATION QUESTIONNAIRE ANALYSES

☐ INDICATES BEST OVERALL PERFORMANCE

	TRACKKEEPING							MANEUVERING				USER ACCEPTANCE	
	ENHANCE LEG 1 (WIND AND CURRENT ASTERN)		EXIT LEG 2 (WIND AND CURRENT PORT QUARTER)		TURN EXECUTION								
	MEAN TRACK	VARIABILITY	MEAN TRACK	VARIABILITY	MEAN TRACK	VARIABILITY	RETURN TO AND STEADY UP ON CENTERLINE	INITIAL TURN RUDDER APPLICATION	CHECK RUDDER APPLICATION	STEERING AND PROPULSION CONTROL	PERCEPTION OF DISPLAY DESIGN	ACCURACY OF PERCEIVED OWN PERFORMANCE	COMPREHENSION OF DISPLAY
SIMPLIFIED DIGITAL DISPLAY	●	●					●		●				
DIGITAL DISPLAY WITH TURN RECOMMENDATIONS	●	●			●	●		●					
GRAPHIC DISPLAY WITH HEADING VECTOR	●	●	●	●	●	●		●	●	●	●	●	●
GRAPHIC DISPLAY WITH COURSE VECTOR	●	●	●	●	●		●	●	●	●	●	●	●
PERSPECTIVE DISPLAY	●	●			●	●			●		●		●
PREDICTOR STEERING DISPLAY	●	●	●	●	●	●	●	●	●	●		●	●
SIMPLIFIED PREDICTOR STEERING DISPLAY	●	●	●	●	●			●	●	●	●	●	●

not delineated, they had no crosstrack reference. In any event, probably only display redesign would solve these performance deficiencies. The perceptual scene is so familiar to pilots that specialized training would defeat the display's single strong advantage of being similar to the visual piloting scene.

The PERSPECTIVE display is not recommended for inclusion in the RA-2 experiment.

The two GRAPHIC and two STEERING concepts showed similar performance to the point that any of them could be recommended for RA-2. The Predictor Steering Display promoted the overall best performance and was only flawed by the subjects' perception of it as too sophisticated to be cost effective or reliable.

The Simplified Predictor Steering Display was well comprehended, believable, and in general very well received. It, however, promoted a large trackkeeping inconsistency among subjects in the turn and when attempting to steady up. Some additional experience with the display may be sufficient to remedy this particular deficiency.

Both GRAPHIC displays promoted commendable pilotage performance and were well accepted by all subjects. The only major difference as indicated in Table 1 was that when the heading vector was used subjects executed the bend well but experienced difficulty in steadying up on Leg 2 and returning to the Leg 2 centerline. When the course vector was used, subjects tended to overshoot through the bend, but were then able to return to the centerline and steady up with little difficulty.

As a function of the pragmatic approach adopted by this project and an appreciation that the RA-2 experiment is attempting to employ the display with "best chance for success," this report recommends that either or both of the GRAPHIC displays (G-1 and/or G-2, heading and/or course vector respectively) be used in the RA-2 experiment.

As the result of a review on the capabilities and validity of the noise and filter models (Appendices A and B), and the U.S. Coast Guard's unique requirements and interests regarding the implementation and performance of electronic radio aids to navigation, it was resolved that the following eight scenarios be recommended for evaluation in the RA-2 experiment.

<u>Run Number</u>

1. ALPHA BETA Filter, 3-second rise time, 32 meter RMS noise.

2. ALPHA BETA Filter, 12-second rise time, 32 meter RMS noise.

3. ALPHA BETA Filter, 24-second rise time, 32 meter RMS noise.

4. ALPHA BETA Filter, 3-second rise time, 8 or 16 meter RMS noise.*

5. ALPHA BETA Filter, 12-second rise time, 8 or 16 meter RMS noise.*

6. ALPHA BETA Filter, 24-second rise time, 8 or 16 meter RMS noise.*

7. ALPHA BETA Filter with gyro aiding, 24-second rise time, 32 meter RMS noise.

8. ALPHA BETA Filter wtih gyro aiding, 24-second rise time, 16 meter noise.

> *A determination of whether to use 8 or 16 meter RMS noise for runs 4, 5 and 6 will be made subsequent to the presimulation runs as a function of subject performance and operational practicality.

All runs will be made in the full length scenario using only the GRAPHIC display (true motion, track up) with the heading vector.

Section 2

INTRODUCTION

Continuing technological advances in electronic information processing, integration, and display are opening new alternatives for shipboard navigation systems previously considered too expensive or unreliable to benefit the maritime industry. In its endeavor to ensure safe pilotage of vessels in restricted waters, yet accommodate cost-effective ship operations, the U.S. Coast Guard has undertaken a program of identifying the performance requirements of such navigation systems, and providing guidelines for their design based upon the operational effectiveness, safety, and cost tradeoff. As a result of miniaturized, high speed, and mass storage computer capabilities, it is now possible to provide accurate positioning information from many sources with both high reliability and repeatability. Information provided by the system, however, is only as effective as the human interface through which it is implemented. To be beneficial it must be easily understood, relevant to the immediate task, clearly and concisely displayed within perceptual limits, and instill confidence in the user.

The program implicitly addresses the restricted waterway environment in which the watch officer is faced with a plethora of task demands in addition to navigation. 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 the pilot. In this environment, the radio navigation system must supplant the visual, providing immediate information not only about present position, but about future position, maneuver timing and vessel momentum. The radio navigation system, electronic processing, display, human pilot, ship and environment all function together in a complex interaction which at present cannot be modelled. This research, then, uses simulation as a means of parametrically and functionally studying certain features of the radio aid that are design controllable or specifiable.

2.1 THE RA-1 EXPERIMENT

The RA-1 experiment is part of an overall program outlined in Figure 1 to trade off the operational effectiveness of various display designs with the computer capabilities and costs required to produce it. The program initiated with a miniexperiment evaluation[2] of three display concepts (DIGITAL, GRAPHIC and PERSPECTIVE) and 18 display variables, all simulated under conditions in which "perfect" ownship position was presented. This miniexperiment was conducted in an abbreviated 15 minute scenario consisting of one 35-degree bend of a 500-foot wide channel. Based on measures of trackkeeping, maneuvering, user acceptance and potential system cost, seven formats were selected for a full length, scenario evaluation. The full length simulation evaluation is the subject of this report. It also was conducted using "perfect" ownship position information.

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[2] Cooper, R. B. and K. L. Marino, Simulator Evaluation of Electronic Radio Aids to Navigation Displays, Interim Report, Washington, D.C., U.S. Coast Guard, March 1980.

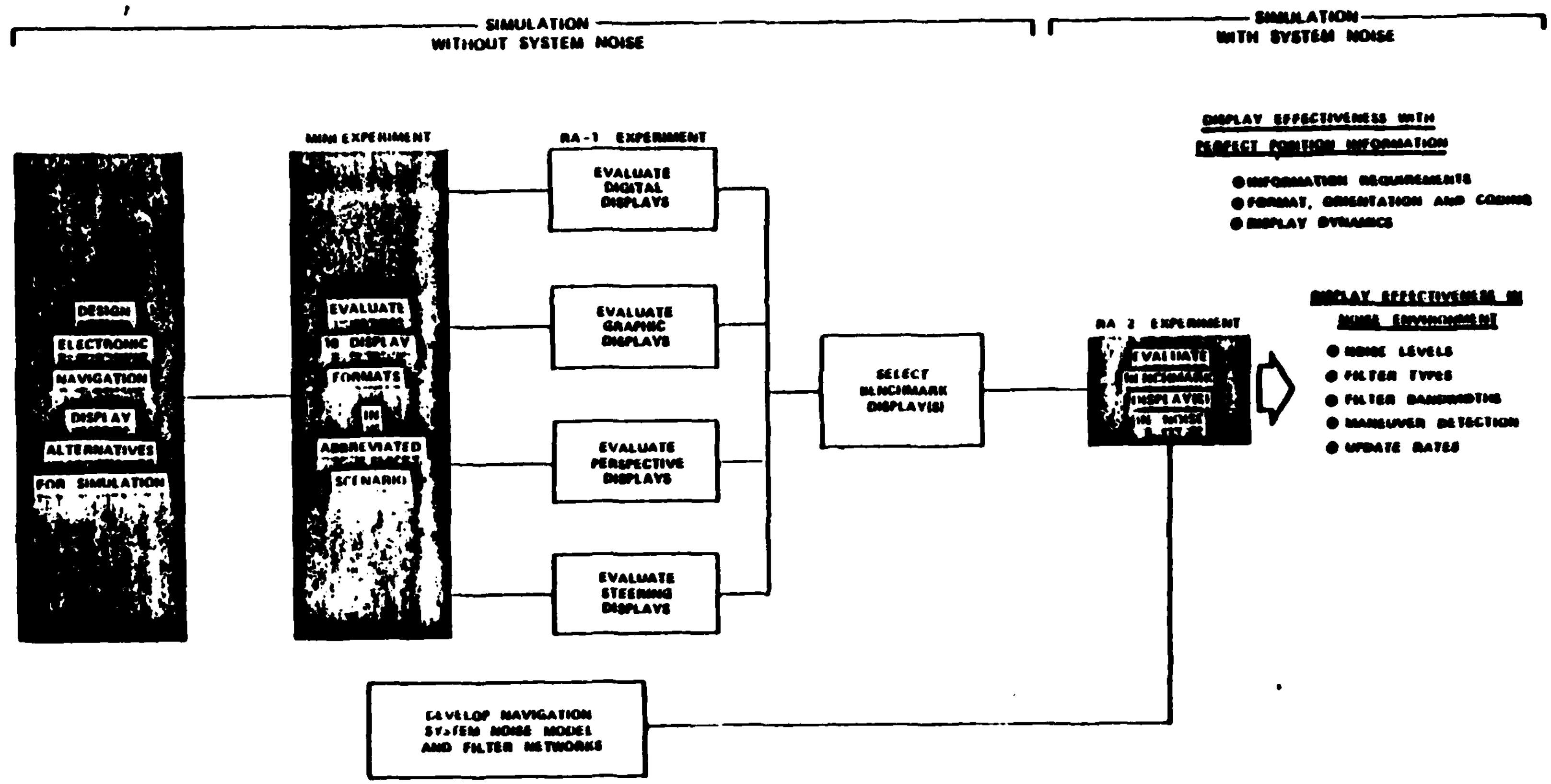

FIGURE 1. PROGRAM FOR THE SIMULATION EVALUATION OF ELECTRONIC RADIO AIDS TO NAVIGATION DISPLAYS

Results of the RA-1 experiment yielded four highly effective displays, two of which are recommended for inclusion in the subsequent RA-2 experiment. The RA-2 experiment will reevaluate the display(s) using the identical scenario and performance metric but with ownship position errors introduced as a result of variations in system noise level, tracker filter characteristics and filter aiding techniques. The result of this final phase of the program will be the design definition of an effective radio aids to navigation display along with the design, operation and cost parameters required for its development.

2.2 NOISE FILTER MODEL DEVELOPMENT

Concurrent with the RA-1 experiment (see Figure 1) a navigation system noise model was developed and tested for use with the RA-2 experiment. The results of this endeavor are presented in Appendices A and B. Appendix A describes the implementation of the ALPHA-BETA (α -β) tracker and the entire navigation system simulation. It also evaluates the system performance for a variety of parametric values. Appendix B validates the system by using actual ship inputs both with and without gyro aiding to produce individual track plots for comparison with real world criteria.

Section 3

EXPERIMENTAL DESIGN

The RA-1 experiment was intended to evaluate the operational effectiveness of seven preselected electronic radio aids to navigation displays in a full length (approximately 45 minutes) scenario. The experiment was designed and conducted similarly to the miniexperiment described by Cooper and Marino, 1980.[3] Noted differences were in the length of the scenario, original position of ownship, and the display designs selected for evaluation. Some changes to the data collection and analysis procedures are discussed in Section 4.

As a result of the miniexperiment findings and recommendations, five displays were adopted from the previous research and two new displays were added. A DIGITAL display was modified (i.e., operationally simplified) to represent a lower cost category than had previously been investigated. The two new displays were a predictor steering display which uses ownship's hydrodynamic equation to compute and display predicted track, and a simplified predictor display which computes and projects ownship track using speed and present rate of turn. These additions provided the RA-1 experiment with three basic display concepts; DIGITAL with two formats, GRAPHIC with two formats, PERSPECTIVE with only one format, and STEERING with two formats.

The RA-1 experiment was conducted in a full-length scenario using the same ship, waterway and environmental characteristics (i.e., wind and current) as employed in the miniexperiment. Ownship, however, originated approximately 1 nautical mile further south than in the miniexperiment and traveled several miles beyond the bend. As a result, although there were only seven display variables to be evaluated, the length of time required for each subject to use all displays was about the same as the miniexperiment.

Instructions to subjects were updated from the miniexperiment as a result of the additional predictor steering displays. Further, recommendations of the miniexperiment report necessitated the administration of a brief but structured interview at the end of each run and at the end of the simulation. This interview was designed to elicit from subjects how they perceived each display, how they felt they performed when they used it, and if they had any recommendations on its design.

Other parameters of the experiment, such as subject familiarization, simulator operation, subject selection, etc., were similar to the miniexperiment.

3.1 EXPERIMENTAL VARIABLES

The following list of variables was derived from the miniexperiment recommendations[4] and is presented here as a rationale for the selection of RA-1 variables.

---

[3] Ibid.

[4] Ibid.

3.1.1 List of Variables

Representing low cost systems (less than $500)

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

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

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

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

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

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

6. 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)

7. 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.

3.1.2 Description

Examples of the display variables as they appeared on the simulator CRT are shown in Figure 2. A complete description of the DIGITAL, GRAPHIC and PERSPECTIVE displays is presented by Cooper and Marino.[5] The additional two steering displays are described as follows:

Simplified Predictor Steering Display

The orientation, motion and spatial characteristics of the predictor steering displays are identical to the graphic displays. The only difference between displays is the information portrayed by ownship's vector as a function of the method used to generate it. With the simplified predictor, a series of straight vectors emit from ownship each with a length equivalent to the distance ownship would travel in 30 seconds increments. The first, or closest vector to ownship, is drawn in the direction ownship is traveling given existing ownship speed and rate of turn. Assuming this speed and rate of turn remains constant, second, third, forth, etc., vectors can also be drawn and attached to each other to form a turn radius. Since

[5] Ibid.

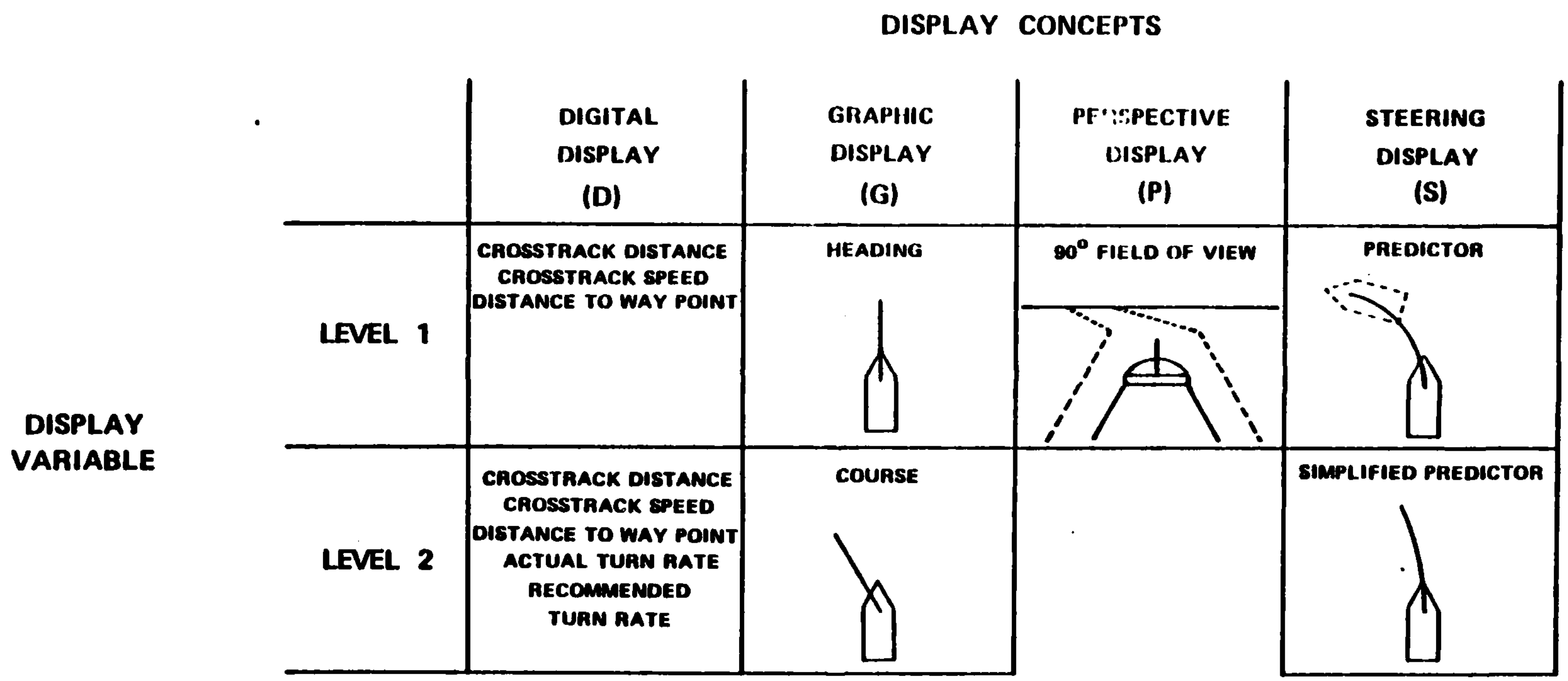

FIGURE 2. IDENTIFICATION OF DISPLAY CONCEPTS AND VARIABLES

turn rate does not remain constant through a maneuver, the vector updates periodically (every 3 seconds in this case) to show a new turn radius resulting from each newly sampled turn rate. The result is a somewhat delayed indication of projected track, responsive not to the helm but to the actual dynamics of the ship. This display and processor system is moderately priced because it requires no mass data storage, elaborate sensing equipment, or high speed computation to generate the vector. Disadvantages and attributes of the information it provides are tested in this experiment.

Predictor Steering Display

The predictor steering display simulator was developed for previous experimentation by Eclectech Associates for the Office of Advanced Ship Operations, U.S. Maritime Administration.[6] It will be used in the evaluation of radio aids to navigation displays to simulate the integration of high cost, high capability steering display graphics with displayed electronic navigation information. The predictor steering concept is relatively new to the maritime industry and has yet to be proven cost effective either in the operational or simulated setting. Van Berlekom, in his 1977 simulator investigations of predictor steering systems reported profound modifications of steering behavior by quartermasters viewing the display.[7] These simulations, conducted at the Swedish Ship Research Foundation (SSPA) and others at Kockums[8], concluded that rudder acitivity (i.e., frequency of actuation) increased, but the number of large rudder angles decreased when predictor steering was used. Subsequent decreased yaw rates resulted in more gradual turns and an overall smoother transition of the simulated waterway. The findings suggest that this type of display might be used by a helmsman the way he uses his rudder angle indicator, gyro repeater and/or turn rate indicator. Van Berlekom's work did not address the display as an aid to pilots or masters, nor its compatibility with pilotage techniques.

Unlike the SSPA and Kockums displays, the predictor steering system to be used in the radio aids display evaluation relies upon sensing of forces which continuously act upon ownship. Their effects are computed in real time using the ship's unique hydrodynamic equation. This prediction assumes all forces will remain constant throughout the duration of the prediction and it displays the projected track accordingly. This display requires some adaptation on the part of the operator since environmental factors characteristically vary through a waterway and cannot be expected to remain constant for the duration of every prediction, particularly when the ship is approaching a channel, bend, or tributary.

---

[6]Cooper, R.B., W.R. Bertsche, and K.P. Logan, Standardization of the Advanced Ship's Bridge Display, Phase II, The Advanced Bridge Design Program, Washington, D.C., U.S. Maritime Administration, July 1978, and Cooper, R.B., W.R. Bertsche, and G.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.

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

[8]Kockums Automation AB, Precise Maneuvering in Confined Waters, Controlled Radial Steering, unpublished, Malmo, Sweden.

Using ownship's hydrodynamic equations, the projected track is continuously recomputed and redrawn from inputs of rudder, rpm, and all forces acting upon ownship including bank effects and passing ship interaction effects. Whenever rudder or throttle actuations are initiated, a resultant projected trackline is displayed, taking into account all previous ship's motion, its aerodynamic and hydrodynamic characteristics, and the immediate effects of environmental influences.

On the display, the track prediction appears as a curved or straight vector emitting from the pivot point of ownship. This vector can be shortened or lengthened using the PREDICTION TIME CONTROL. In essence, vector length is the distance ownship will travel in the selected "prediction time." A dashed line, ownship symbol is drawn at the end of the track vector. This image shows the computed attitude (i.e., drift angle) of ownship by the time it reaches the full prediction. By shortening "prediction time," it is possible to examine ownship's swing all along the entire projected track.

The accurate presentation of drift angle information is predicated upon a precise determination and display of the vessel's pivoting point. The pivoting point, which is located on the horizontal centerline of the vessel, moves forward if the ship is trimmed down at the head, and aft if it is trimmed down at the stern. It is normally in the forward one-third length of the vessel and seldom varies enough to cause difficulty in shiphandling. Since experimental consistancy is desired for the evaluation of displays, the pivot point and navigation system reference point (i.e., antenna location) will be located together.

The display and processor system is highly priced because of relatively large memory, sensor and computational requirements. To be completely reliable, the hydrodynamic algorithm of each ship in which the system is installed would have to be derived and validated. All of these items make the predictor steering display as it is depicted in the simulation quite costly. Disadvantages and attributes of combining predictor steering and precise navigation information on an electronic bridge display have been the subject of previous MarAd work. The resultant display was found to significantly improve pilotage by individuals less familiar with the ship's handling characteristics and in less familiar waters.[9] There was also statistically supportable evidence that the integrated predictor steering and precise navigation display promoted more rapid comprehension of shiphandling characteristics and maneuvering requirements for the pilotage. Individuals totally familiar with the ship and waterway found the combined display a significant advantage in poor visibility conditions.[10]

These conclusions have promoted an intense interest in the display's overall effectiveness and its potential for implementation, both among parties engaged in the design of steering display systems and among those developing and evaluating navigation systems. It is because of this interest that an evaluation of electronic radio aids to navigation displays would be incomplete without examining the integrated predictor steering concept.

[9] Cooper, R.B., W.R. Bertsche, and K.P. Logan, op. cit.

[10] Cooper, R.B., W.R. Bertsche, and G.J. McCue, op. cit.

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.[11] 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 subsequent radio aids experiments, it will also model navigation system noise, system filter characteristics, and display update rates. The computer facility also provides a continuous automatic recording of ship position, ship status, and bridge control manipulations for subsequent data reduction, graphic and statistical analysis.

3.3 SIMULATION SCENARIO

The RA-1 scenario differed from the miniexperiment in two respects. First, ownship was initially off-set 92 feet to the right of the centerline necessitating the pilot to maneuver within the channel to return to its center. Second, the entrance and exit legs (Leg 1 and Leg 2) were each 2.3 nautical miles long enabling the pilot to demonstrate his ability to steady up after the initial return-to-centerline maneuver and also his trackkeeping ability beyond the bend.

3.3.1 Ownship Characteristics

The ship was similar in all characteristics to the one run during the miniexperiment,[12] the AN-CAORF experiment,[13] and the AN/VISUAL experiment.[14]

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

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

[12] Ibid.

[13] Eclectech Associates, Inc., Aids to Navigation Presimulation Report, AN-CAORF Experiment, U.S. Coast Guard, September 1979.

[14] Eclectech Associates, Inc., Aids to Navigation Presimulation Report, AN-VISUAL Experiment, Washington, D.C., U.S. Coast Guard, October 1979.

Initial speed:	6.5 knots through the water (8 knots ground speed)
Initial heading:	341^{o}T gyro

3.3.2 Operating Area

The scenario waterway and starting position of ownship is shown in Figure 3. This waterway was also used in the abbreviated scenario of the miniexperiment[15] and is comparable to the AN-CAORF scenarios 17 through 24,[16] and AN-VISUAL scenarios 18, 20, 22, and 24.[17] There are, of course, 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, 2.3 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). 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 (341 degrees true), negotiated the turn, steadied up beyond the bend, and maintained the centerline through the exit leg (306 degrees true). Speed control and use of the rudder was also analyzed.

3.4 SUBJECT SELECTION

Eight licensed pilots from local and mid-Atlantic pilots' associations acted as subjects for the experiment. Each used all seven variations of the DIGITAL, GRAPHIC, PERSPECTIVE, and STEERING displays. All runs were completed within 8 hours thus minimizing fatigue effects. This included time for the postrun and postsimulation interviews and the administration of display operating instructions. All subjects selected were familiar with the response characteristics of a 30,000 dwt tanker. Nevertheless, they were also given an opportunity to maneuver the simulated ship during a preexperiment familiarization run. Subjects were encouraged to voice their opinions and recommendations both for display design and in regard to the overall simulation.

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

[16] Eclectech Associates, Inc., Aids to Navigation Presimulation Report, AN-CAORF Experiment.

[17] Eclectech Associates, Inc., Aids to Navigation Presimulation Report, AN-VISUAL Experiment.

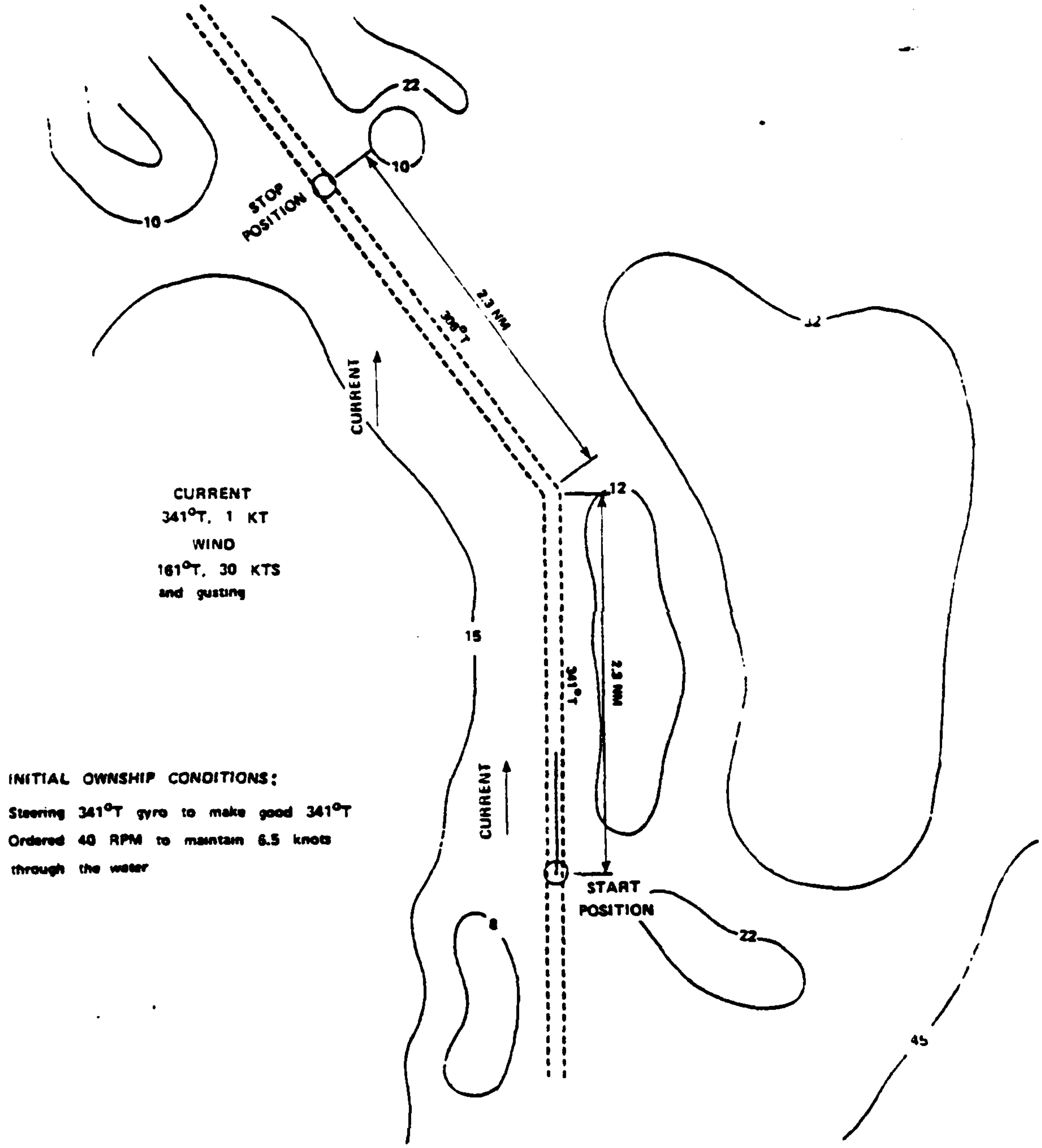

FIGURE 3. SCENARIO WATERWAY

3.5 ADMINISTRATION

3.5.1 Experimental Design

The simulator experiment was intended as an evaluation of overall operational effectiveness and of potential user acceptance of the various displays. The unique variables and levels of information which the displays present were systematically arranged in the experimental design so that each variable and level was presented ahead of all the others on at least one occasion within the experiment. This counterbalancing order is shown in Table 2. It is designed to negate not only learning effect between concepts (e.g., DIGITAL, GRAPHIC, PERSPECTIVE, STEERING), but also between levels of variables.

Administration of the display variables is 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, means 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). For this reason, a test for order effect was conducted on all data.

3.5.2 Assignment Schedule

Table 3 shows the actual subject assignments which were derived from the experimental design. Note that the order of administration of all variables is counterbalanced to compensate for learning. Abbreviations (e.g., D, G, P, and S) are used to identify each concept and numbers (e.g., 1, 2, or 3) identify each level. These are further described in Figure 2.

Subject assignments define the order in which all variables were administered. For example, Subject 1 first used the DIGITAL display which included crosstrack distance, crosstrack speed, and di[illegible] to waypoint. For his second run, he used the DIGITAL display again, this [illegible] ith crosstrack distance, crosstrack speed, distance to waypoint, actual tur[illegible] recommended turn point. The variables for his other runs and the othe[illegible]s' runs can similarly be determined from Table 3.

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 confidence.

TABLE 2. EXPERIMENTAL DESIGN

	ORDER OF VARIABLE ADMINISTRATION	ORDER OF LEVEL ADMINISTRATION			
SUBJECT NUMBER	DISPLAY	DIGITAL (D)	GRAPHIC (G)	PERSPECTIVE (P)	STEERING (S)
1	D–G–P–S	1–2	1–2	1	1–2
2		2–1	2–1		2–1
3	G–P–S–D	1–2	1–2	1	1–2
4		2–1	2–1		2–1
5	P–S–D–G	1–2	1–2	1	1–2
6		2–1	2–1		2–1
7	S–D–G–P	1–2	1–2	1	1–2
8		2–1	2–1		2–1

LETTERS CORRESPOND TO EXPERIMENTAL VARIABLES AND NUMBERS TO VARIABLE LEVELS AS SHOWN IN FIGURE 2.

TABLE 3. SUBJECT ASSIGNMENTS

ORDER OF ADMINISTRATION	SUBJECT NUMBER 1	2	3	4	5	6	7	8
1ST	D–1	D–2	G–1	G–2	P–1	S–2	S–1	S–2
2ND	D–2	D–1	G–2	G–1	S–1	S–1	S–2	S–1
3RD	G–1	G–2	P–1	S–2	S–2	D–2	D–1	D–2
4TH	G–2	G–1	S–1	S–1	D–1	D–1	D–2	D–1
5TH	P–1	S–2	S–2	D–2	D–2	G–2	G–1	G–2
6TH	S–1	S–1	D–1	D–1	G–1	G–1	G–2	G–1
7TH	S–2		D–2		G–2		P–1	

LETTERS AND NUMBERS CORRESPOND TO VARIABLE AND LEVEL DESCRIBED IN TABLE 2, EXPERIMENTAL DESIGN.

Section 4

DATA COLLECTION AND ANALYSIS

Data collection and analysis of performance for the experiment of radio aids to navigation displays without system noise (RA-1) were conducted similar to the previous miniexperiment[18] with the following exceptions:

1. The combined track plots of the miniexperiment were expanded to include the entire entrance and exit legs (Leg 1 and Leg 2).

2. To aid in comparing these plots between display variables, separate graphs showing mean crosstrack differences and crosstrack variability were added to the analysis and tested statistically.

3. Graphs showing location of the ship at each rudder command, course command and engine order were also provided as was a statistical analysis of their frequency of occurrence.

4. An analysis of subject response to Post-Run and Post-Simulation Questionnaires also provided insight into subject perceptions of the display's usefulness and of their own performance when they used it. This in effect provided a measure of user acceptance of the display.

Conclusions of the experiment, then, are based upon three unique but interactive analyses; trackkeeping performance, maneuvering performance, and user acceptance.

4.1 TRACKKEEPING ANALYSIS

The trackkeeping analysis of runs performed during the simulation of radio aids to navigation displays includes "Combined Track Plots" similar to and for comparison with the miniexperiment results. The RA-1 analysis, however, is further expanded to include graphic representations of trackkeeping similar to those employed in the AN-CAORF and AN-VISUAL experiments. These representations of track data (i.e., mean track and group crosstrack standard deviation) are presented for interpretation of the statistical results reported in Appendix F. The graphs describe the track mode by the center of gravity (CG) of ownship as it transitted the waterway.

The horizontal axis in each of the graphs in Appendix F represents discrete along channel positions at equal 475-foot intervals. These intervals are called "data lines." The performance measure plotted on the upper graph is the trace of the mean across channel position of the ship's center of gravity averaged at each along channel position over all sample transits made. 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.

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

The vertical scale in the lower graph is an absolute scaler quantity in feet. The data represent the standard deviation of the ship's CG for all transits calculated at each along track position.

The far right of each Leg 1 graph, and the far left of each Leg 2 graph (Data Line zero) represents the center of the bend.

4.2 MANEUVERING PERFORMANCE

This analysis was conducted for two major maneuvers and the transit of a straight leg with wind and current astern, and a straight leg with wind and current from the port quarter. The maneuvers were to return to the centerline from a position 92 feet to the right of centerline and to negotiate a 35-degree left bend in the channel. To analyze maneuvering performance when the different displays were used, the following measures were statistically compared. A description of these measures and how they were extracted from the data is presented in Appendix E.

1. Return to and steady up on the channel centerline following the initial off set (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 Entrance Leg 1

   d. Following negotiation of the bend (wind and current port quarter) — along track distance required to steady up on the centerline of Exit Leg 2

2. Initial turn rudder applied before the bend

   a. Along track distance before the bend that 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

   e. Technique used in the application of turn rudder; i.e., gradually increasing (I), gradually decreasing (D) or fluctuating (F).

3. Check rudder applied beyond the bend

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

   b. Magnitude of the check rudder

Statistical differences as determined from the t-statistic at the 90 percent level of confidence ($p < .10$) are indicated on the tables in which all measures are presented.

In addition to the above measures, an analysis of the overall distribution and frequency of rudder commands, course commands and engine orders was performed. The distribution of control activities is illustrated for each display concept and display variable in each of the two legs of the scenario. Since some of the display comparisons involve unequal sample sizes the graphs are useful only to identify groupings or relative concentrations of activities within the waterway. Actual quantitative comparisons in control activities between the displays is accommodated by the statistical analysis presented in Table 6 in Section 5.

The consistency of ship speed between display variables was essential for a valid analysis of trackkeeping and control activity analysis. Since pilots were ultimately free to choose a "safe" speed even though they had been asked to try to maintain 6.5 knots through the water, it was required that overall speed be statistically examined. The results of this analysis, which are shown in Table 4, indicate that all displays were run at comparable speeds (i.e., no significant difference at the $p < .10$ level of confidence), and that all speeds will be assumed to have been comparable for the subsequent discussions of analysis.

4.3 USER ACCEPTANCE ANALYSIS

As in the miniexperiment, subject acceptance of each display was elicited by asking them to compare display variables. Unlike the miniexperiment, however, this was conducted on structured interview sheets to accomodate a quantitative analysis. Observations of the test administrators and subject opinions, recommendations, etc., were also recorded and are addressed in the conclusions.

The structured interviews were administered by the test director both at the end of each run and at the end of the entire simulation. This enabled subjects not only to respond to questions about the run and each display while it was fresh in their minds, but also to make comparisons between variables after all displays had been used. 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 5 minutes for normal administration) and addressed three specific areas of interest.

1. Perceived display design and its effectiveness
2. Perceived individual performance (self-appraisal)
3. Perceived simulation validity and realism

With these objectives in mind, three categories of questions were developed and arranged in the questionnaires so that comparisons could be made both between display variables (i.e., DIGITAL, GRAPHIC, PERSPECTIVE, and STEERING) and between the levels of information presented within each variable (i.e., heading vector versus course vector, etc.). These categories and the questions they contain are presented in Appendix D. Question categories were administered as follows:

TABLE 4. MEAN OVERALL TRANSIT SPEED AND RPM

EXPERIMENTAL VARIABLES	KNOTS OVER THE GROUND	SHAFT RPM
<u>Display Design</u>		
Digital Display	8.16	42.63
Graphic Display	8.33	43.55
Perspective Display	8.92	45.93
Steering Display	8.15	42.14
Simplified Digital Display	8.20	43.00
Digital Display with Turn Recommendations	8.21	43.06
Graphic Display with Heading Vector	8.40	44.16
Graphic Display with Course Vector	8.25	42.95
Predictor Steering Display	8.12	41.88
Simplified Predictor Steering Display	8.17	42.39
<u>Effect of Learning Simplified Digital Display</u>		
First Use	7.92	41.10
Second Use	7.84	39.52

NOTE: No statistically significant difference between variables was detected at the $p < .10$ level of confidence.

RUN	QUESTION CATEGORY
• First time each DIGITAL, GRAPHIC, PERSPECTIVE OR STEERING display was used	1
• Second time the DIGITAL display was used	1 and 2
• Second time the GRAPHIC display was used	1 and 3
• Second time the STEERING display was used	1 and 4
• After all displays were used	5

Section 5

RESULTS AND CONCLUSIONS

In light of the measures and statistical analyses performed, the RA-1 experiment reveals a wide diversification of trackkeeping performance, pilotage behavior and user acceptance as a function of the seven display design variables which were tested. Because of the limited amount of instruction and familiarization each subject received prior to using the displays, it must be acknowledged that poor pilotage performance or low user acceptance does not necessarily eliminate the design from all consideration as a potential radio aids to navigation display. Instead it is suggested that those display designs which did not promote the best performance could, in fact, be improved through redesign of the display format and/or more intensive operating instruction. While this experiment endeavored to select the one or two most effective displays for further testing with system noise, it also recommends improvement and reevaluation of those displays which appeared to be less effective, but which given proper development consideration could become more cost effective.

Of the 56 runs which were conducted during the experiment, none produced effects considered serious enough to invalidate the run. Numerous excursions from the channel occurred as a result of overshooting and/or undershooting the bend. This, it will be shown, was directly attributable to the type and way information was presented in the different displays. 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 in good visibility.

5.1 EFFECTIVENESS OF DISPLAY CONCEPTS

The analysis comparing display concepts (e.g., DIGITAL, GRAPHIC, PERSPECTIVE and STEERING) required combining runs as follows:

DIGITAL represented by D-1 and D-2 displays

GRAPHIC represented by G-1 and G-2 displays

PERSPECTIVE represented by all P-1 displays

STEERING represented by S-1 and S-2 displays

As a result, the performance measures for each concept were actually derived from two different display designs (except for the PERSPECTIVE display), each of which could have promoted unique or opposite behavior. For this reason, final conclusions on the effectiveness of concepts should be reserved until the analysis comparing individual display variables (Sections 4.2 through 4.4) has also been reviewed.

5.1.1 Trackkeeping and Maneuvering Performance

The evaluation of display concept effectiveness was conducted by a relative comparison of pilotage performance between runs in which each of the displays were used. Figure 4 shows the mean track and variability of tracks at the bend for all runs within each display concept. These plots were used to compare the RA-1 results in trackkeeping performance with the miniexperiment runs.[19]

It was shown that while overall greater variability in trackkeeping was in evidence for the RA-1 experiment, mean tracks for each concept were comparable. The most prominent, and probably only significant difference in pilotage performance between the RA-1 and miniexperiment occurred for the DIGITAL concept. The "DIGITAL DISPLAYS" part of Figure 4 shows a wide variability in resultant ship tracks not exhibited in the miniexperiment. This RA-1 variability was due not to deficient trackkeeping, but instead as a result of where the pilots chose to initiate their turns. Unlike the miniexperiment in which pilots were told by the display when to start their turn, the RA-1 experiment required them to make their own determination and initiate the turn at a time of their choosing. The RA-1 results suggest that while this individual turn selection process may be more to the pilots' liking, they do require considerable experience using it on the waterway before it can be considered a comparable substitute for the visual scene.

As a result, the introduction of individual turn point or "haul line" selection to the DIGITAL concept only further increased the wide variability of trackkeeping performance which it exhibited in the miniexperiment.

Figures 5 and 6 show a summary of the plot analyses compared statistically in Appendix F. In Leg 1 of the waterway (Figure 5) ownship originates at the extreme left of the plot, 92 feet to the right of the centerline (CG mean-feet). Variability (SD - feet) is zero at this point. In returning to the centerline the majority of overshoot was experienced when the STEERING display, was used. This overshoot, while significantly greater than for the other displays, does not in itself indicate deleterious performance.

Once steadied up on the centerline, the DIGITAL display resulted in the lowest overall crosstrack variability. This variability reduced even more on approach to the bend. It was caused by the "numerical resolution" of the DIGITAL display which encouraged subjects to attempt to "zero" the crosstrack distance and crosstrack velocity. The results do indicate the usefulness of such a display in instances where very precise trackkeeping is desired and few maneuvering perterbations are experienced. Otherwise it might be accused of promoting an artificial goal.

Just prior to entering the bend (Data Line 0) the same high subject variability which was revealed in Figure 4 is in evidence for the DIGITAL display.

This turnmaking variability continues onto Leg 2 (Figure 6) showing additional major consequences in difficulty returning to the new centerline. It is obvious from the high crosstrack variability and prevailing inconsistent mean track exhibited by the DIGITAL display, that it did not provide adequate information to recover from the turn and steady up on the new required course. More explicitly, the subjects had difficulty determining from the displayed information when and how much check rudder to apply, what was their actual orientation (i.e., attitude) in the channel, and what were the effects of wind and current on their ship.

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[19] Ibid.

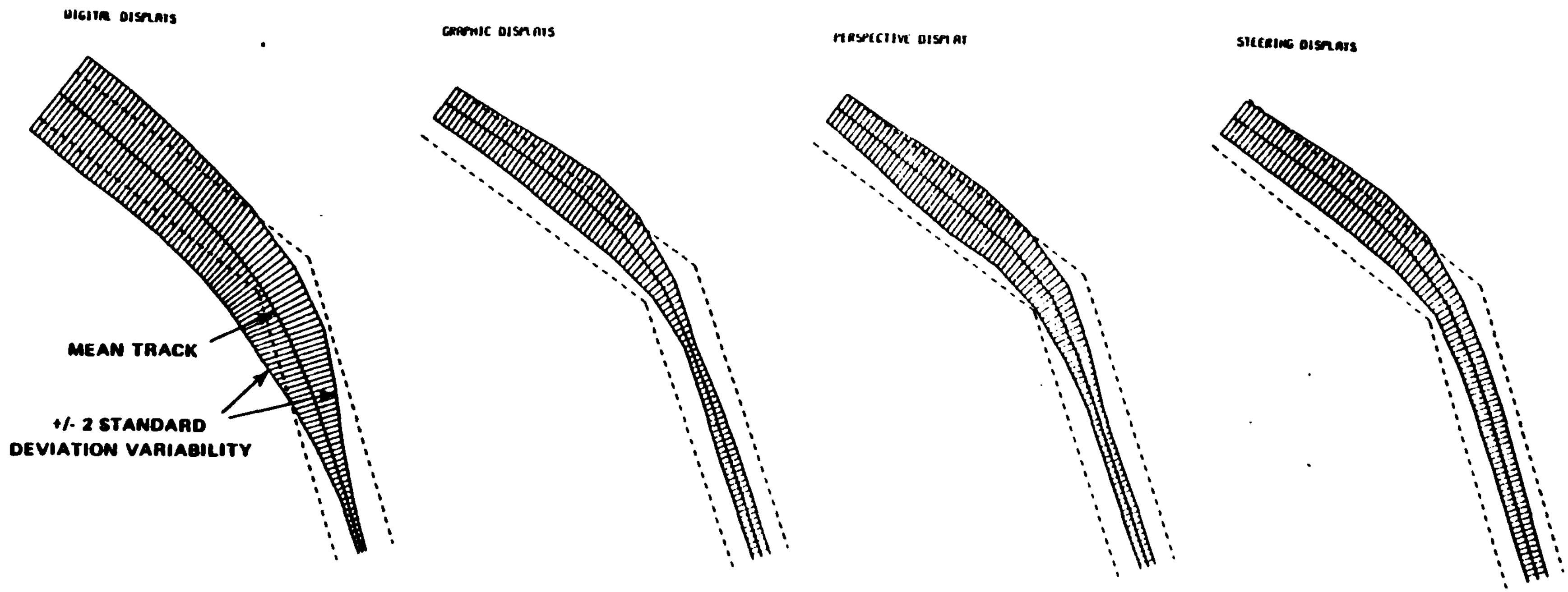

FIGURE 4. COMBINED TRACK PLOTS FOR EACH DISPLAY CONCEPT

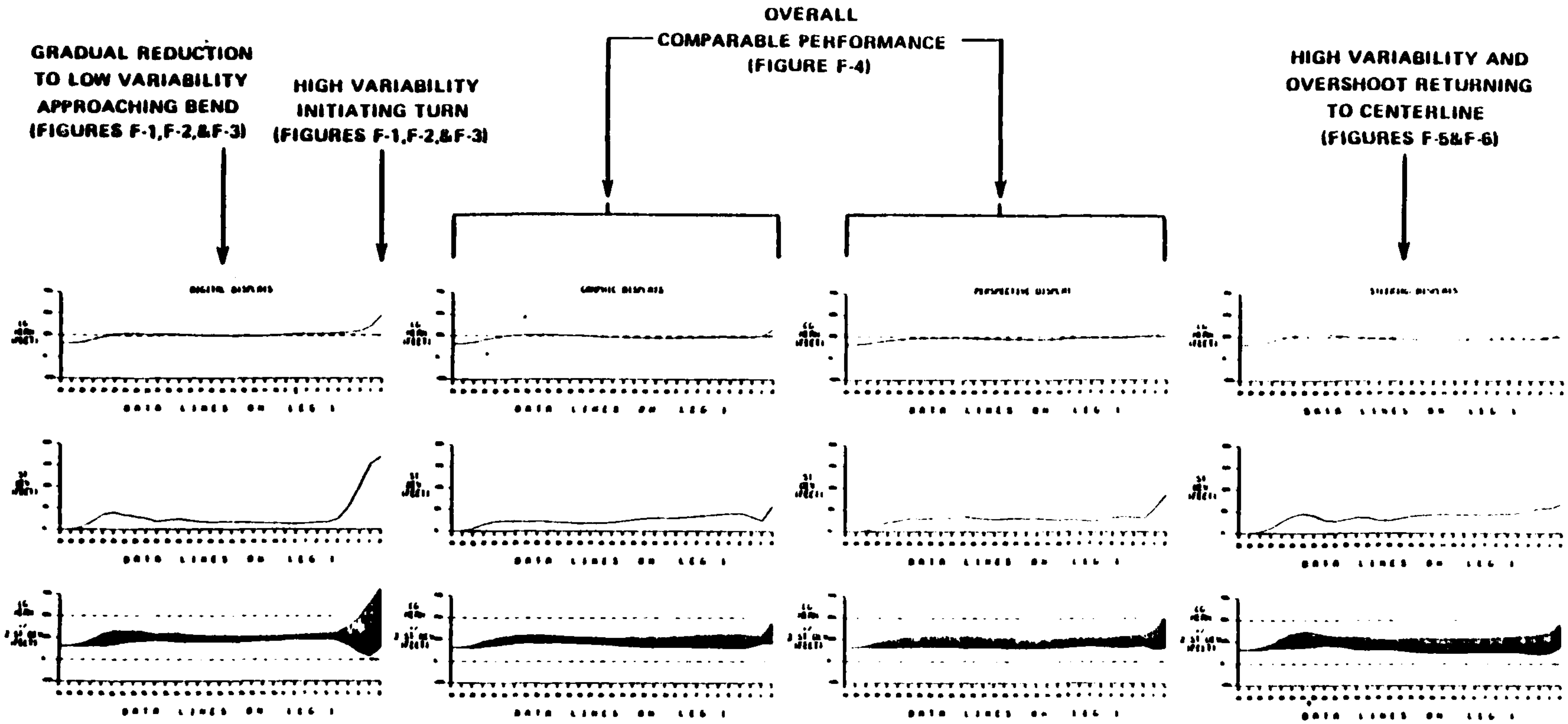

FIGURE 5. SUMMARY PLOT ANALYSIS OF LEG 1 – DISPLAY CONCEPTS

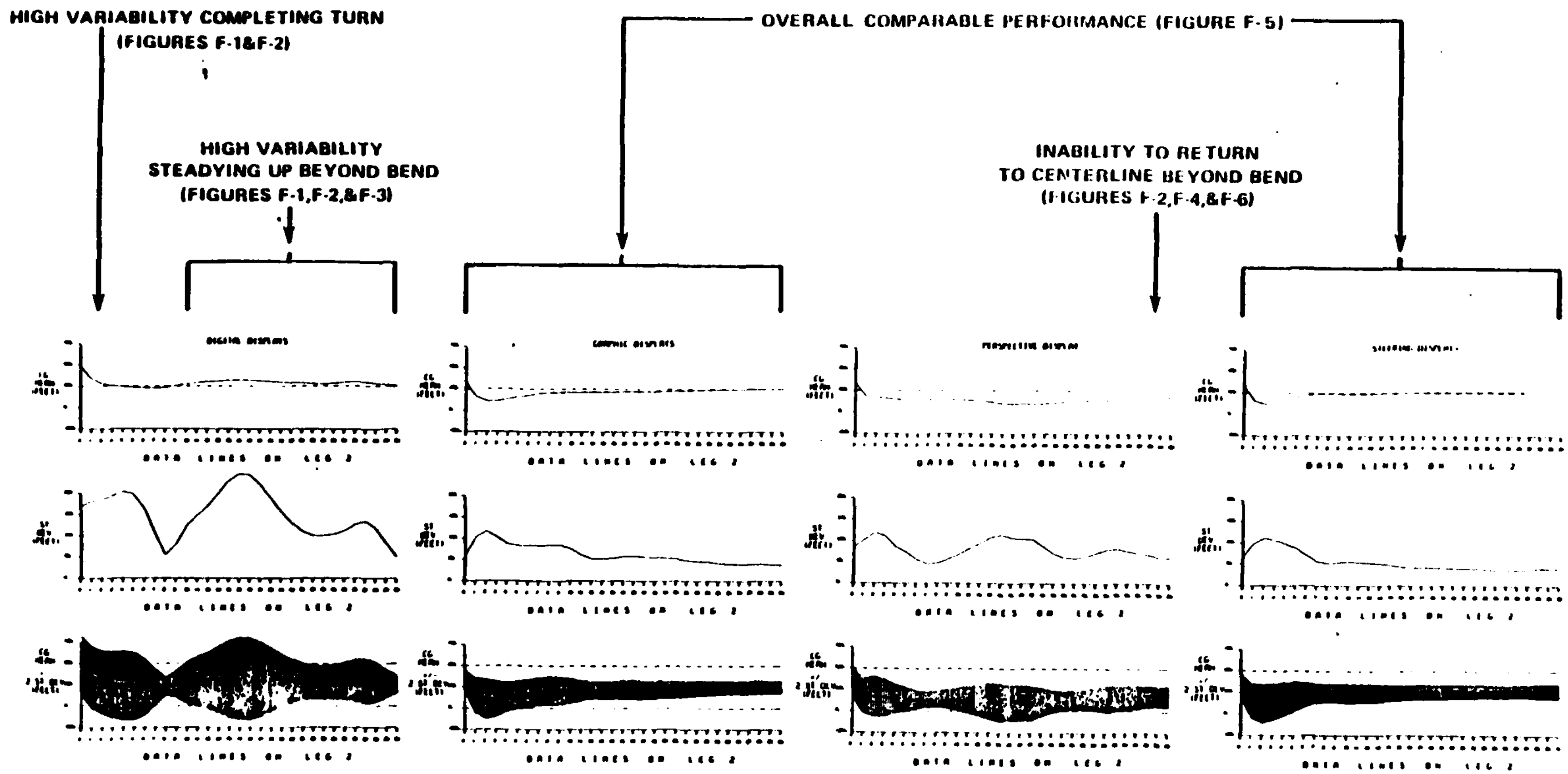

FIGURE 6. SUMMARY PLOT ANALYSIS OF LEG 2 – DISPLAY CONCEPTS

With the PERSPECTIVE display (also Figure 6) recovery from the turn was appropriate but subjects were unable to adequately judge this distance off the centerline, and subsequently never returned to it.

In conclusion, the best trackkeeping performance as summarized in Figures 4 through 6 was exhibited by the GRAPHIC and STEERING displays. Appropriateness of the methodology employed in accomplishing this trackkeeping is discussed using Table 5.

Table 5 is a statistical comparison of maneuvering performance for all display concepts using preselected measures of shiphandling (see Section 4.0). The results indicate an overall too gradual return to the centerline and steady up in both legs when the PERSPECTIVE display was used. This table also indicates that initial turn rudders were applied too late and too little with the PERSPECTIVE display, leading to subsequent fluctuations and inconsistencies in rudder activity throughout the turn.

With the DIGITAL display, initial rudder application tended to be earlier than all other displays and larger in magnitude. The result, shown in Figure 4 was a tendency to unknowingly pass close to the point of the bend. The STEERING display promoted the most "conservative" overall application of rudder (Table 5). They were early, small and few, all with relatively commendable trackkeeping performance.

A statistical comparison was made between the way pilot orders were administered to determine if subjects modified their pilotage techniques as a result of the display information they were receiving. In the display concept comparison of Table 6 it is shown that pilots used significantly more rudder commands when they used the DIGITAL display, but that the frequency of course commands remained comparable. The result is not surprising in light of the way the DIGITAL display cues for continuous rudder changes throughout the bend. However, a review of Figures 7 and 8 show high rudder command utilization even in the straight legs. This can be explained by two hypotheses which correlate to the trackkeeping behavior.

First, in Leg 1 subjects attempted to "zero" their crosstrack distance and could only do so by using rudder commands. This is shown in Figure 7.

Second, in Leg 2 subjects experienced such a major proportion of trackkeeping difficulty as a result of wind, current and trying to steady up that they either (1) felt more confident in trying to steer the ship themselves (i.e., rudder commands) or (2) were unable to determine an appropriate course to command and were trying to "feel" the ship.

In summary, the results of Table 6 and Figures 7 and 8 show conclusively the overall difficulty pilots had when using the DIGITAL display concept. Note that for all displays other than DIGITAL, the majority of rudder commands are grouped around the maneuvering areas (i.e., initial return to centerline and the bend in the waterway) and course commands are distributed normally throughout the straight legs. This is considered the more traditional pilot behavior.

With the PERSPECTIVE display there was a proportionately high number of course commands and engine orders (Table 6). Obviously, pilotage difficulties were also experienced with this display.

TABLE 5. COMPARISON IN MANEUVERING PERFORMANCE BETWEEN DISPLAY CONCEPTS

MEASURE[1]	Display				SIGNIFICANT DIFFERENCE[2]
	Digital	Graphic	Perspective	Steering	
Return to and Steady Up on Centerline					
1. Distance to return to centerline (nm)	.378	.511	.533	.364	Slower return to centerline w/perspective and graphic
2. Overshoot following return to centerline (ft)	38.4	24.5	44.3	32.3	-none-
3. Distance to steady up in entrance leg 1 (nm)	.588	.593	.607	.699	Slower steady up w/perspective and steering
4. Distance to steady up in exit leg 2 (nm)	.773	.763	1.160	.621	Slower steady up w/perspective
Initial Turn Rudder Application					
1. Distance before bend at initial rudder (nm)	.210	.142	.094	.155	Earlier initial rudder w/digital Later initial rudder w/perspective
2. Magnitude of initial turn rudder (deg)	19.3	17.2	10.0	14.0	Larger initial rudder w/digital & graphic Smaller initial rudder w/perspective
3. Maximum initial turn rudder (deg)	28.4	31.5	35.0	18.1	Smaller maximum rudder w/steering
4. Frequency of turn rudder actuations	6.3	5.9	6.3	5.2	-none-
5. Technique of turn rudder application	I,D	I	I,F	I	Decrease from initial rudder w/digital Fluctuations from initial rudder w/perspective
Check Rudder Application					
1. Distance beyond bend of check rudder (nm)	.127	.163	.110	.207	Later check rudder w/steering
2. Magnitude of check rudder (deg)	14.1	16.2	21.6	6.9	Smaller check rudder w/steering

[1]Rationale for the deviation of these measures are presented in Appendix B.

[2]Statistically significant at $p < .10$ level of confidence.

TABLE 6. MEAN FREQUENCY OF CONTROL ACTIVITIES

EXPERIMENTAL VARIABLES	RUDDER COMMANDS	COURSE COMMANDS	ENGINE ORDERS
Display Design			
Digital Display	34.55*	10.76	1.03
Graphic Display	19.31	13.31	1.63
Perspective Display	19.00	18.75*	2.50*
Steering Display	11.25	11.60	0.75*
Simplified Digital Display	25.30	12.40	0.80
Digital Display with Turn Recommendations	43.80	9.10	1.30
Graphic Display with Heading Vector	18.62	14.87	1.62
Graphic Display with Course Vector	20.00	11.75	1.63
Predictor Steering Display	13.00	13.10	0.38
Simplified Predictor Steering Display	15.10	10.10	0.62
Effect of Learning Simplified Digital Display			
First Use	17.25	16.75	0.00
Second Use	30.50	12.50	0.25

*Statistically significant difference between variables at the $p < .10$ level of confidence.

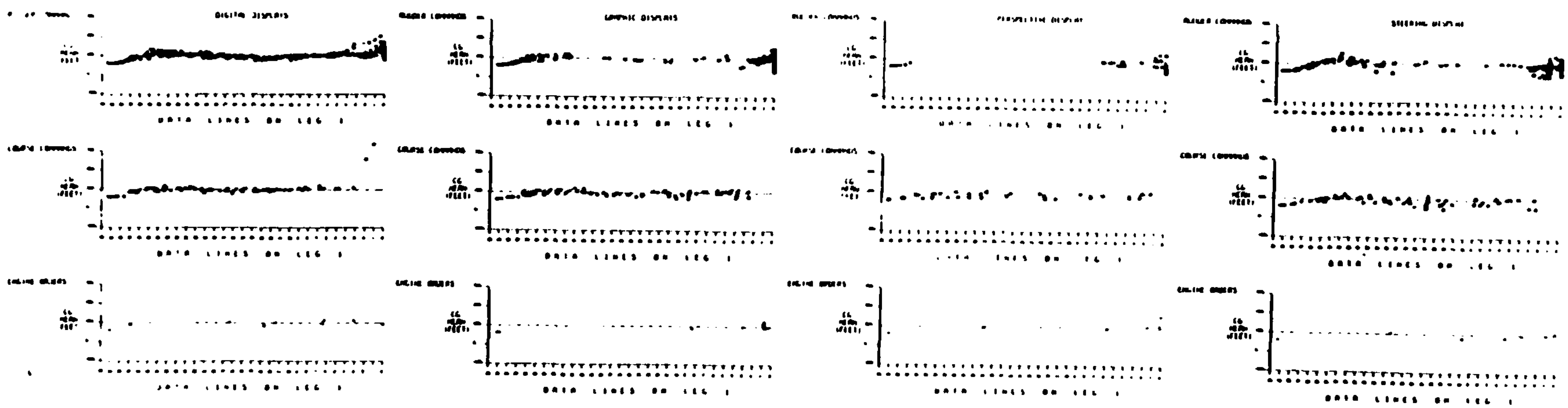

FIGURE 7. PROFILE OF CONTROL ACTIVITIES IN LEG 1 – DISPLAY CONCEPTS

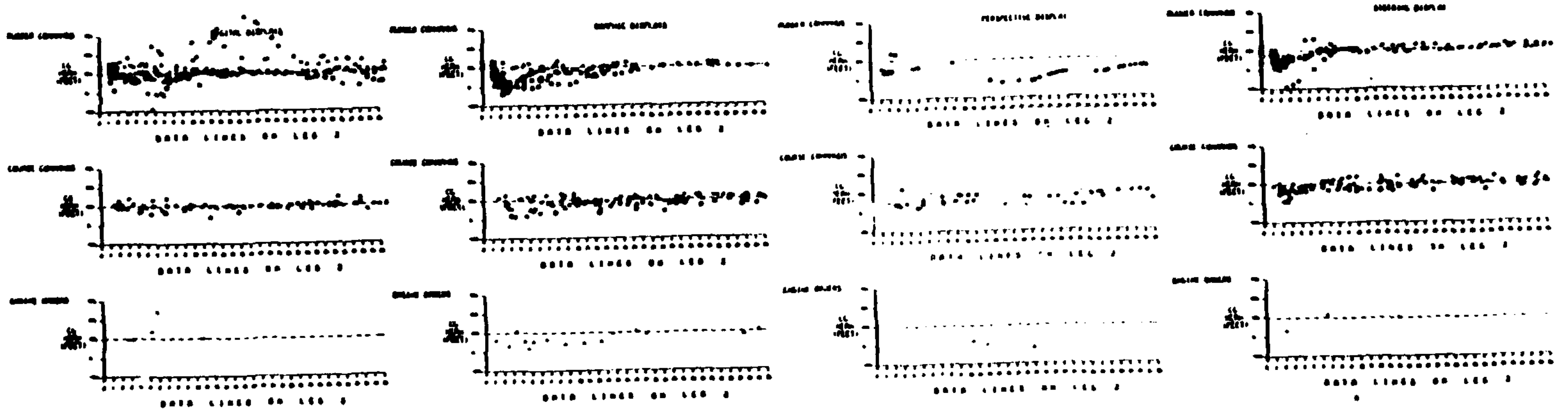

FIGURE 8. PROFILE OF CONTROL ACTIVITIES IN LEG 2 – DISPLAY CONCEPTS

5.1.2 User Acceptance

A major factor in the design effectiveness of human interfacing systems is how the operator perceives the system, whether it is aiding him in his required task and whether it can be relied upon consistently. The results of Post Run and Post Simulation Questionnaires were analyzed to compare subject perceptions of how well they had performed when they used each display concept and their overall perception of each concept's design.

Post Run Questionnaire Findings

In the analysis of each individual's own pilotage performance, two hypotheses are proposed.

First, because the subjects never received any feedback on how well they actually performed in each run, only the information presented on their display gave them any clue of their performance. They were never shown a resultant track-made-good or told whether or not they had remained within the channel. The hypothesis suggests that if the displayed information was valid and useful then the subjects' perception of how well they had performed should correlate positively with how well they actually did.

Second, if a pilot is presented with adequate information about his task, he will tend to exercise freedoms which will make the accomplishment of his goals easier, safer, more expedient, etc. For example, if the pilot is satisfied with the adequacy of his information but previous experience indicates an increased speed would make for better shiphandling, he probably would opt for the change in speed. If, on the other hand, his information was incomplete, deficient or undependable he probably would make no change and might even elect a more conservative posture.

The results of Table 7 when weighed in light of these hypotheses suggest that the STEERING display instilled in subjects the most valid image of their actual performance. The GRAPHIC display also proved comparably reliable, perhaps with the exception of items #1 and #2 in Table 7. DIGITAL and PERSPECTIVE displays presented a less valid portrayal. Initial turn rudder with the DIGITAL display was too early but there was no way the operator could have known this (item #4). The high numbers and "unanticipated behavior" of the DIGITAL display, however, did clue most subjects of their relatively poor performance (item #6). Neither the too slow maneuver to the Leg 1 centerline nor the inability to steady up on the Leg 2 centerline were revealed by the PERSPECTIVE display (items #2 and #5), although subjects were made aware of their overall "fair" performance by difficulties in selecting appropriate turn rudder.

In general, it is concluded that subjects' perceptions of their own performance when using a display may not alone be a good indicator of their acceptance of the display, and in fact, a poor display could lull them into the belief that they had actually performed well when they had not. This analysis has shown, however, that pilots judge their own performance on many things besides display information. The transit pace, continuity and techniques required during the pilotage are, themselves, often sufficient to clue the pilot about his performance. It goes without saying, of course, that a good radio aids to navigation display with effective feedback and reinforcement is always most welcome.

TABLE 7. SUBJECTS' PERCEPTION OF OWN PERFORMANCE AS A FUNCTION OF WHICH DISPLAY CONCEPT THEY USED*

	WHEN I USED:			
	DIGITAL	GRAPHIC	PERSPECTIVE	STEERING
1. My overall transit speed tended to be -	too slow	adequate	too slow	too slow
2. My initial maneuver to the centerline was -	adequate	adequate	adequate	too slow
3. Ownship was on the channel centerline	usually	usually	usually	usually
4. My initial turn rudders tended to be -	adequate	too late	too late	too late
5. My check rudders tended to be -	too late	adequate	too small	adequate
6. My overall pilotage was-	fair to poor	fair	fair	good to fair

*Derived from the Post-Run Questionnaire (Appendix C) in which subjects were asked to describe each run using a forced multiple choice questionnaire

Post Simulation Questionnaire Findings

An indicator of subjects' perceptions of each display's design was derived from their responses to the Post-Simulation Questionnaire snown in Table 8. These data suggest the following:

1. That the GRAPHIC display was preferred by the individual pilot for the performance of his own pilotage, but each felt that the STEERING display would be more beneficial to other pilots. While they themselves performed well with the GRAPHIC display, most pilots indicated that the STEERING display offered substantially more information and should be of greater value during pilotage.

2. That the least beneficial display to pilotage was the DIGITAL display, primarily because they were unfamiliar with it and not because of its lack of information content. The PERSPECTIVE display was indicated to have provided the least information of any of the displays.

3. That the tradeoff of cost differences of displays with the need for special training and experience required to safely use the display was perceived with high accuracy by the subjects.

4. That the degree of information resolution such as found on numerical or scalar displays may affect the perception of display update rate which in turn may contribute to the overall perception of display accuracy. Subjects attributed both the fastest update rate and the greatest accuracy to the DIGITAL display while the PERSPECTIVE display was said to have the slowest update rate and least accuracy. In actuality, both displays were updated equally but were very different in format design.

5. That simplicity of display design is a primary consideration in the acceptance by pilots of a pilotage display, even at the expense of high accuracy, computed ship status information and low cost. In summary, pilots would rather use a simple display and compensate for its known deficiencies than to employ a sophisticated device with no knowledge of its deficiencies.

5.2 EFFECTIVENESS OF DIGITAL DISPLAY VARIABLES

The analysis of DIGITAL display variables compared pilots' performance between when they used the Simplified Digital Display (D-1) and the Digital Display with Turn Recommendations (D-2).

5.2.1 Trackkeeping and Maneuvering Performance

Figure 9 shows the mean track and variability of tracks at the bend for all runs within each D-1 and D-2 variable. A subsequent statistical analysis shown in Figure F-6 of Appendix F shows no significant difference in the two mean tracks, but a highly significant difference in crosstrack variability beyond the bend.

Obvious conclusions as supported by Figure 10 are that there is no difference between the displays as a function of straight track or course keeping and in the selection of an initial turn point. Once the turn was initiated, however, only the Digital Display with Turn Recommendations promoted any maneuvering consistency among the pilots. Beyond the bend (Figure 11) subjects using the display with turn recommendations experienced considerable difficulty steadying up on the centerline.

TABLE 8. SUBJECTS' PERCEPTION OF DISPLAY CONCEPTS *

	DISPLAY			
	DIGITAL	GRAPHIC	PERSPECTIVE	STEERING
Desirable Attributes				
1. Most effective display for overall pilotage				●
2. Easiest display to learn		●		
3. Most beneficial to own performance		●		
4. Easiest display to determine				
- ship's position in the channel		●		
- ship's speed through the waterway		●		
- serving of the ship or rate of turn				●
5. Easiest display to select				
- point at which to initiate the turn				●
- amount of rudder required for the turn				●
6. Perceived as the most accurate display	●			
7. Perceived as the fastest update display	●			
8. Perceived most simplistic design		●		
9. Perceived most expensive design				●
10. Most likely to be accepted by pilots		●		
Undesirable Attributes				
1. Least effective display for overall pilotage	●			
2. Most difficult display to learn	●			

*Summary of responses from Post-Run Questionnaires and Post-Simulation Questionnaires (Appendix C) in which subjects were asked to compare display designs by ranking them in a continuum of desirable to undesirable attributes.

TABLE 8. SUBJECTS' PERCEPTION OF DISPLAY CONCEPTS (CONTINUED)

	DISPLAY			
	DIGITAL	GRAPHIC	PERSPECTIVE	STEERING
3. Least beneficial to own performance	●			
4. Most difficult display to determine				
- ship's position in the channel			●	
- ship's speed through the waterway			●	
- swing of the ship or rate of turn			●	
5. Most difficult display to select				
- point at which to initiate the turn			●	
- amount of rudder required for the turn			●	
6. Perceived as the least accurate display			●	
7. Perceived as the slowest update display			●	
8. Perceived as the most complex design	●			
9. Perceived as the least expensive design	●			
10. Least likely to be accepted by pilots	●			

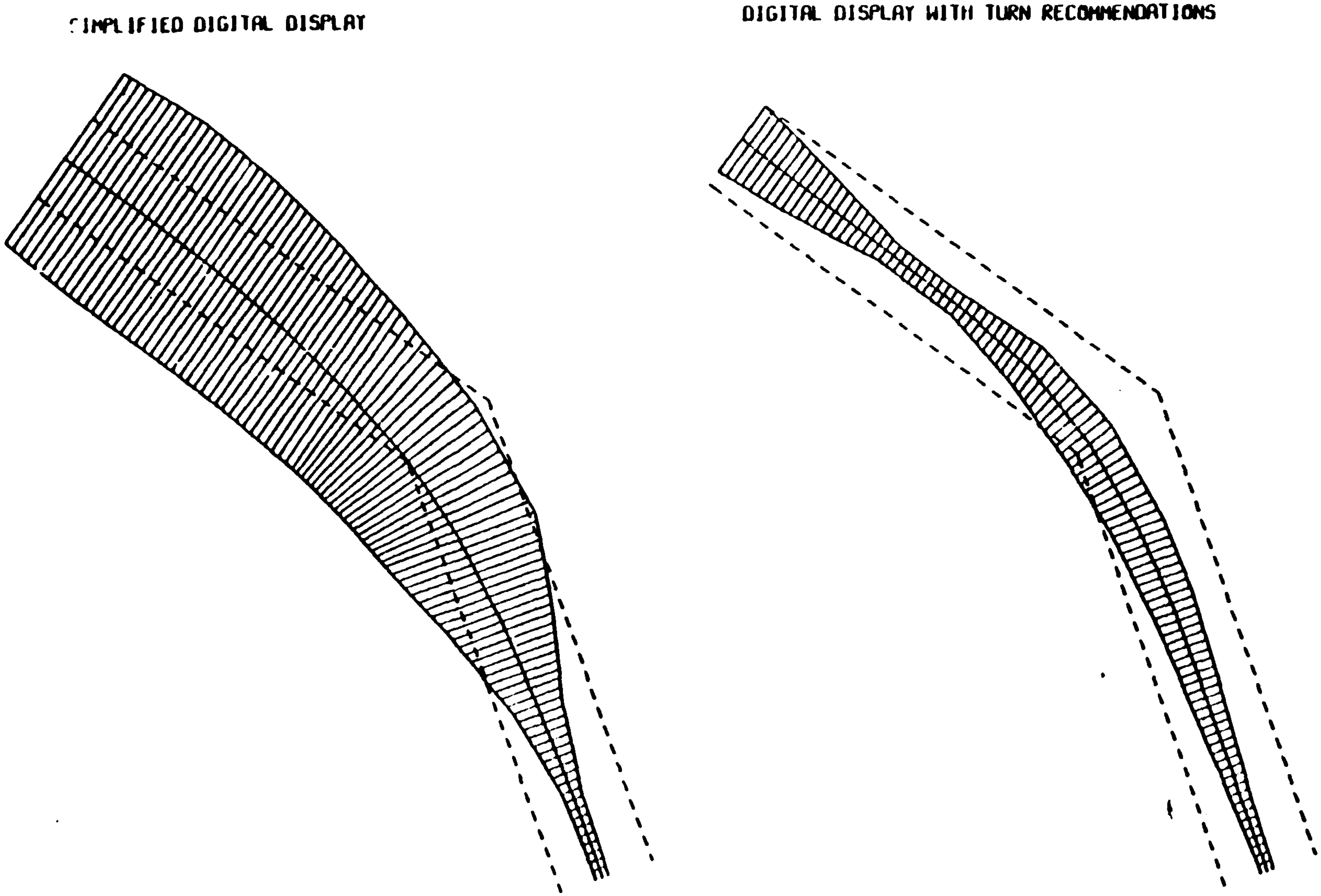

FIGURE 9. COMBINED TRACK PLOTS FOR DIGITAL DISPLAYS

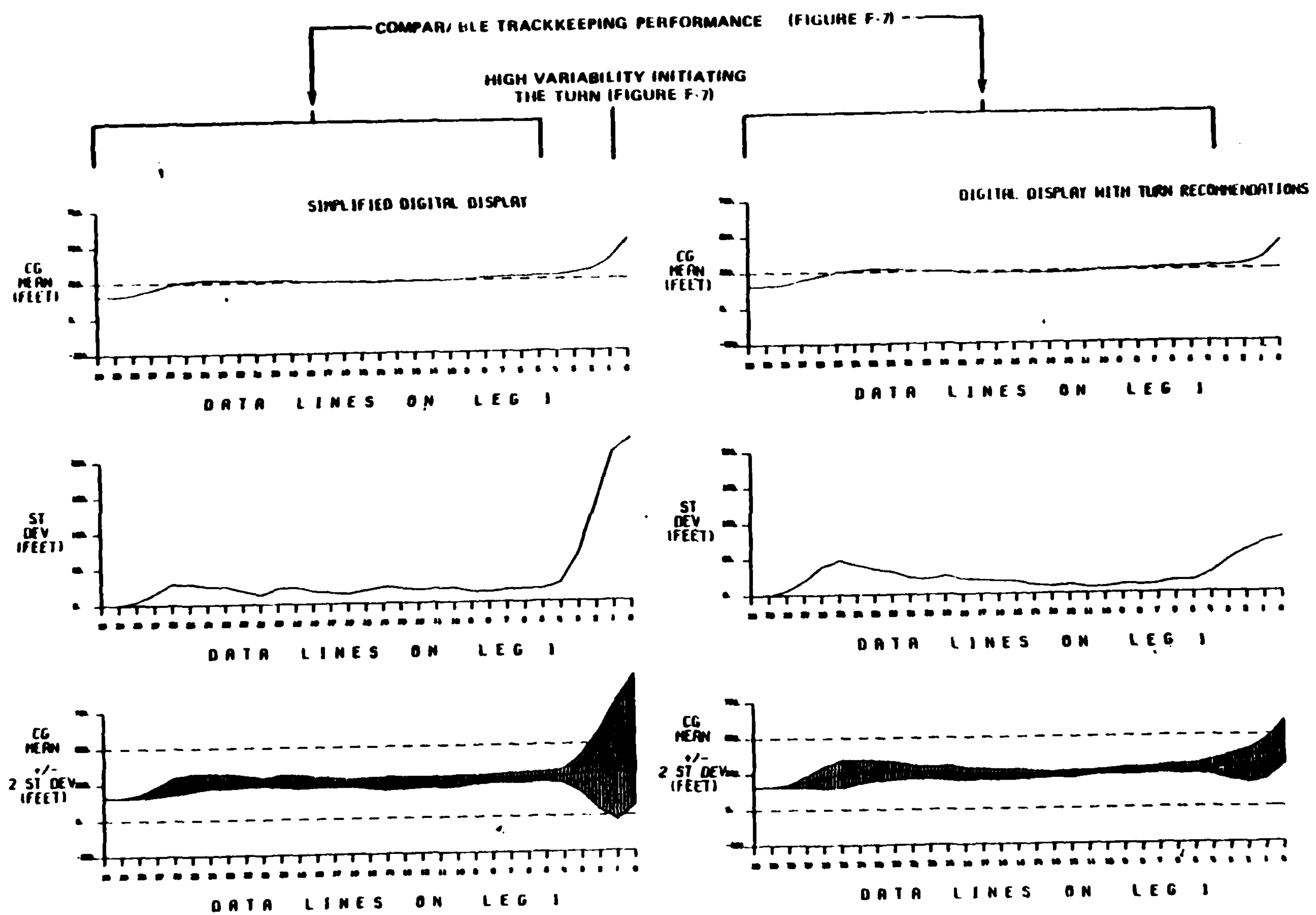

FIGURE 10. SUMMARY PLOT ANALYSIS OF LEG 1 – DIGITAL DISPLAYS

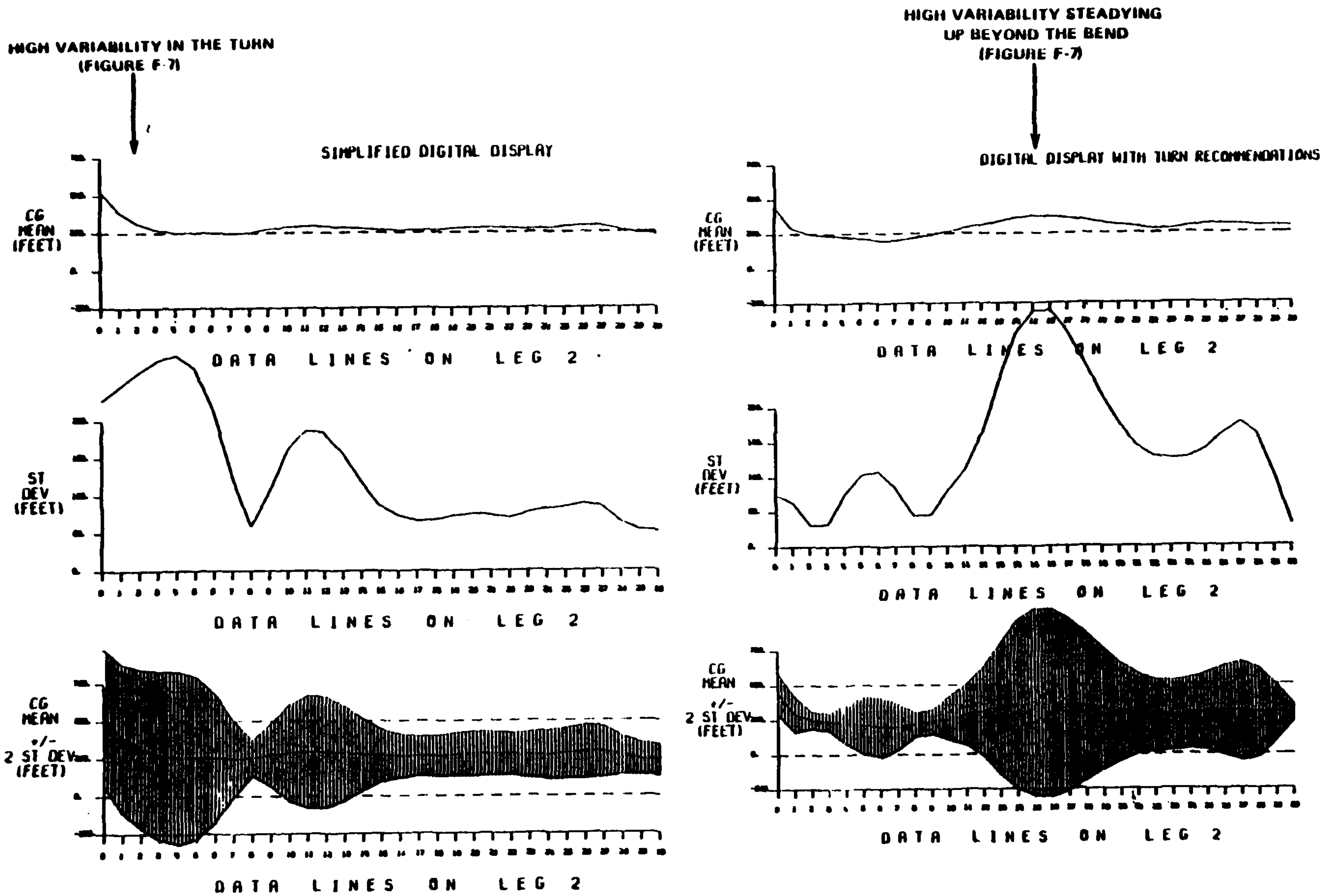

FIGURE 11. SUMMARY PLOT ANALYSIS OF LEG 2 – DIGITAL DISPLAYS

This "flip-flop" of performance is well illustrated by the Appendix F figure (F-6). It is attributed to the fact that when no turn recommendations were provided, the pilots had to judge their rate of turn by watching the compass and were well aware of when to apply check rudder to steady up on the new leg. On the other hand, when turn recommendations were provided, there was a preoccupation with trying to match the recommended turn rate of the display, which frequently resulted in overshoots of the new course. In all probability, this difficulty would be resolved through additional experience with the D-2 display particularly once the presently unfamiliar skill of "turn rate matching" is perfected.

Table 9, the statistical comparison of maneuvering performance shows relatively insignificant differences between the pilotages of D-1 and D-2. There was a greater number of rudder actuations when turn recommendations were displayed. This is also reflected in the higher number of rudder commands (though not statistically significant) of Table 6, and would be expected as a function of the way the display operates.

It is noteworthy (again Table 9) that when no turn recommendations were provided (C-1) initial rudder was approximately 20 degrees and was occasionally reduced through the bend. When turn recommendations were provided (C-2) initial turn rudder was about 15 degrees and was gradually increased to accommodate the display.

Figures 12 and 13 show the somewhat abnormal trend of maintaining rudder commands through the straight legs for both displays. The dispersion of rudder commands in Leg 2 indicates the considerable difficulty subjects had in steadying up well beyond the turn, particularly with the Digital Display with Turn Recommendations.

In general, neither of the DIGITAL displays promoted exemplary trackkeeping or maneuvering performance.

5.2.2 User Acceptance

Responses from the Post Run Questionnaires on a comparison between the two DIGITAL displays is presented in Table 10. Of all the subjective comparisons for all the different display concepts, the DIGITAL display received the most concurrent responses. Obviously, subjects were all well aware of their poor performance when they used the display without turn recommendations. However, all thought they also did well with the D-2 display in Leg 2, which they did not.

This finding suggests that the pilot's main concern was rounding the bend satisfactorily, and that steadying up in the next leg was a minor consequence given the amount of time and distance allotted to the task. It can be concluded from Table 10 that a very strong preference existed among subjects for the inclusion of turn recommendations on the DIGITAL display. This is further reinforced in the analysis of trackkeeping which shows that when subjects used the D-2 display their pilotage performance was in fact superior through what they considered the critical maneuver.

TABLE 9. COMPARISON IN MANEUVERING PERFORMANCE BETWEEN DIGITAL DISPLAYS

MEASURE[1]	Digital Display		SIGNIFICANT DIFFERENCE[2]
	Simplified	With Turn Recommend.	
Return to and Steady Up on Centerline			
1. Distance to return to centerline (nm)	.334	.402	-none-
2. Overshoot following return to centerline (ft)	35.5	41.3	-none-
3. Distance to steady up in entrance leg 1 (nm)	.522	.637	-none-
4. Distance to steady up in exit leg (nm)	.78[illegible]	.767	-none-
Initial Turn Rudder Application			
1. Distance before bend at initial rudder (nm)	.218	.202	-none-
2. Magnitude of initial turn rudder (deg)	21.8	16.8	-none-
3. Maximum initial turn rudder (deg)	26.8	30.0	-none-
4. Frequency of turn rudder actuations	4.6	8.1	More rudder activity w/turn recommendations
5. Technique of turn rudder application	D	I	Increase from initial rudder w/turn recommendations Decrease from initial rudder w/o turn information
Check Rudder Application			
1. Distance beyond bend of check rudder (nm)	.177	.138	-none-
2. Magnitude of check rudder (deg)	10.6	17.5	-none-

[1]Rationale for the deviation of these measures are presented in Appendix B.

[2]Statistically significant at $p < .10$ level of confidence.

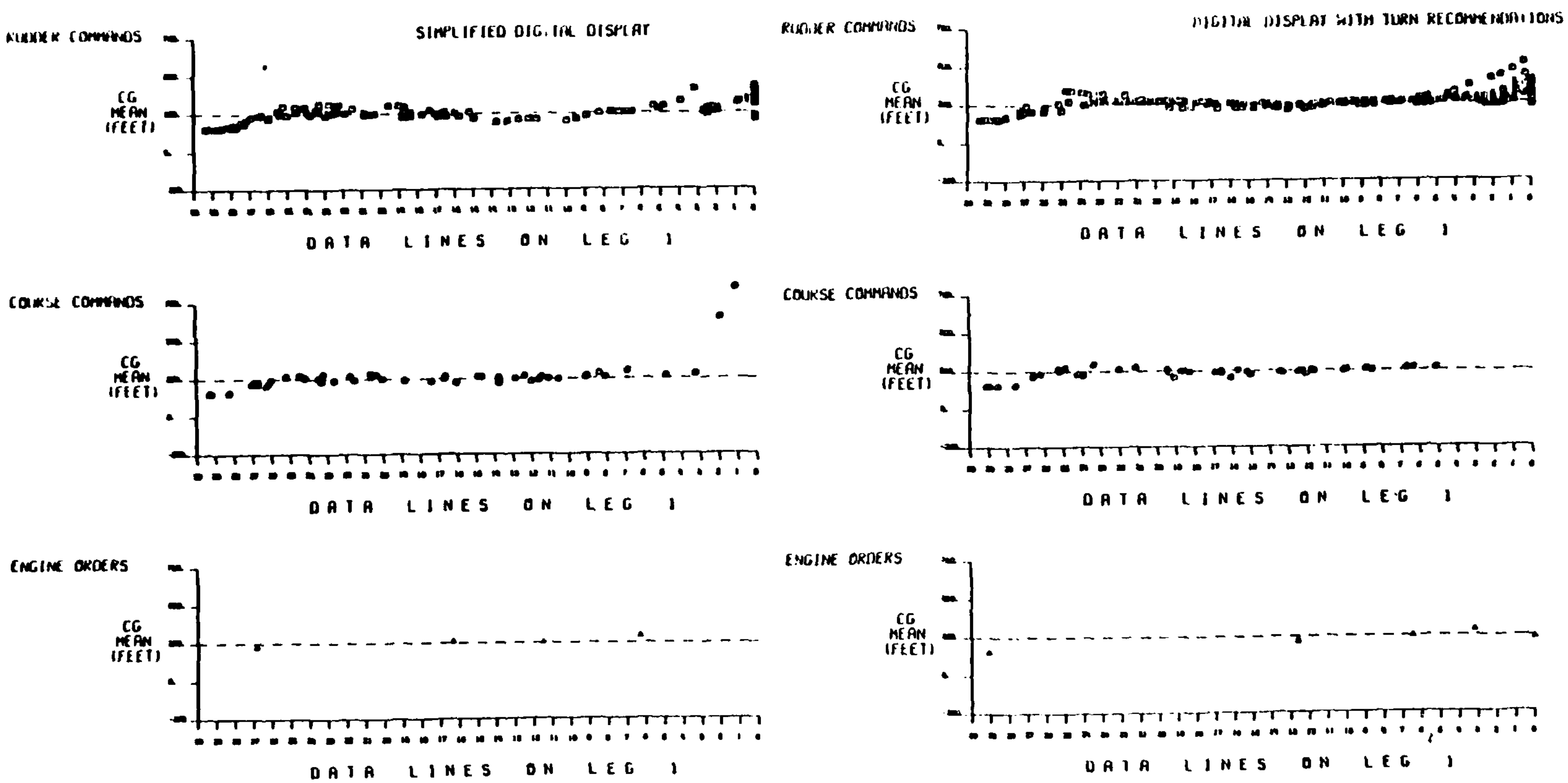

FIGURE 12. PROFILE OF CONTROL ACTIVITIES IN LEG 1 – DIGITAL DISPLAYS

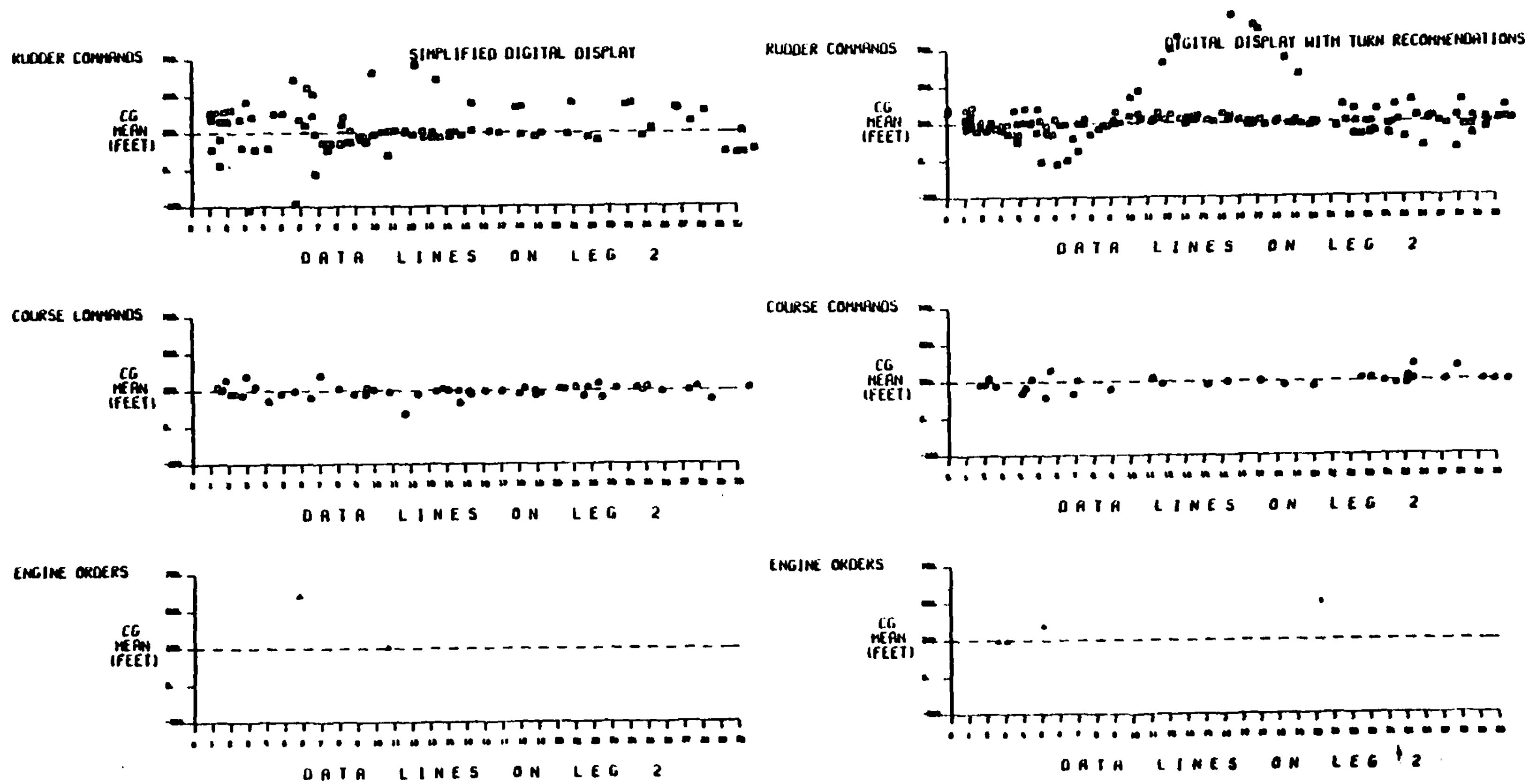

FIGURE 13. PROFILE OF CONTROL ACTIVITIES IN LEG 2 - DIGITAL DISPLAYS

TABLE 10. SUBJECTS' PERCEPTION OF OWN PERFORMANCE AS A FUNCTION OF INFORMATION PRESENTED ON DISPLAY*

Comparison Between Runs Within Each Display Concept

1. With turn recommendations on the DIGITAL display, I:
   - found the display more useful
   - initially steadied up on the centerline better
   - transited the straight legs better
   - rounded the bend better
   - steadied up in the second leg better
   - was better able to determine ownship speed
   - was better able to determine ownship position
   - was better able to determine ownship swing
   - used the gyro repeater less

2. With the heading vector on the GRAPHIC display, I:
   - used less overall rudder

3. With the course vector on the GRAPHIC display, I:
   - initially steadied up on the centerline better
   - steadied up in the second leg better
   - was better able to determine ownship position

4. With the simplified STEERING display, I:
   - used less overall rudder
   - used the gyro repeater less

*Derived from the Postsimulation Questionnaire (Appendix C) in which subjects were asked to compare their pilotage performance as a function of which display they used. Only responses receiving more than 70% concurrence are reported.

5.3 EFFECTIVENESS OF GRAPHIC DISPLAY VARIABLES

The analysis of GRAPHIC display variables compared pilots' performance between when they used the Graphic Display with Heading Vector (G-1) and the Graphic Display with Course Vector (G-2).

5.3.1 Trackkeeping and Maneuvering Performance

In the comparison of pilotage performance between the use of the two GRAPHIC displays, it is important to remember how the displays differed. The G-1 display exhibited a heading vector very similar to a PPI (radar) heading flash, and subsequently very familiar to all pilots. The G-2 display exhibited a course vector showing the direction of motion of ownship out to a distance equivalent to 3 minutes of travel. This type of vector was easily understood by the pilots but few had ever seen, much less used, such a display. The overall results of the comparison in performance between the two displays might best be summed up as a function of this lack of experience. Pilots tended to perform very well in the straight legs using the course vector and, in fact, showed remarkable ability to maneuver within the straight legs. Beyond the bend, however, large crosstrack variability was experienced, probably due to individuals' inability to anticipate how the course vector should actually appear through the bend.

Figure 14 illustrates this problem best. Note also from Figure 15 that there was no statistically supportable difference in trackkeeping anywhere in the first leg. Beyond the bend, however, (Figure 16) the course vector was shown to excel in returning to and maintaining the centerline; but not in steadying up from the turn.

The maneuvering performance analysis of Table 11 supports this conclusion indicating a slow return to the centerline both initially in the run and onto Leg 2. No other differences are indicated. Likewise, Table 6 shows no differences in control activities (frequency of course commands, rudder commands or engine orders); nor is the distribution of commands in Figures 17 and 18 abnormally distributed. Note the well defined groups of rudder commands at the maneuver points and equal distribution of course commands through the straight legs.

In conclusion, the analysis of trackkeeping and maneuvering performance on the two GRAPHIC displays reveals that both achieved very commendable performance. Further, given the relative unfamiliarity of the course vector display to the subject group, yet the remarkable trackkeeping performance which they achieved with it, it is recommended that both these displays be considered for future experiments.

5.3.2 User Acceptance

Results of the "perceived own performance" and "perceived display design" analysis support the conclusion that both vector displays were received favorably by the pilots and that either would be considered acceptable for pilotage over all the others tested. Table 10 findings (items #2 and #3) suggest that pilots felt more comfortable with the course vector display for steadying up and maintaining a straight trackline. This conclusion is supported also by the statistical analysis of actual trackkeeping performance.

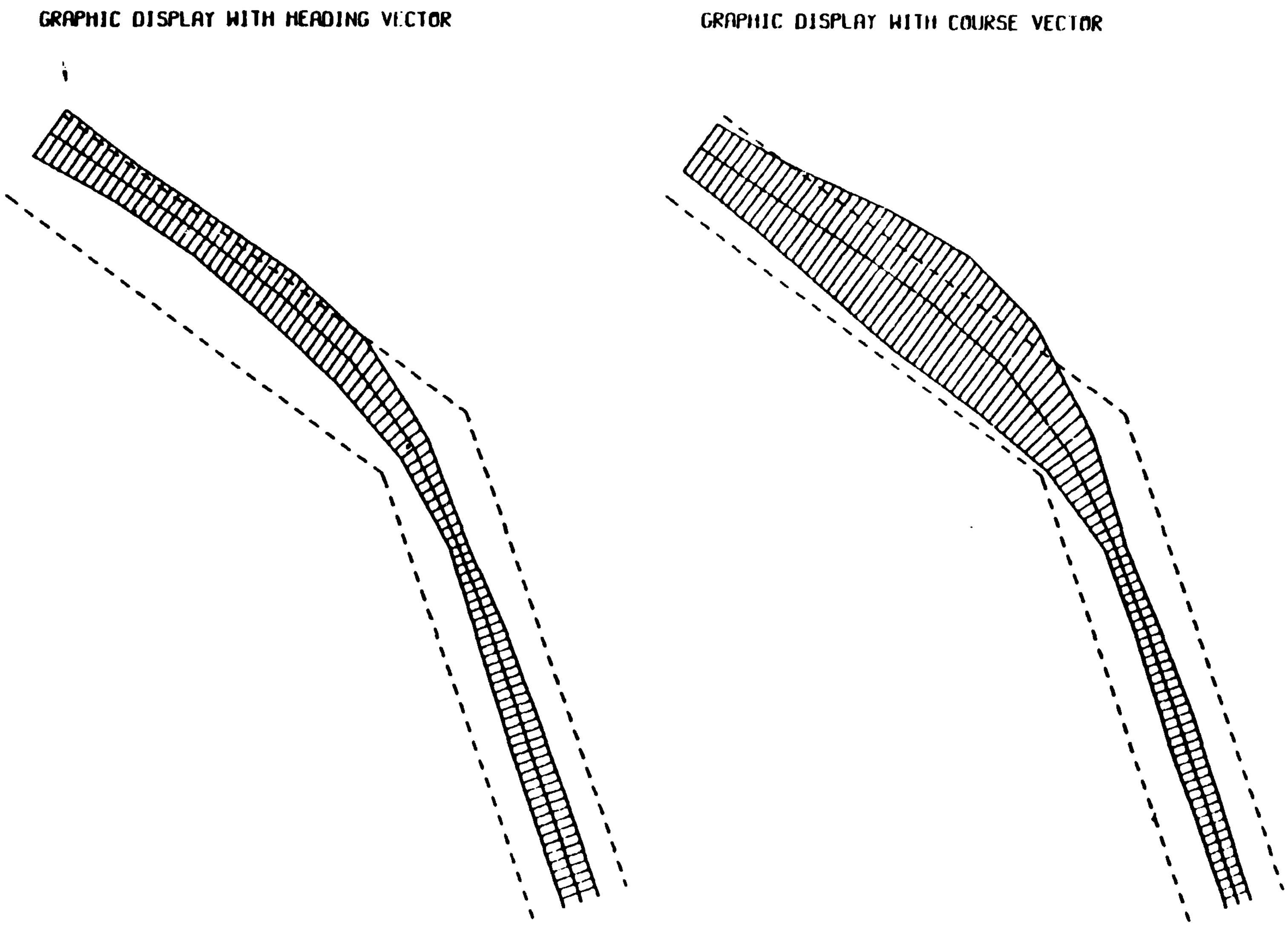

FIGURE 14. COMBINED TRACK PLOTS FOR GRAPHIC DISPLAYS

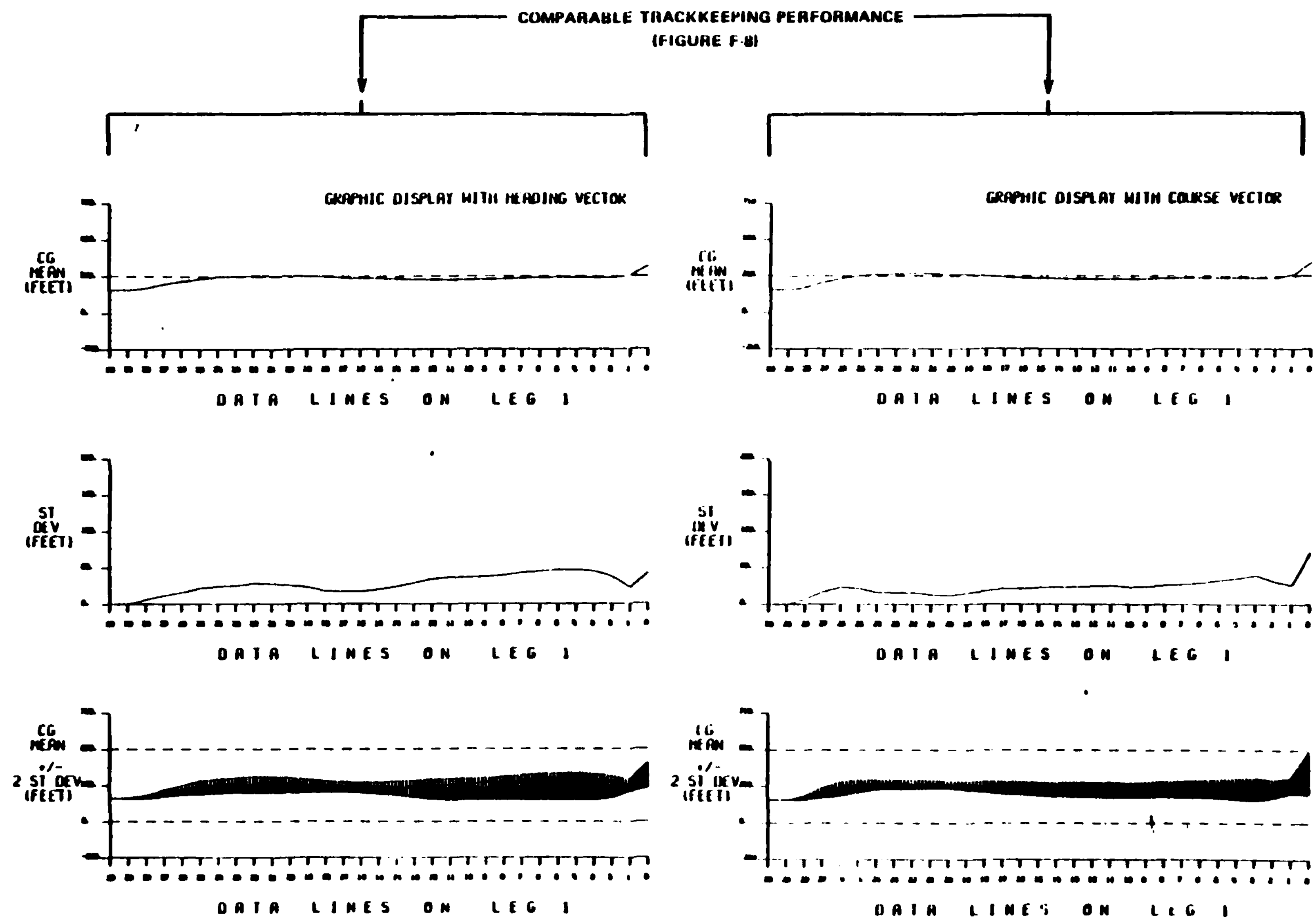

FIGURE 15. SUMMARY PLOT ANALYSIS OF LEG 1 – GRAPHIC DISPLAYS

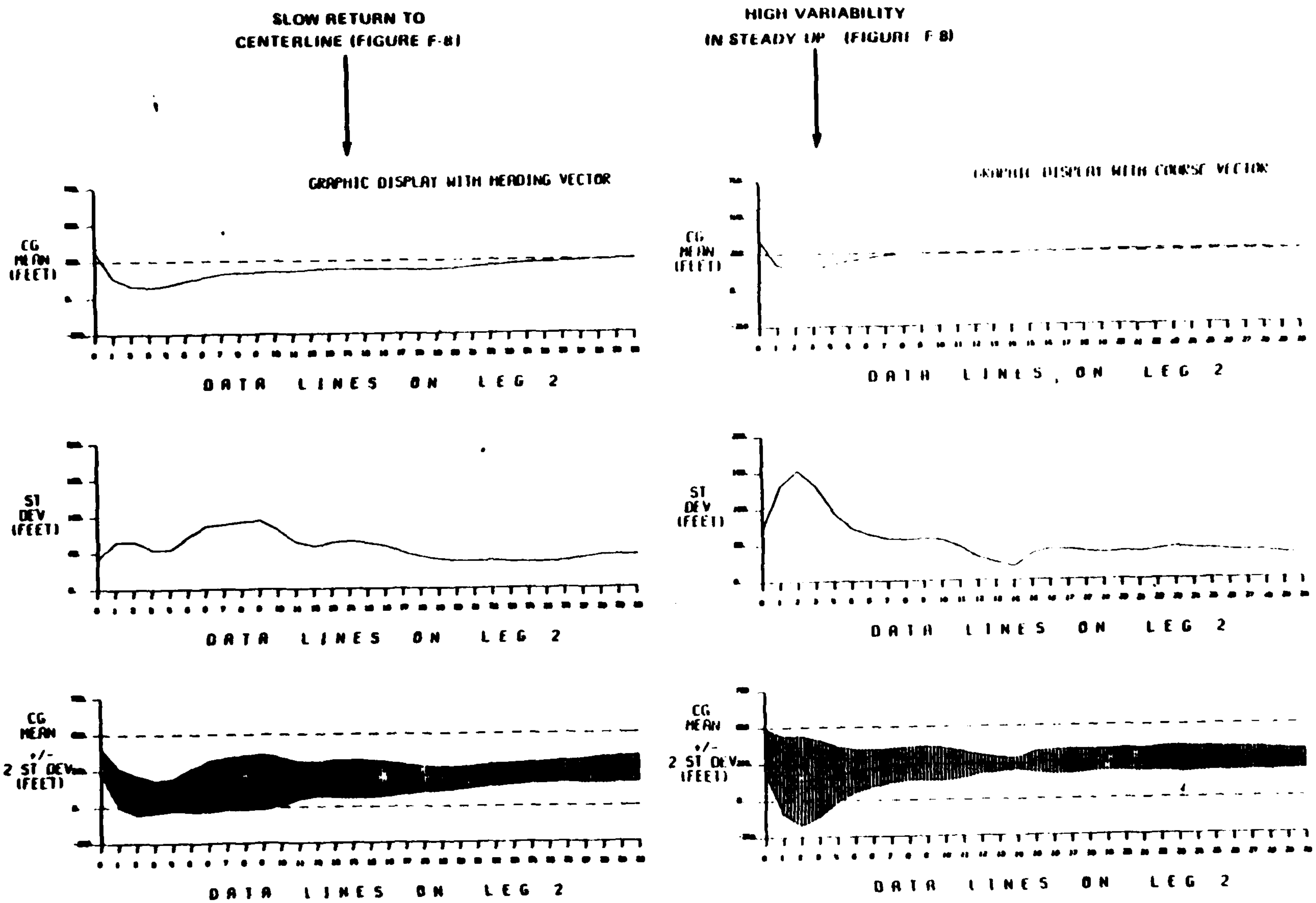

FIGURE 16. SUMMARY PLOT ANALYSIS OF LEG 2 -- GRAPHIC DISPLAYS

TABLE 11. COMPARISON IN MANEUVERING PERFORMANCE BETWEEN GRAPHIC DISPLAYS

MEASURE[1]	Graphic Display: With Heading Vector	Graphic Display: With Course Vector	SIGNIFICANT DIFFERENCE[2]
<u>Return to and Steady Up on Centerline</u>			
1. Distance to return to centerline (nm)	.675	.364	Slow return to centerline w/heading vector
2. Overshoot following return to centerline (ft)	20.9	28.1	-none-
3. Distance to steady up in entrance leg 1 (nm)	.617	.569	-none-
4. Distance to steady up in exit leg 2 (nm)	.950	.577	Slow steady up w/heading vector
<u>Initial Turn Rudder Application</u>			
1. Distance before bend at initial rudder (nm)	.133	.152	-none-
2. Magnitude of initial turn rudder (deg)	15.6	18.8	-none-
3. Maximum initial turn rudder (deg)	31.2	31.9	-none-
4. Frequency of turn rudder actuations	5.5	6.3	-none-
5. Technique of turn rudder application	1	1	-none-
<u>Check Rudder Application</u>			
1. Distance beyond bend of check rudder (nm)	.150	.177	-none-
2. Magnitude of check rudder (deg)	19.3	13.3	-none-

[1]Rationale for the deviation of these measures are presented in Appendix B.
[2]Statistically significant at $p < .10$ level of confidence.

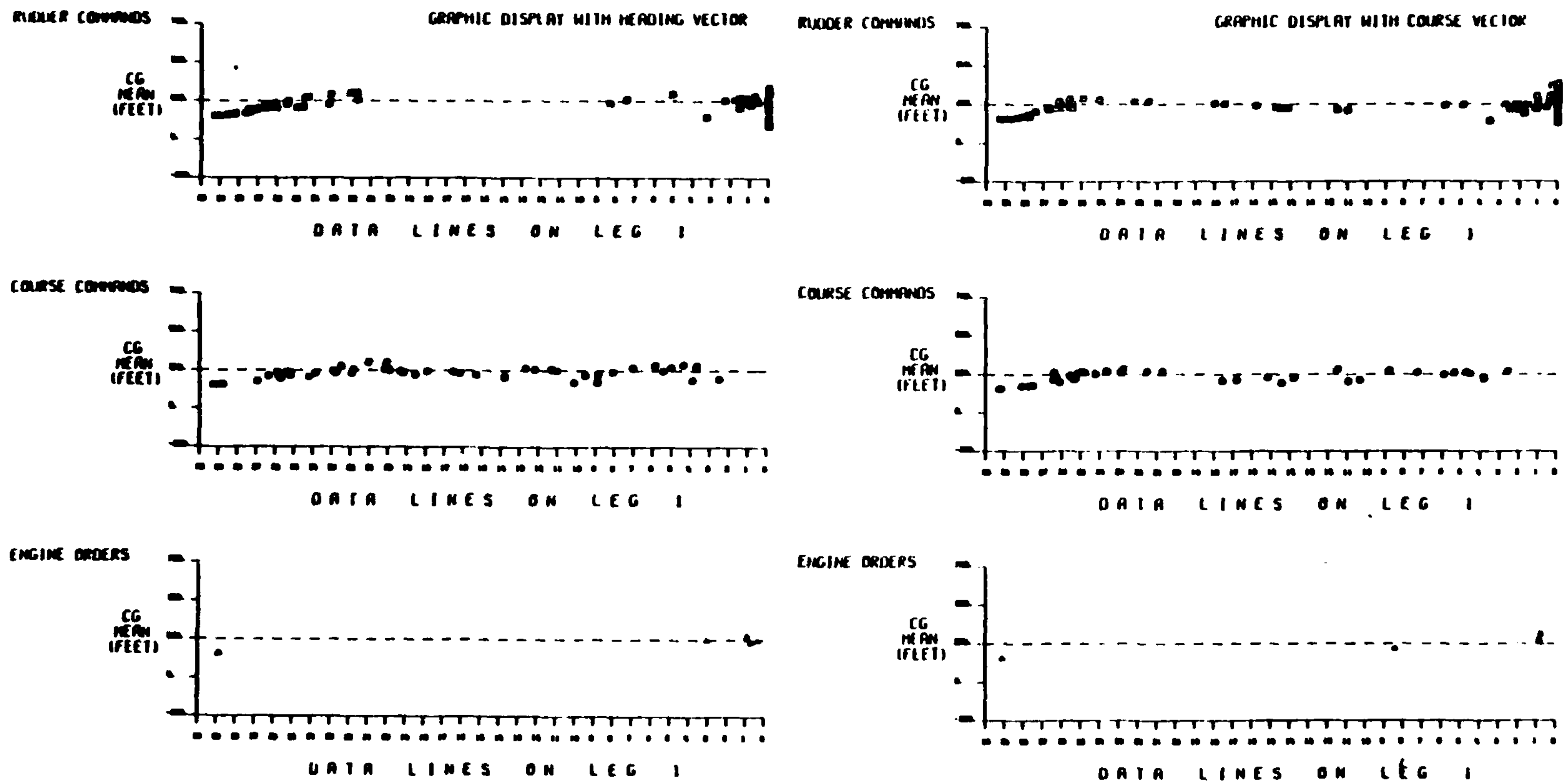

FIGURE 17. PROFILE OF CONTROL ACTIVITIES IN LEG 1 – GRAPHIC DISPLAYS

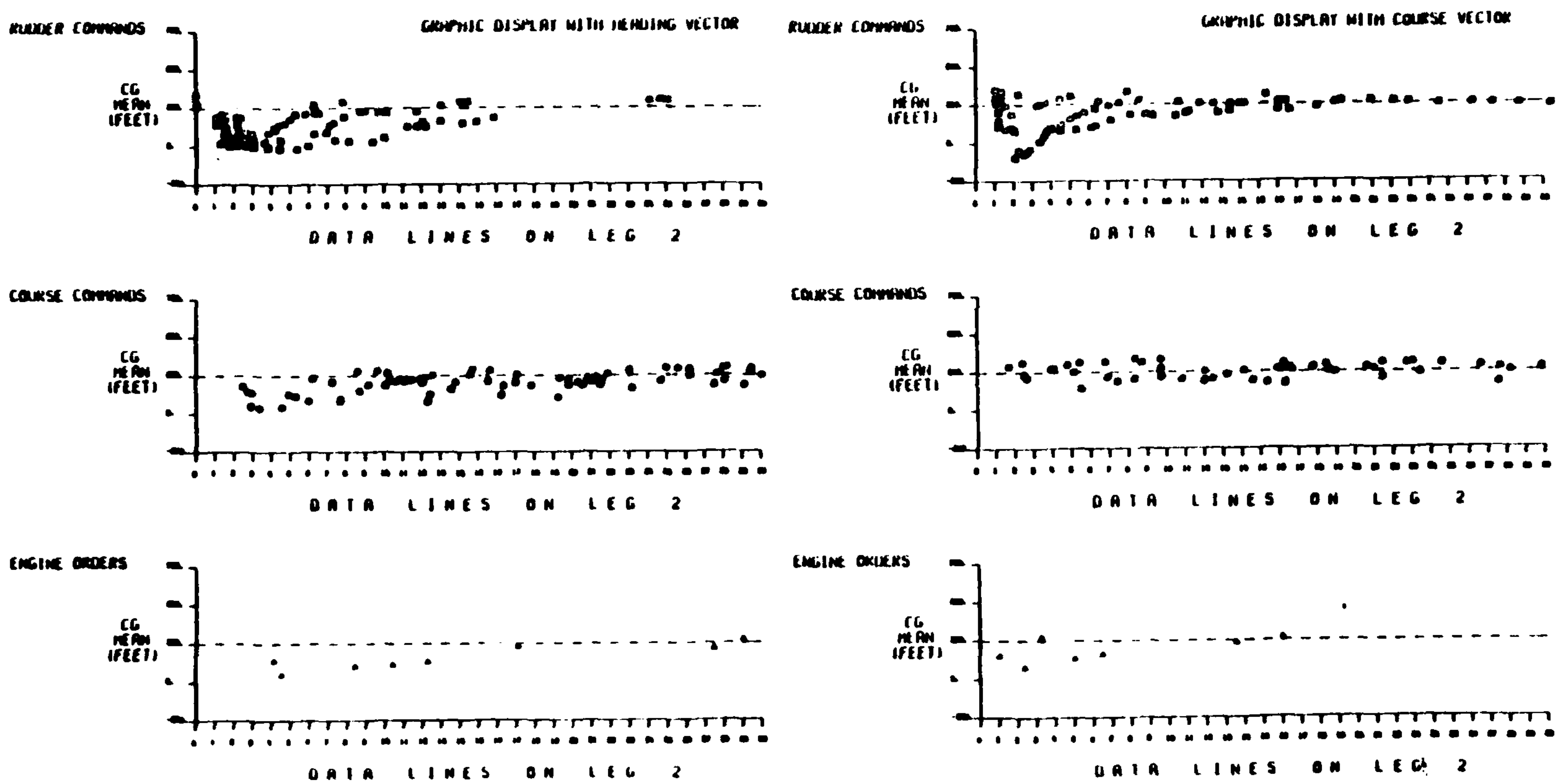

FIGURE 18. PROFILE OF CONTROL ACTIVITIES IN LEG 2 GRAPHIC DISPLAYS

5.4 EFFECTIVENESS OF STEERING DISPLAY VARIABLES

The analysis of STEERING display variables compared pilots' performance between when they used the Predictor Steering Display (S-1) and the Simplified Predictor Steering Display (S-2).

5.4.1 Trackkeeping and Maneuvering Performance

The comparison of pilotage performance between S-1 and S-2 displays demonstrates some effect of the predictor mechanization, but in general is not decisive enough to warrant final conclusions on either design's effectiveness. Since subjects were initially unfamiliar with either display, "a priori" factors contributed little to no difference in performance. It must be assumed, then, that differences in trackkeeping and maneuvering performance can be attributed to the unique design and operation of each STEERING display.

Figure 19 shows that the overall superior trackkeeping performance of the entire experiment was performed using the Predictor Steering Display.

This was expected and had been hypothesized from previous research using the STEERING display concept.[20,21,22] On the other hand, the Simplified Predictor Steering Display developed expressly for this experiment showed many signs of comparable performance with specific weaknesses only for the steady up task. The statistical analyses summarized in Figures 20 and 21 suggest that since cost effectiveness is a major factor with these two STEERING displays, the overall differences in performance may actually be overcome through relatively inexpensive familiarization or training.

In fact, Table 12 shows the only maneuvering differences to occur in favor of the predictor steering display while all control activity distributions (Figures 22 and 23) remain comparable.

To summarize, the analysis of trackkeeping and maneuvering performance shows very little significant difference between the S-1 and S-2 displays, but being a relatively sophisticated and operationally untried concept certainly recommends a continuation of evaluation in various other settings.

5.4.2 User Acceptance

The information in Table 10 regarding the Simplified Predictor Steering Display is less than indicative of a concise conclusion. Nevertheless, it does support conclusions of Van Berlekom's[23] findings which suggest fewer and smaller rudders when an effective predictor display is used.

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[20] Cooper, R.B., W.R. Bertsche, and K.P. Logan, op. cit.

[21] Cooper, R.B., W.R. Bertsche, and G.J. McCue, op. cit.

[22] Van Berlekom, W.B., op. cit.

[23] Ibid.

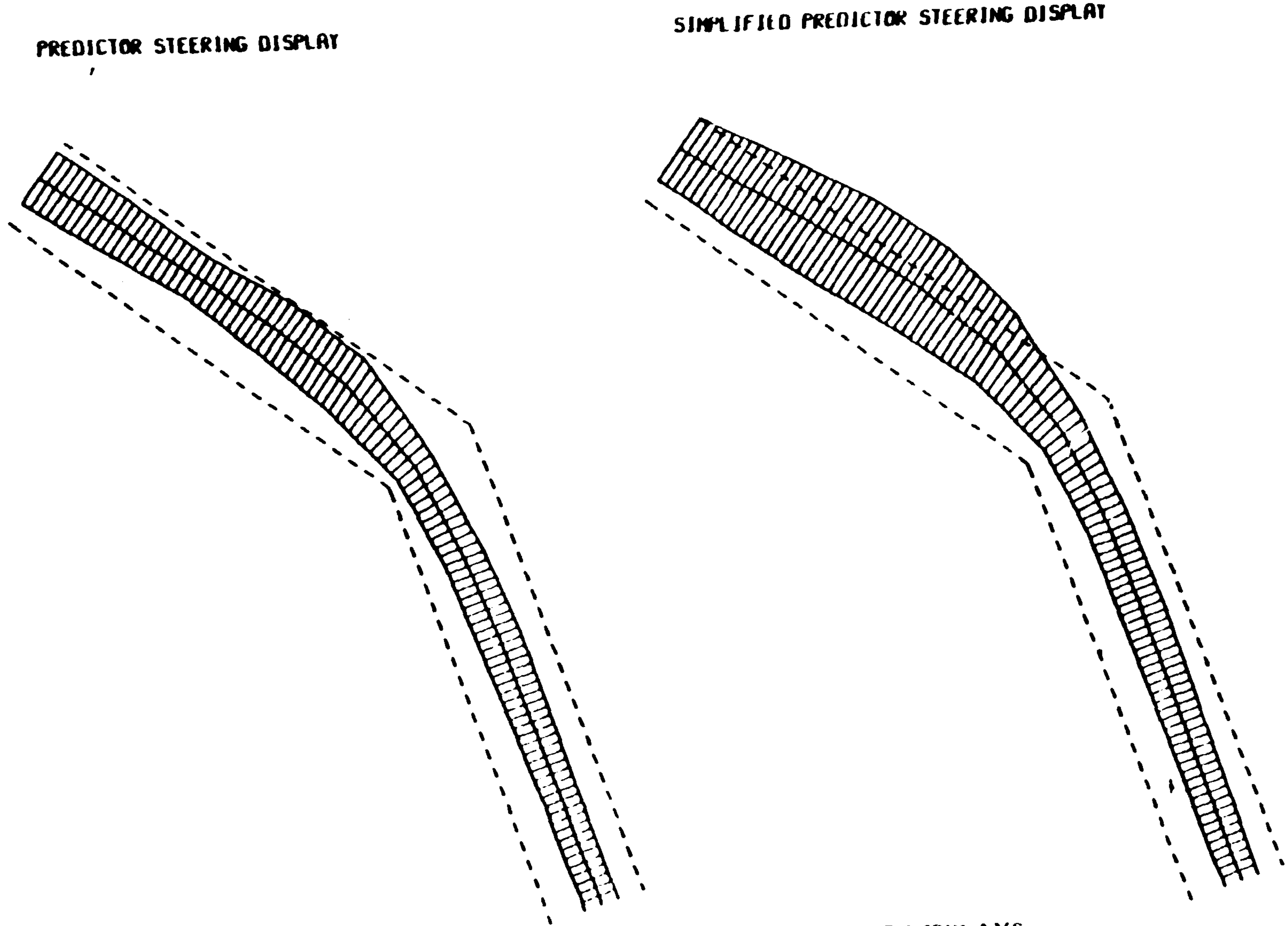

FIGURE 19. COMBINED TRACK PLOTS FOR STEERING DISPLAYS

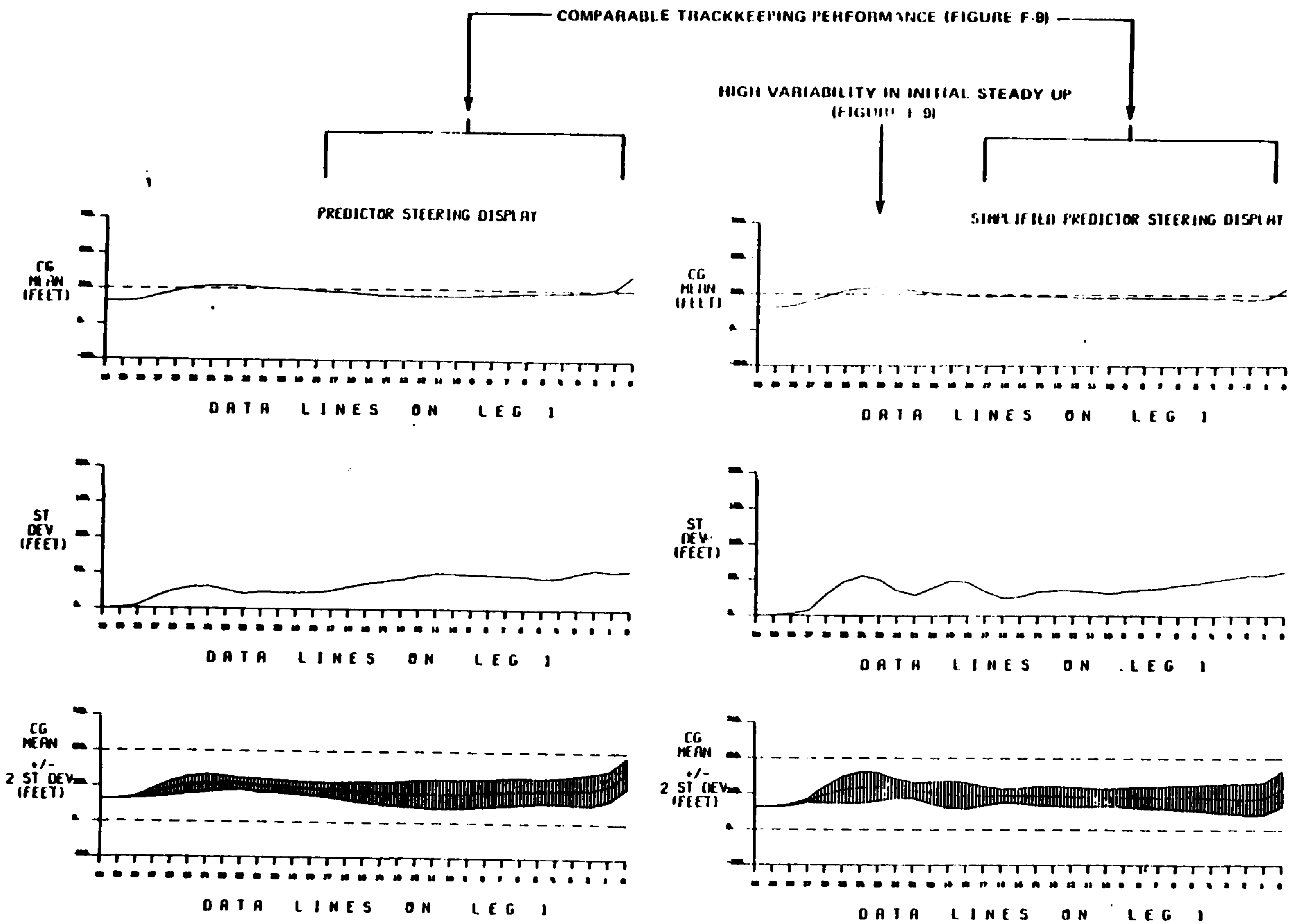

FIGURE 20. SUMMARY PLOT ANALYSIS OF LEG 1 – STEERING DISPLAYS

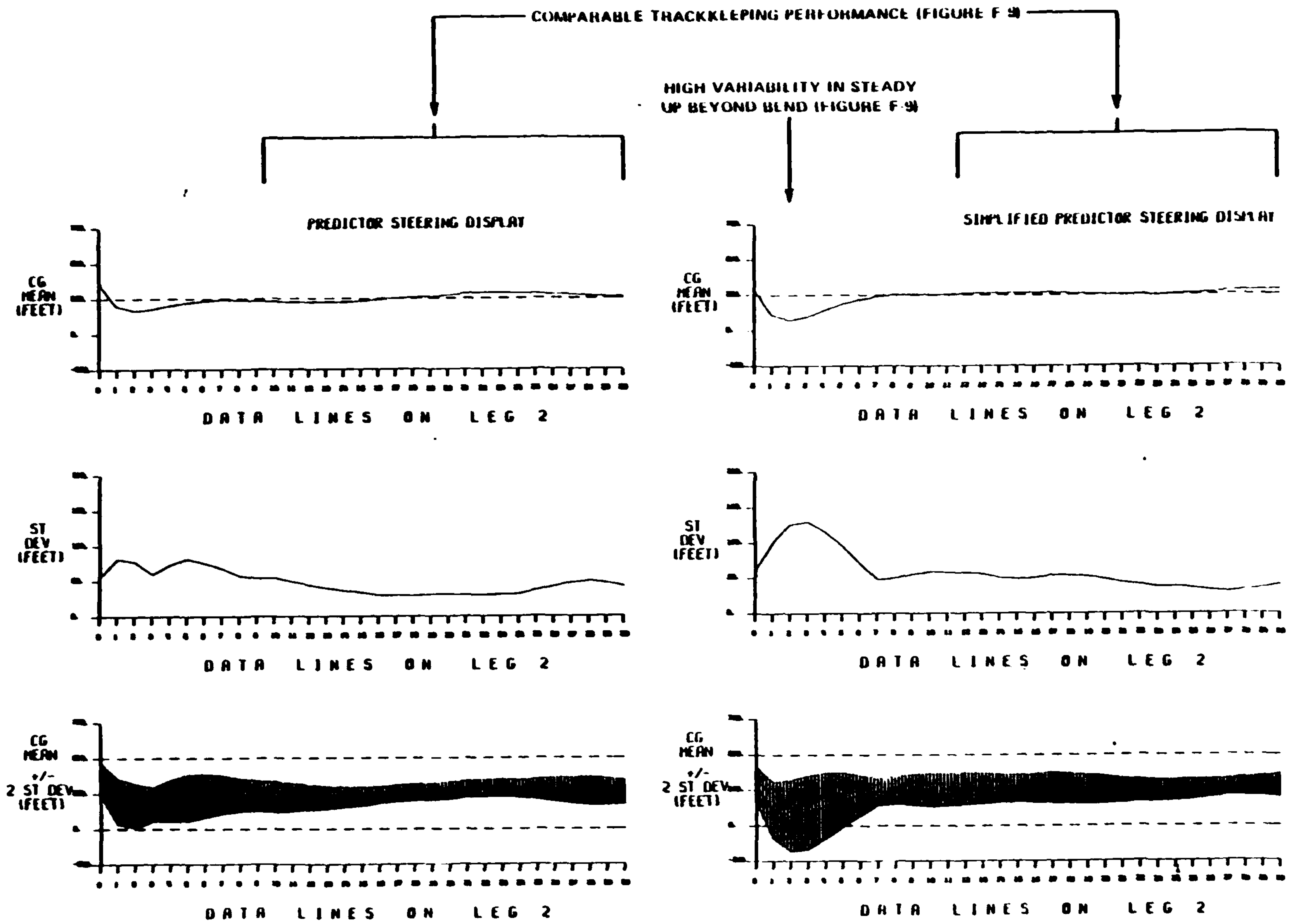

FIGURE 21. SUMMARY PLOT ANALYSIS OF LEG 2 – STEERING DISPLAYS

TABLE 12. COMPARISON IN MANEUVERING PERFORMANCE BETWEEN STEERING DISPLAYS

MEASURE[1]	DISPLAY		SIGNIFICANT DIFFERENCE[2]
	Predictor Steering	Simplified Predictor Steering	
Return to and Steady Up on Centerline			
1. Distance to return to centerline (nm)	.326	.401	-none
2. Overshoot following return to centerline (ft)	32.0	63.1	Overshoot of centerline w/predictor steering
3. Distance to steady up in entrance leg 1 (nm)	.666	.732	-none-
4. Distance to steady up in exit leg 2 (nm)	.546	.697	-none-
Initial Turn Rudder Application			
1. Distance before bend at initial rudder (nm)	.178	.132	-none-
2. Magnitude of initial turn rudder (deg)	11.8	16.2	-none-
3. Maximum initial turn rudder (deg)	30.6	32.5	-none-
4. Frequency of turn rudder actuations	5.6	4.8	-none-
5. Technique of turn rudder application	I	I	-none-
Check Rudder Application			
1. Distance beyond bend of check rudder (nm)	.173	.242	-none-
2. Magnitude of check rudder (deg)	7.5	6.3	-none-

[1]Rationale for the deviation of these measures are presented in Appendix B.

[2]Statistically significant at $p < .10$ level of confidence.

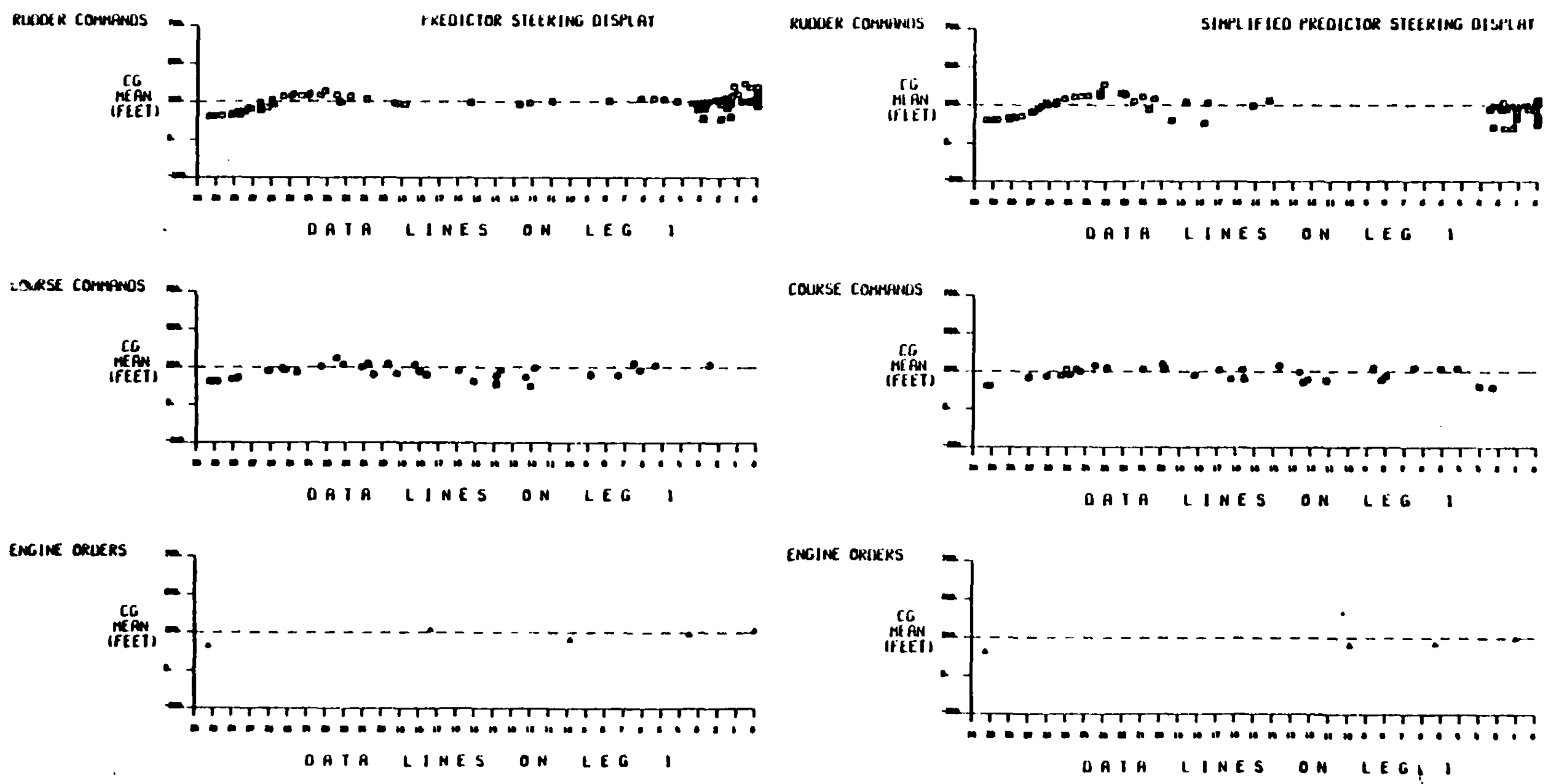

FIGURE 22. PROFILE OF CONTROL ACTIVITIES IN LEG 1 – STEERING DISPLAYS

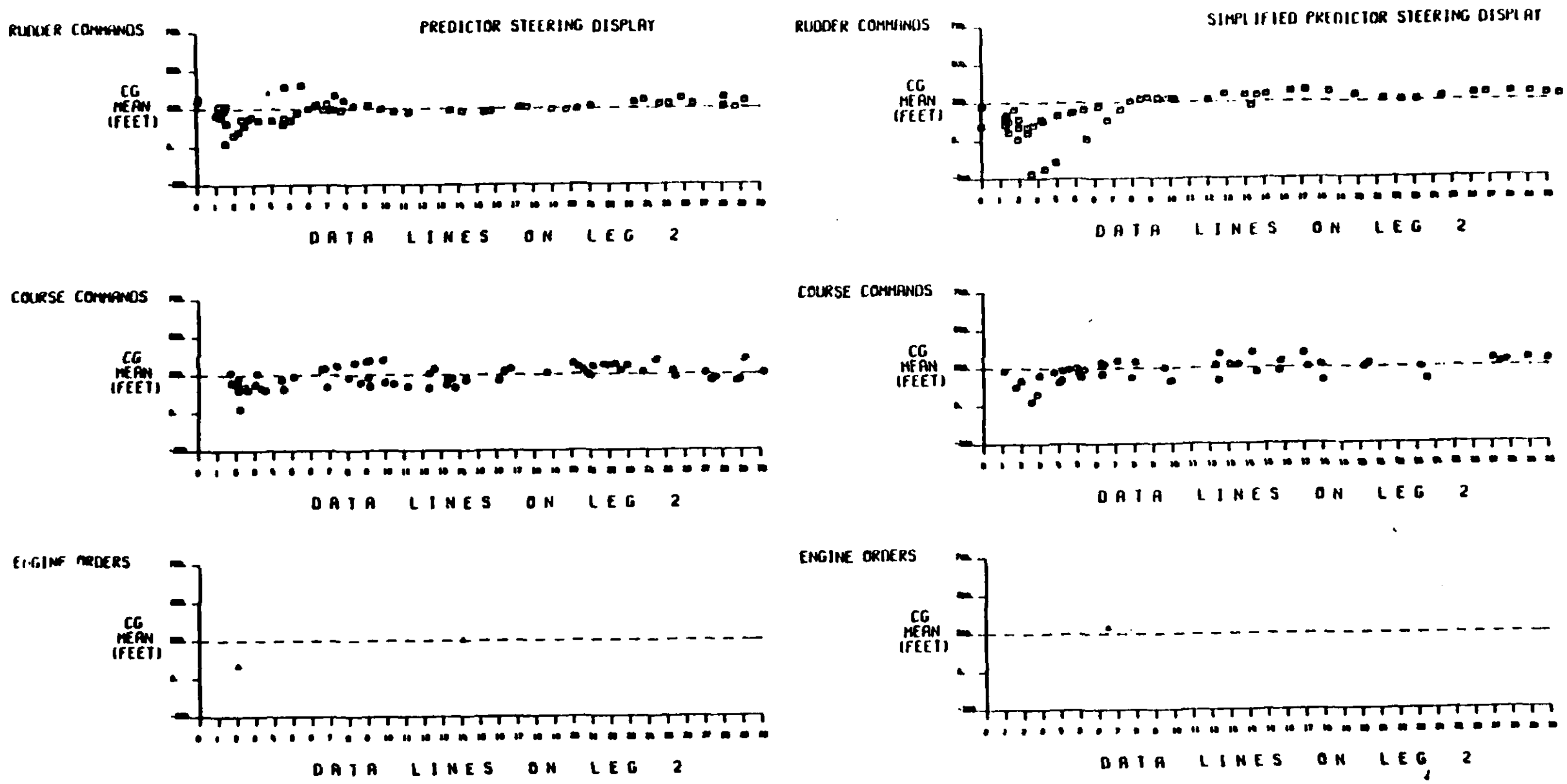

FIGURE 23. PROFILE OF CONTROL ACTIVITIES IN LEG 2 – STEERING DISPLAYS

Some additional comments from the subjects with regard to the Predictor and Simplified Predictor Displays are as follows:

1. The projected ship's image could possibly be confused with ownship's image. (This never occurred in the experiment.)

2. The sporatic behavior of the S-1 vector was potentially distracting since applied rudder would not be retained for the full duration of the projection. (In the experiment the projected image was rarely outside the channel and should not have prompted the complaint.)

3. The steering display was only useful for maneuvering through bends and around hazards.

4. The projected vector was too short providing insufficient projection time for the given ship speed and handling characteristics.

5. The steering display might better be used by a helmsman for steering.

In conclusion, it is suggested that either the S-1 or S-2 displays hold extreme promise for augmenting a radio aids to navigation display. In light of the performance metric and pilotage requirements of this experiment, however, it would be difficult to justify recommending that a STEERING display be substituted in lieu of the much more readily accepted GRAPHIC display for the final RA-2 evaluation.

5.5 POTENTIAL FOR LEARNING SIMPLIFIED DIGITAL DISPLAY

The analysis of learning potential for the Simplified Digital Display compared pilots' performance between when they used the Simplified Digital Display the first time (D-1) and when they used it the second time (D-3).

This analysis was conducted from an "experiment of opportunity" in which a small sample of the subject population was asked to repeat the Simplified Digital Display run at the end of their day. Since some subjects had received their first exposure (D-1) early in the day, some of their improvement in performance must be attributed to learning the waterway and simulation. Nevertheless, the comparison in performance between D-1 and D-3 is valuable because it shows areas in which there was no improvement either as a result of learning the waterway or the display. These areas are of most concern in the event the Simplified Digital Display is ever to be developed, taught, evaluated or implemented.

The findings of this section are secondary to the overall project and should not be regarded as conclusive evidence of the trainability or lack of trainability of a simplified digital radio aid to navigation display.

5.5.1 Trackkeeping and Maneuvering Performance

A review of Figure 24 reveals marked differences not only in the variability but also in the mean track between first and second Simplified Digital Display runs. While the approach to the bend (Figure 25) shows identical and relatively commendable pilotage performance, Figure 26, the second leg, shows major differences both in recovering from the turn and in transiting the straight leg.

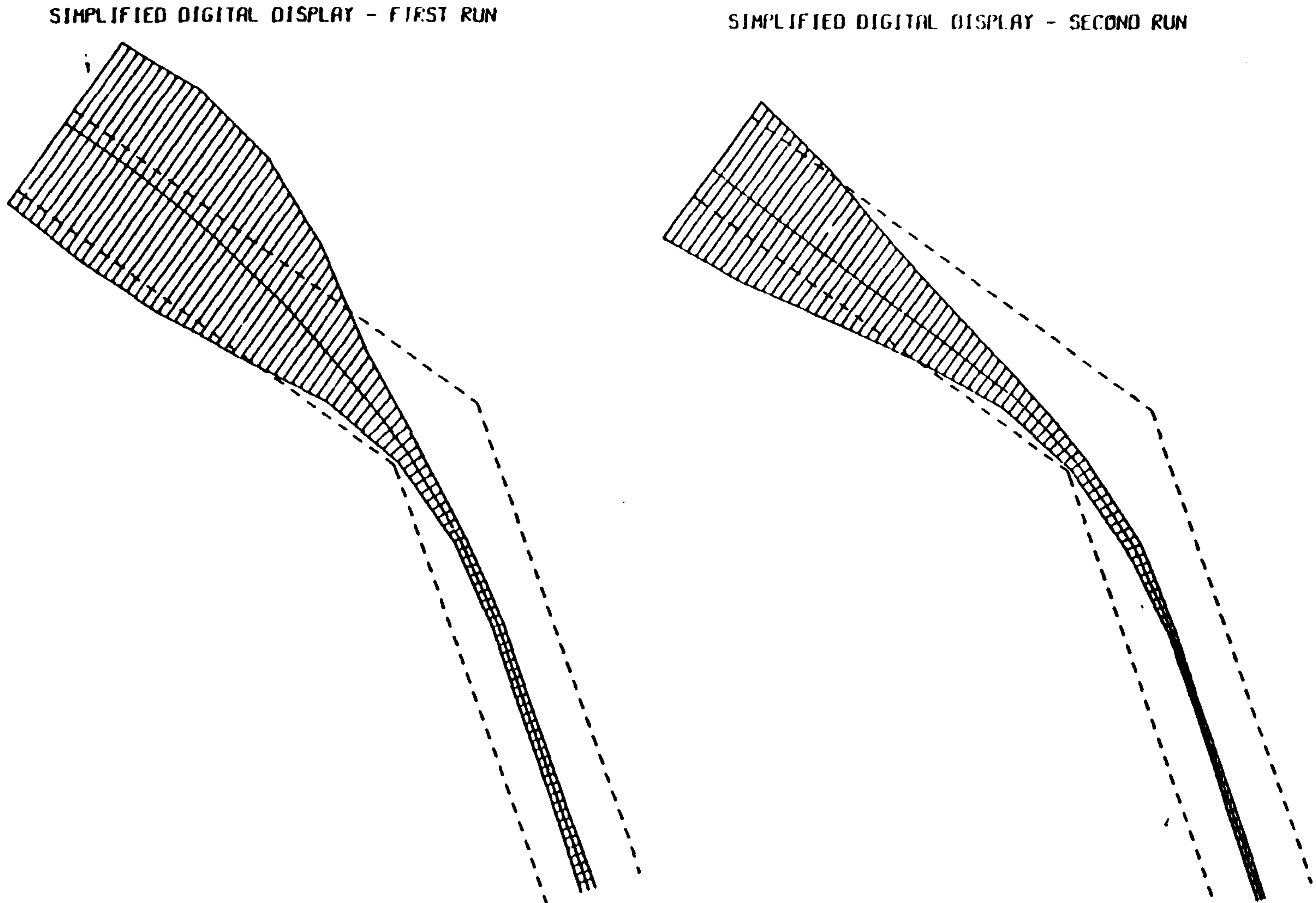

FIGURE 24. COMBINED TRACK PLOTS FOR SIMPLIFIED STEERING DISPLAY

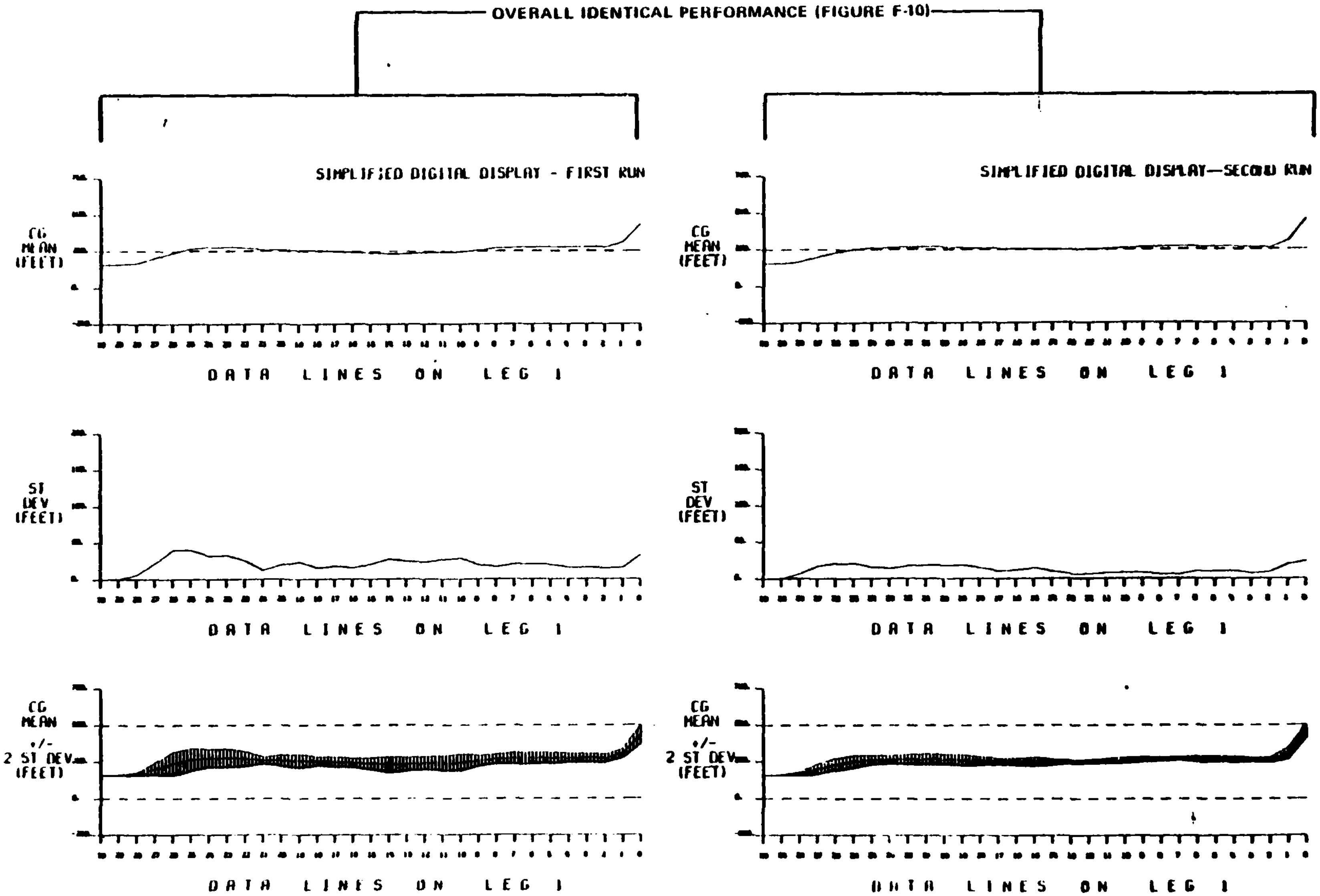

FIGURE 25. SUMMARY PLOT ANALYSIS OF LEG 1 – SIMPLIFIED STEERING DISPLAY

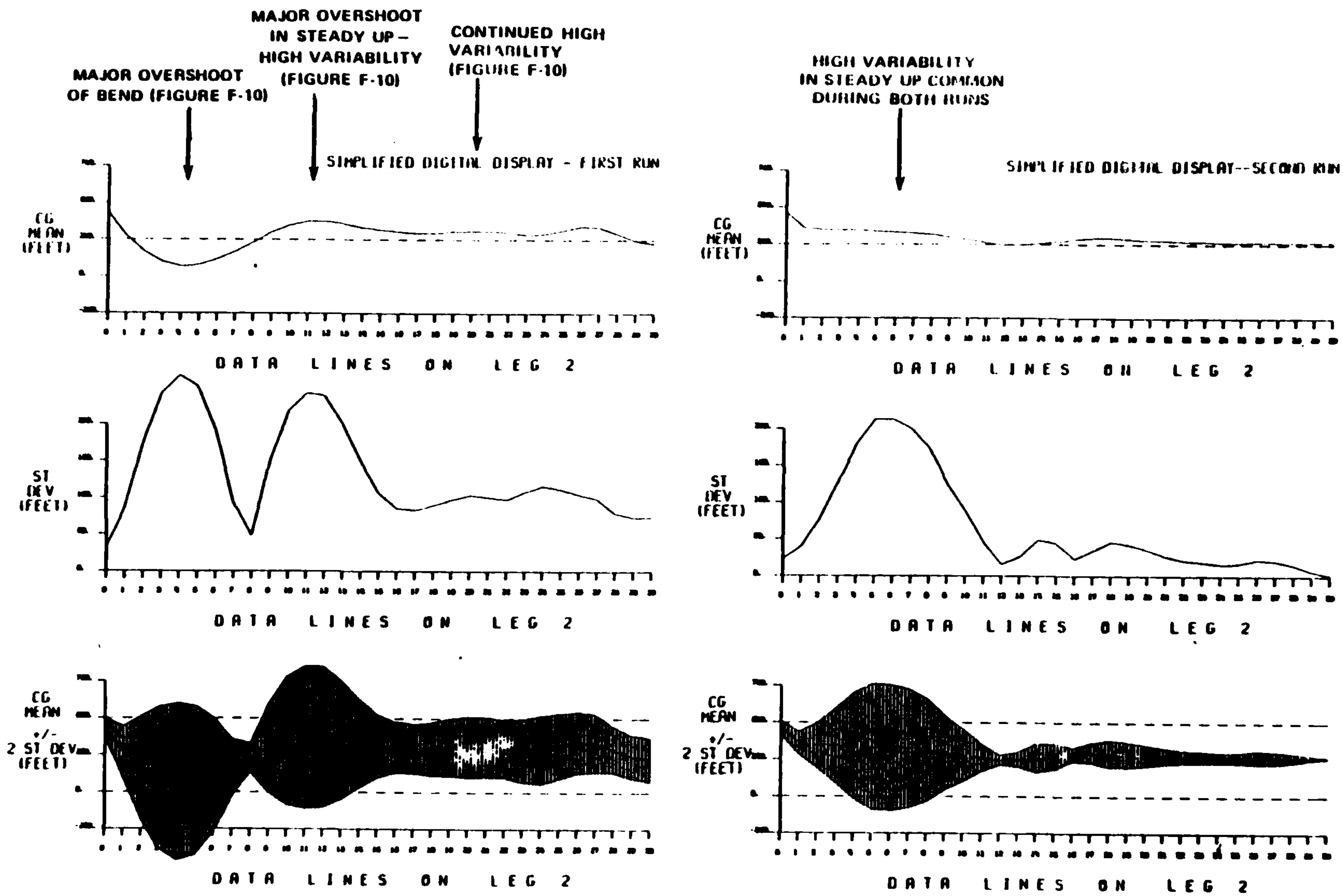

FIGURE 26. SUMMARY PLOT ANALYSIS OF LEG 2 – SIMPLIFIED STEERING DISPLAY

Note in Figures 24 and 26 the major overshoot of the mean track in the bend during the first run. In the second run there is no overshoot whatsoever indicating a learning process and the determination of an appropriate initial rudder angle. Major overshoot in the steady up and a continued high variability throughout Leg 2 (Figure 26) also has been remedied in the second run. This too can be attributed to learning.

A high variability in steadying up from the bend persists, however, in both runs. This is a major indicator of the difficulty which may be experienced for maintaining performance consistency among pilots using this type of display.

In conclusion, there are positive indicators to suggest that pilots can be trained to use the Simplified Digital Display; and perhaps quite readily. Nevertheless, a persistent high variability among subjects also implies that the learning will not be uniform; and that, in fact, some pilots may never perform up to the level exhibited when they used the other types of displays in this experiment.

Section 6

DEVELOPMENT OF NOISE AND FILTER MODEL FOR RA-2 SIMULATION

Coincident with the RA-1 pilotage simulation, Eclectech Associates, Incorporated developed and tested a computer model to simulate the noise characteristics of a radio aid signal at the channel, the lag errors introduced by an ALPHA-BETA navigation system filter itself, and the effect of a gyro input to the filter equation.

For the RA-2 experiment (to be conducted at a future date), signal/noise error will be introduced prior to the filter system. The $\alpha - \beta$ tracker then provides estimates of position and velocity but with crosstrack error and course error due to its inherent lag. The different magnitudes of ownship position error which appear on the electronic radio aids to navigation display vary considerably as a function of different noise levels, different filter rise times and whether or not the filter is gyro aided. The intent of the RA-2 experiment will be to see how well restricted waters pilotage can be performed for these varied error conditions.

A thorough description of this noise model and its recommended implementation in the RA-2 experiment is presented in Appendix A. The tracker performance data appears in Appendix B. In summary, the research which examined tracker rise times of 3, 6, 12, 24, 42, and 54 seconds with rms noise of from 2 meters (6.6 feet) to 64 meters (211.2 feet), concluded:

- The optimal $\alpha - \beta$ tacker 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 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.
- For gyro aided trackers: Rise times which achieve minimum errors fall between 20 and 42 seconds, compared to 2 to 20 seconds for the unaided trackers; the minimum error values are less sensitive to the value of rise time as a function of noise level; and 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 crosstrack and along track velocity information.

APPENDIX A

RADIO AID NAVIGATION SYSTEM FOR RA-2 SIMULATION

A.1 INTRODUCTION

The radio aid experiments seek to determine the empirical relationships between the pilot's trackkeeping performance and both the noise characteristics of a radio aid signal at the channel and the lag errors introduced by the radio aid navigation system itself. The ship's actual position information is degraded by the addition of normally distributed random noise with a given rms value to ownship's actual position (i.e., signal). The radio aid navigation system is represented by optimally damped $\alpha - \beta$ trackers with selectable rise time. Gyro-aiding is provided to the tracker to simulate the behavior of more sophisticated system filters (e.g., Kalman filters). The implementation of the α-β trackers and the entire navigation system simulation is described in this appendix. The performance of the system in the experimental scenario is evaluated for a variety of parametric values. These data are presented in Appendix B.

<u>α - β Tracker Description and Behavior</u>

The α - β tracker is a second order recursive filter which represents an optimum compromise between transient performance and noise reduction.[24] The difference equations that describe the filter are:

$$\hat{X}_{n+1} = \hat{X}^1_{n+1} + \alpha \; X_{n+1} - \hat{X}^1_{n+1} \qquad \text{(A-1)}$$

$$\hat{\dot{X}}_{n+1} = \hat{\dot{X}}_n + \frac{\beta}{T} \; X_{n+1} - \hat{X}^1_{n+1} \qquad \text{(A-2)}$$

$$\hat{X}^1_{n+1} = \hat{X}_n + T\,\hat{\dot{X}}_n \qquad \text{(A-3)}$$

where:

$\hat{X}_n$ = filter's estimate of position at sample point n

$\hat{\dot{X}}_n$ = filter's estimate of velocity at sample point n

$\hat{X}_{n+1}$ = filter's estimate of position at sample point n+1

$\hat{\dot{X}}_{n+1}$ = filter's estimate of velocity at sample point n+1

$\hat{X}^1_{n+1}$ = predicted position at sample point n+1 based on velocity and position estimates at sample point n

---

[24] T.R. Benedict and G.W. Bordner. "Synthesis of Radar Track-While-Scan Smoothing Equations." IEEE Transactions on Automatic Control, July 1962.

X_{n+1} = noise measurement of position at sample point n+1

T = sampling interval

α, β = filter gain parameters

The α - β tracker is optimal damped in the class of time invariant linear filters under the condition that

$$\beta = \alpha^2/(2 - \alpha) \qquad \text{(A-4)}$$

For optimal damping applications of the tracker the selection of a value for α will uniquely determine the tracker's transient response. We have selected the tracker's rise time as the parameter controlled by alpha so that tracker performance may be compared to other filtering techniques. We define rise time to be:

Rise time: The time period (in seconds) required for the filter output to achieve 66.7% of the filter input value given a step input value.

Figure A.1 shows the dynamic response of the filter to a unit step input at time equal to 10 seconds. A time period (T) of 1 second was utilized, the value of α was 0.110. Table A.1 lists the discrete filter estimates of output "position" and "velocity" for the data. These data show that for this example the rise time is approximately equal to 6 seconds. The overshoot is 0.195 or approximately 20 percent.

Figure A.2 shows a plot relating rise time to selected values of α. Table A.2 lists values of α utilized in the tracker analyses described in subsequent sections.

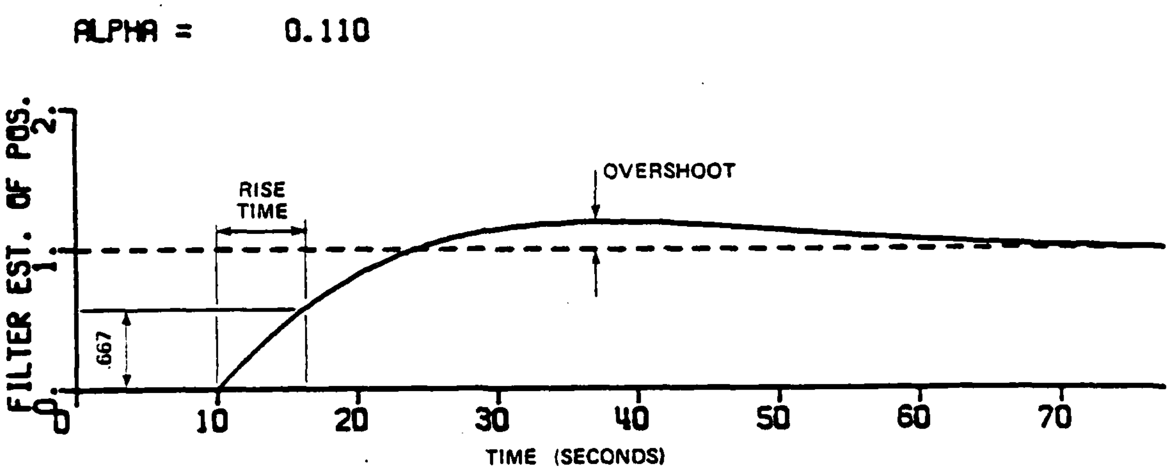

Figure A-1. α - β Tracker Response to Unit Step Input at 10 Seconds Critically Damped

TABLE A.1 α - β TRACKER RESPONSE TO UNIT STEP INPUT AT 10 SECONDS, OPTIMALLY DAMPED

ALPHA - BETA FILTER TEST PROGRAM ---- ALPHA = 0.110

TIME	X(WITH NOISE)	X(FILTER EST)		VEL(FILTER EST)
1	0.000	0.000		0.000
2	0.000	0.000		0.000
3	0.000	0.000		0.000
4	0.000	0.000		0.000
5	0.000	0.000		0.000
6	0.000	0.000		0.000
7	0.000	0.000		0.000
8	0.000	0.000		0.000
9	0.000	0.000		0.000
10	1.000	0.110	↑	0.006
11	1.000	0.214		0.012
12	1.000	0.311	RISE	0.017
13	1.000	0.402	TIME	0.021
14	1.000	0.487		0.025
15	1.000	0.565		0.028
16	1.000	0.638	↓	0.031
17	1.000	0.705		0.033
18	1.000	0.767		0.035
19	1.000	0.823		0.036
20	1.000	0.875		0.037
21	1.000	0.921		0.037
22	1.000	0.963		0.038
23	1.000	1.000		0.038
24	1.000	1.034		0.037
25	1.000	1.063		0.037
26	1.000	1.089		0.036
27	1.000	1.112		0.035
28	1.000	1.131		0.034
29	1.000	1.147		0.033
30	1.000	1.161		0.032
31	1.000	1.172		0.031
32	1.000	1.180		0.030
33	1.000	1.187		0.028
34	1.000	1.192		0.027
35	1.000	1.195		0.026
36	1.000	1.196	*MAXIMUM	0.024
37	1.000	1.196	OVERSHOOT	0.023
38	1.000	1.195		0.021
39	1.000	1.192		0.020
40	1.000	1.189		0.019
41	1.000	1.185		0.017
42	1.000	1.180		0.016
43	1.000	1.174		0.015
44	1.000	1.168		0.014
45	1.000	1.162		0.012
46	1.000	1.155		0.011
47	1.000	1.148		0.010
48	1.000	1.141		0.009
49	1.000	1.133		0.008
50	1.000	1.126		0.007
51	1.000	1.119		0.006
52	1.000	1.111		0.006
53	1.000	1.104		0.005
54	1.000	1.097		0.004
55	1.000	1.090		0.004
56	1.000	1.083		0.003
57	1.000	1.077		0.002
58	1.000	1.071		0.002
59	1.000	1.065		0.001

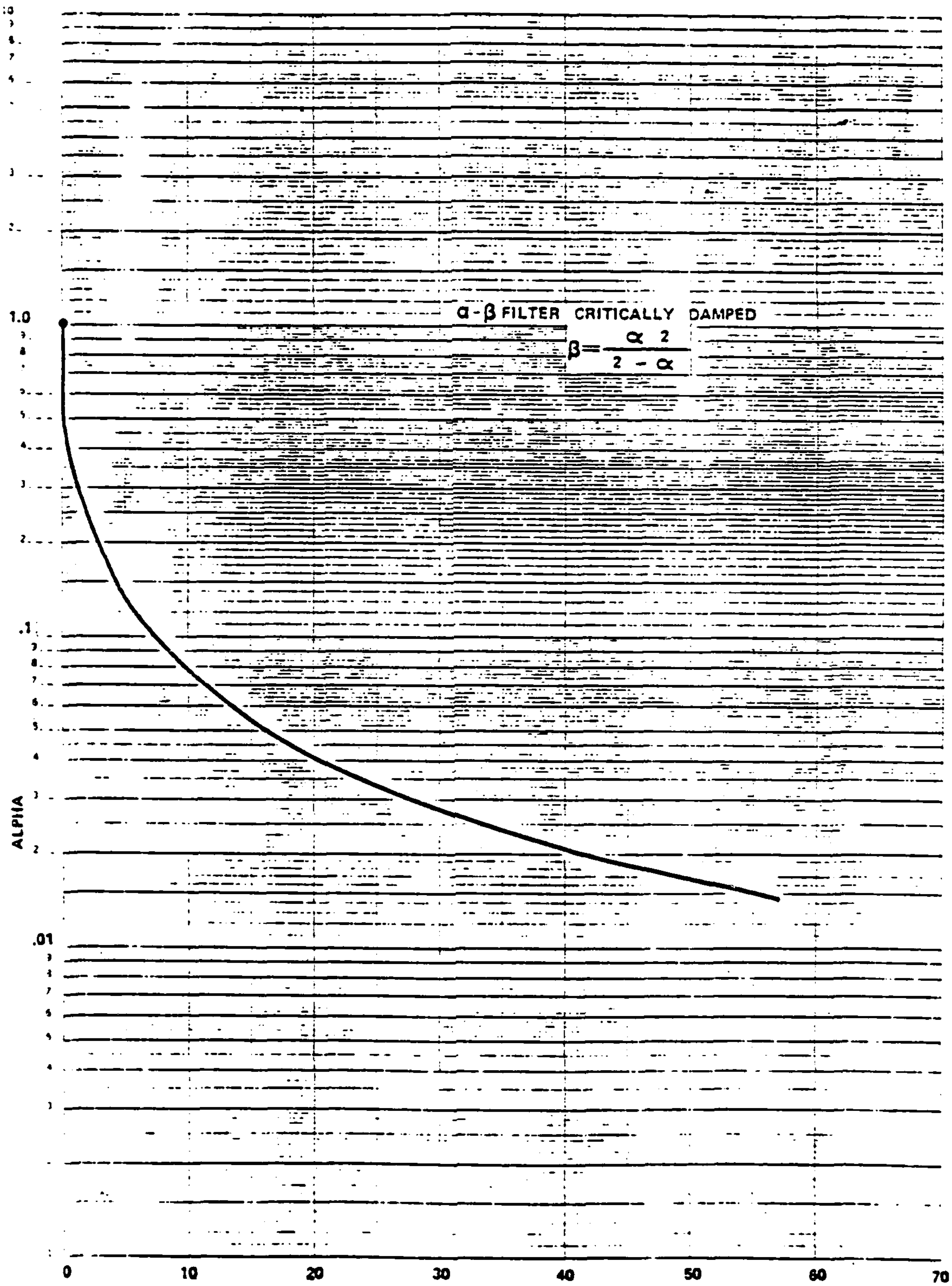

Figure A.2 Rise Time (Sec): Time to Reach 66% of Final Value Step Input

TABLE A-2. VALUES OF ALPHA VERSUS TRACKER TIME
T = 1 SECOND

RISE TIME (SECONDS)	ALPHA
3	0.190
6	0.110
12	0.065
18	0.044
24	0.034
30	0.027
42	0.019
54	0.015

Implementation of α - β Trackers as a Radio Aid Navigation System for Ships

Radio aid navigation systems are presently being implemented to facilitate ship piloting in narrow waterways. Such systems include typically a radio receiver, a signal processing unit (filter) and a position display device. Given state-of-the-art electronics, most systems are now micro-computer based and utilize digital filtering techniques. The basic system elements are shown in Figure A.3. For our analyses we have chosen to represent the receiver and signal processing unit as single trackers, thus, we have implemented a system shown in Figure A.4. Experimental results and filter analyses pertaining to this diagram should thus not be wholly attributed to either the receiver or signal processing unit: through system performance pertains.

A two-axis radio signal system has been assumed for the implementation. A 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.

The navigation system is implemented as shown in Figure A.5. Note 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. Optimal damping is assumed for both trackers, $\beta = (\alpha^2)/(2 - \alpha)$. Equations identical to equations (A-1) to (A-4) were implemented in each tracker with the appropriate changes to notation (x and y).

Performance of the navigation system was evaluated by using the system to track a 30,000 dwt tanker through a 35-degree turn, at 8 knots. Full ship hydrodynamic equations were used to represent the ship response. This ship is identical to that used in the previous real-time radio aid display simulation experiments described in this report. A simple autopilot was utilized for executing the turn to achieve repeatability.

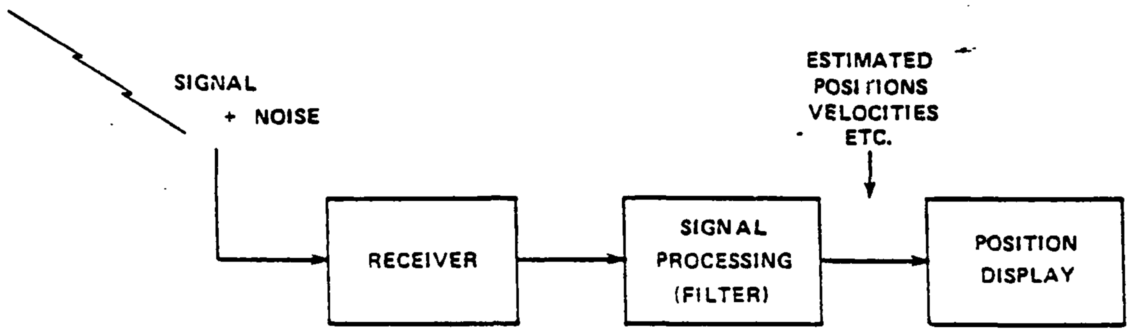

Figure A.3. Basic Elements of a Radio Navigation System

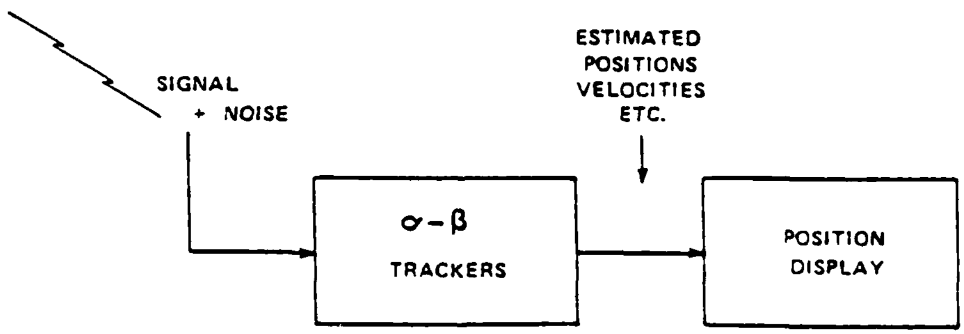

Figure A.4. Representation of a Radio Navigation System with α- β Trackers

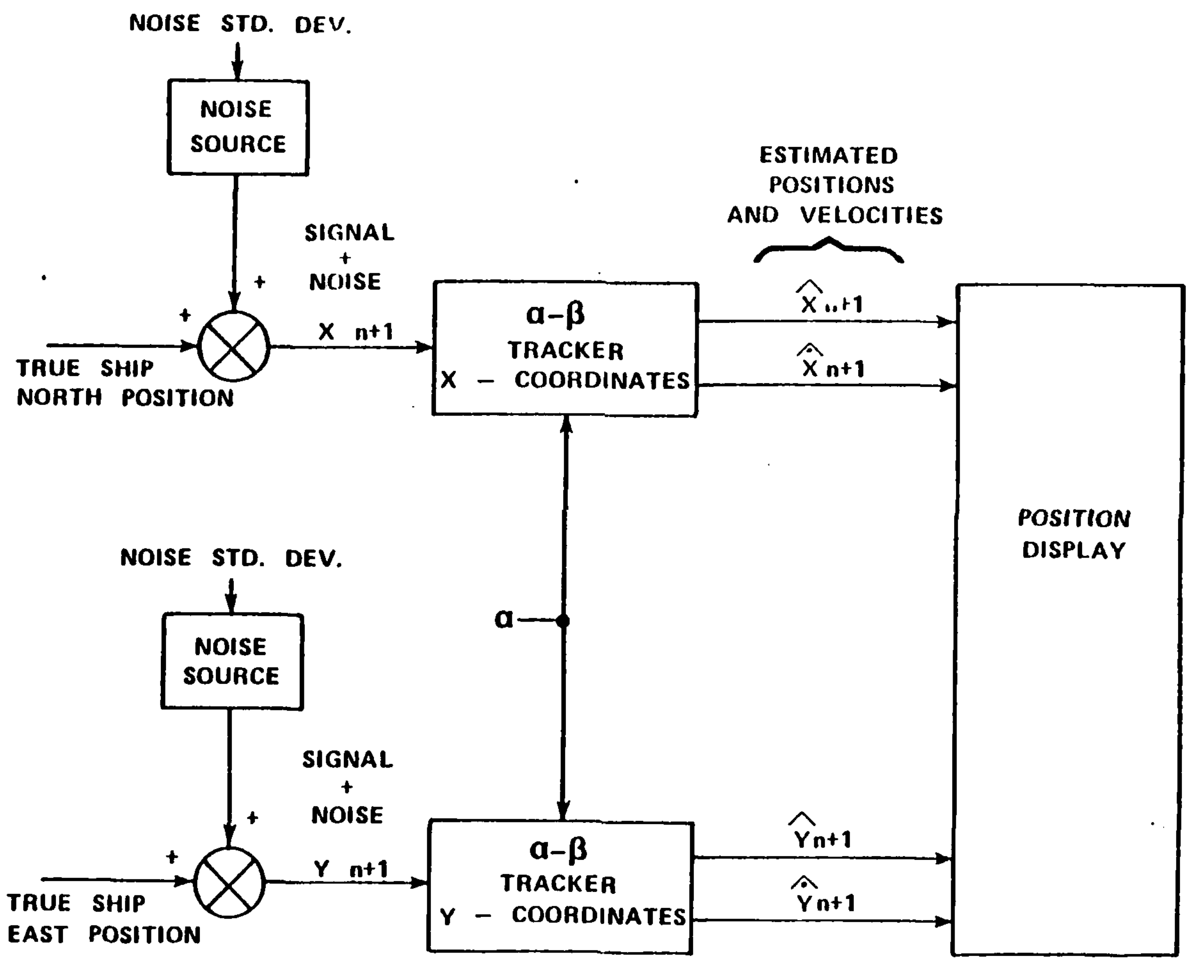

Figure A-5. Implementation of Navigation System for Experimentation

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

where:

$$\delta_R = \text{rudder angle}$$

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 A.6 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 following 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.

While oscillatory response and time response are of interest, a performance measure which appear important to safe navigation is the maximum crosstrack distance error (see Figure A.6). As this parameter places the ship relative to the channel edge, it is related to the potential for grounding. Another performance parameter is course error as calculated based on estimated velocities. Course error would falsely indicate the ship was moving toward the channel edge and may similarly be related to the potential for grounding. Crosstrack error (and alongtrack error) and course error data were calculated for each run according to the following equations:

Crosstrack error: (positive to right of actual position)

$$\text{CRTERR} = \hat{Y}_{n+1} - Y^*_{n+1} \cos\theta - \hat{X}_{N=1} - X^*_{n+1} \sin\theta \qquad \text{(A-5)}$$

Alongtrack error: (positive ahead of actual position)

$$\text{ALTERR} = \hat{Y}_{n+1} - Y^*_{n+1} \sin\theta + \hat{X}_{n+1} - X^*_{n+1} \cos\theta \qquad \text{(A-6)}$$

Course error: (positive to stbd of actual course)

$$\text{CRSERR} = \tan^{-1} \hat{\dot{Y}}_{n+1}/\hat{\dot{X}}_{n+1} - \tan^{-1} \dot{Y}^*_{n+1}/\dot{X}^*_{n+1} \qquad \text{(A-7)}$$

for:

$$\sin \theta = \dot{Y}^*_{n+1}/V^*_{n+1} \qquad \text{(A-8)}$$

$$\cos \theta = \dot{X}^*_{n+1}/V^*_{n+1} \qquad \text{(A-9)}$$

$$V^*_{n+1} = \left(\dot{X}^{*2}_{n+1} + \dot{Y}^{*2}_{n+1} \right)^{1/2} \qquad \text{(A-10)}$$

where:

X^*_{n+1} = ship's true north position at sample point n+1

Y^*_{n+1} = ship's true east position at sample point n+1

$\dot{X}^*_{n+1}$ = ship's true north velocity at sample point n+1

$\dot{Y}^*_{n+1}$ = ship's true east velocity at sample point n + 1

$\hat{X}_{n+1}$ = *filter's estimate of north position at sample point n+1*

$\hat{Y}_{n+1}$ = filter's estimate of east position at sample point n+1

$\hat{\dot{X}}_{n+1}$ = filter's estimate of north velocity at sample point n+1

$\hat{\dot{Y}}_{n+1}$ = filter's estimate of east velocity at sample point n+1

One additional performance measure was evaluated: the rms value of the crosstrack error for the entire transit. This was calculated as the standard deviation of the crosstrack error taken at all sample points.

Analysis of the tracker performances was made by varying the standard deviation of the signal noise and by varying the trackers' rise times. Runs were conducted with a standard deviation of noise equal to 64 m, 32 m, 16 m, and 2 m (211 feet, 105 feet, 52 feet, and 6.6 feet, respectively). Tracker rise time was varied between 3 and 54 seconds. Figures A.7, A.8 and A.9 show the variation in performance measures across these variables. Figures B.1 through B.24 in Appendix B show the individual track plots.

The greatest insight into the trackers' performance may be acquired through review of the individual tracks with 2 m rms noise, Figures B.1 through B.6. The 2 m rms noise can be considered to have a negligible effect on all the plots and the evident crosstrack errors and course errors can be attributed to tracker lag associated with long rise times. Data in Figure B.4 (24 second rise time) for example show that as actual ship velocities (north and east) change to describe a path through the 35-degree turn, the tracker positions continual forward and respond only after a lag to the right turn. Eventually the tracker positions reconverge with

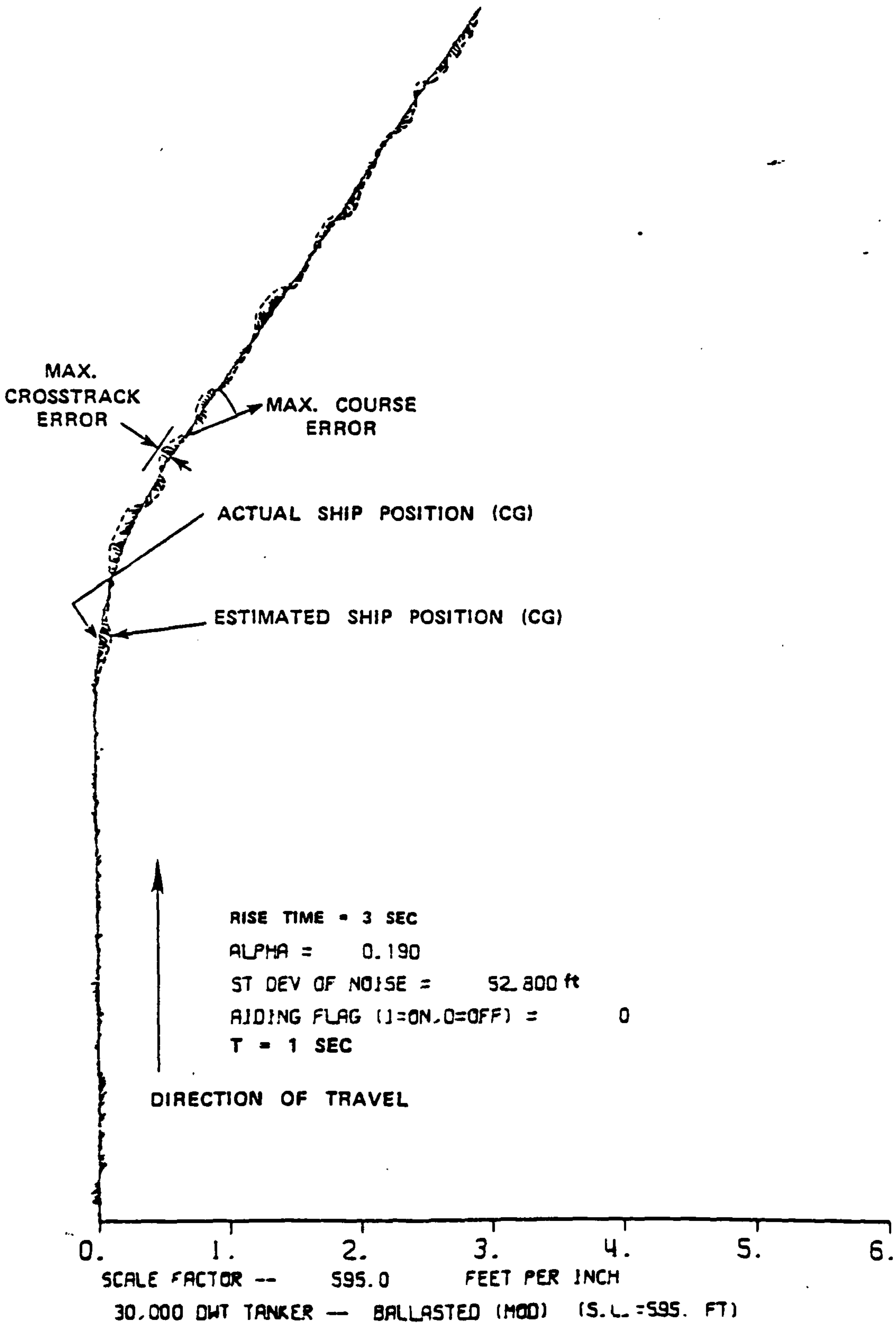

Figure A.6. Typical Plot of Tracker Response to 35 Degree Turn

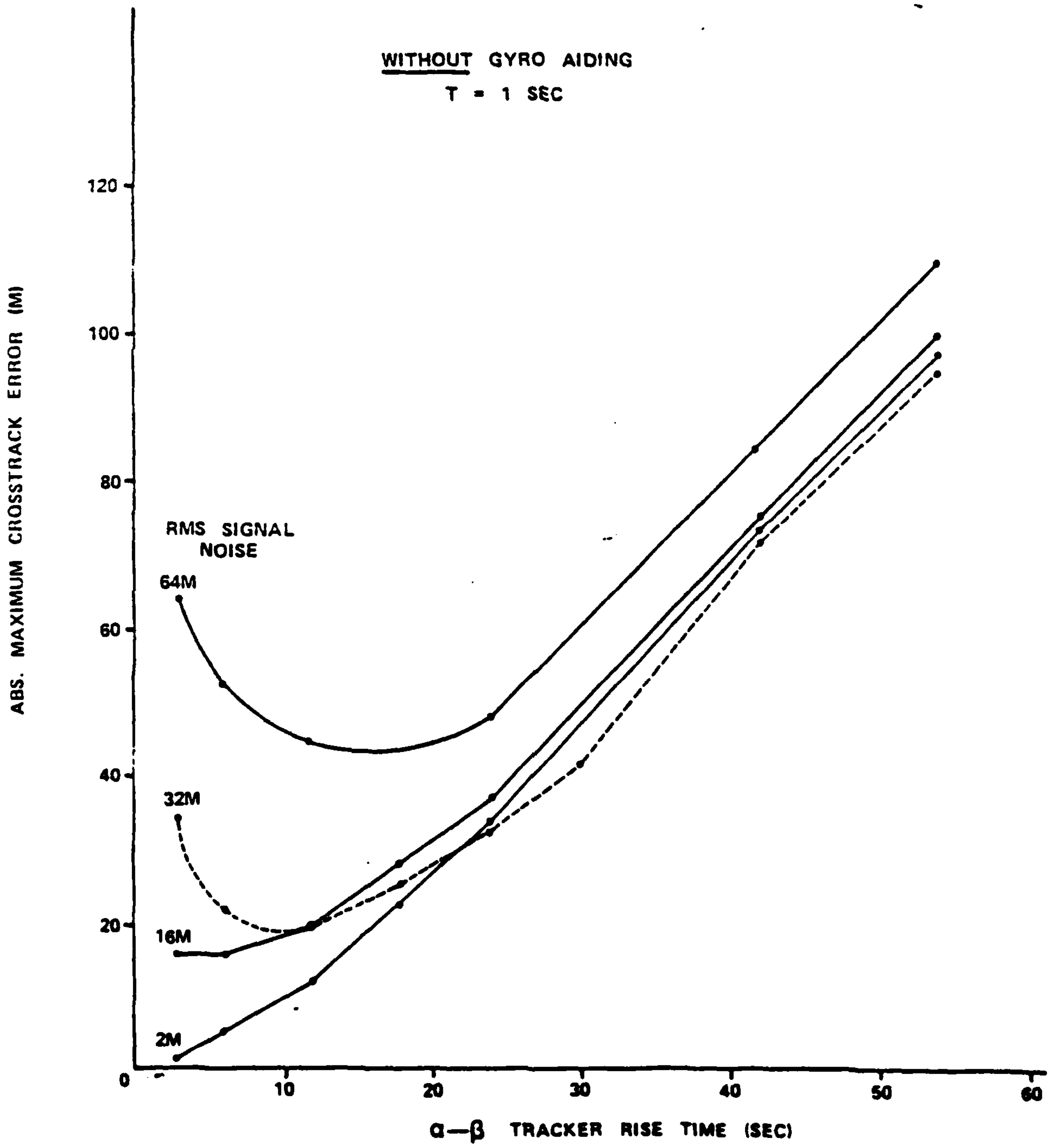

Figure A.7. Absolute Value of the Maximum Crosstrack Position Error for α - β Trackers, 30,000 dwt Tanker, 35 Degrees Turn, 8 Knots

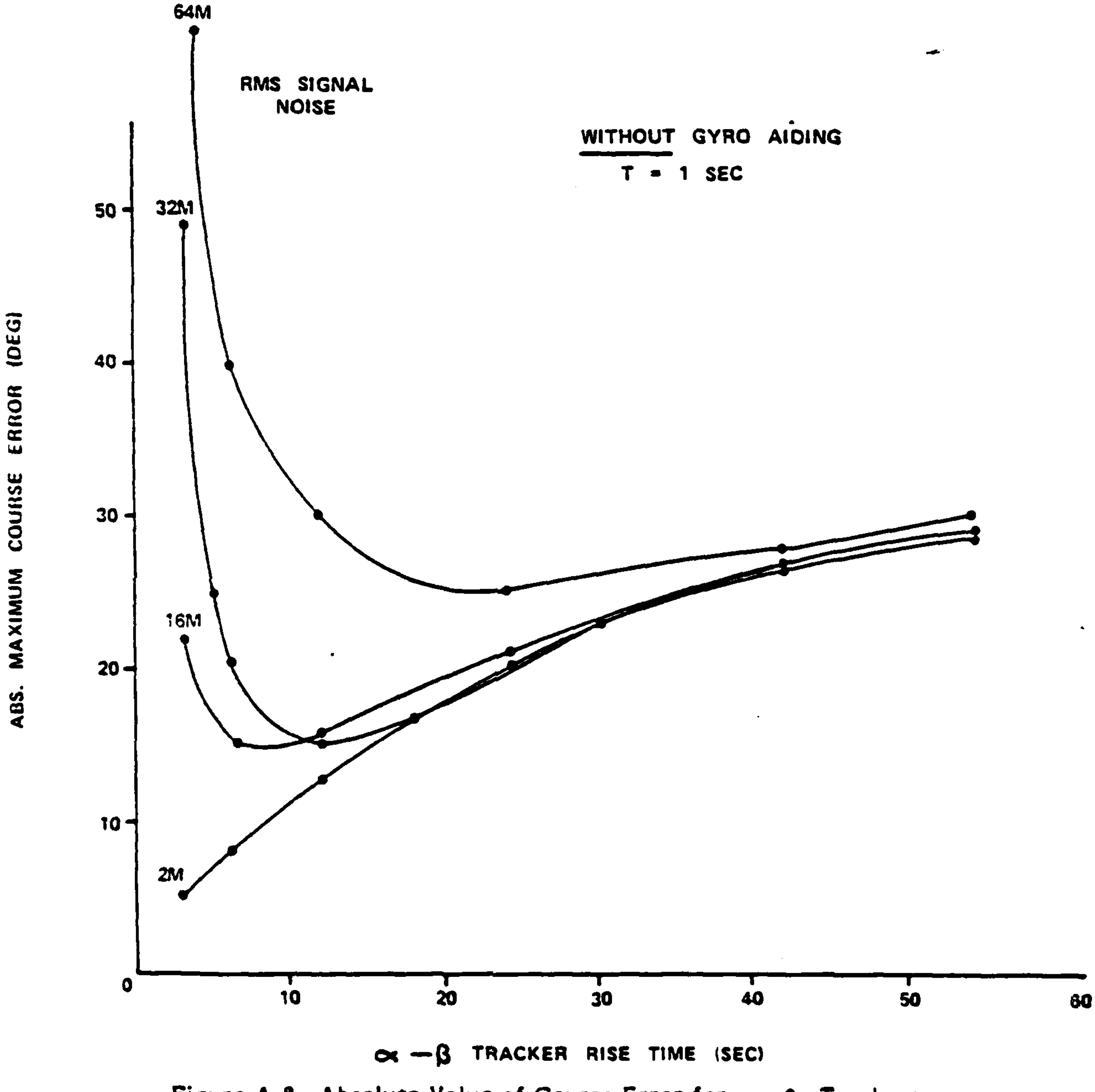

Figure A.8. Absolute Value of Course Error for α-β Trackers
30,000 dwt Tanker, 35 Degree Turn, 8 Knots

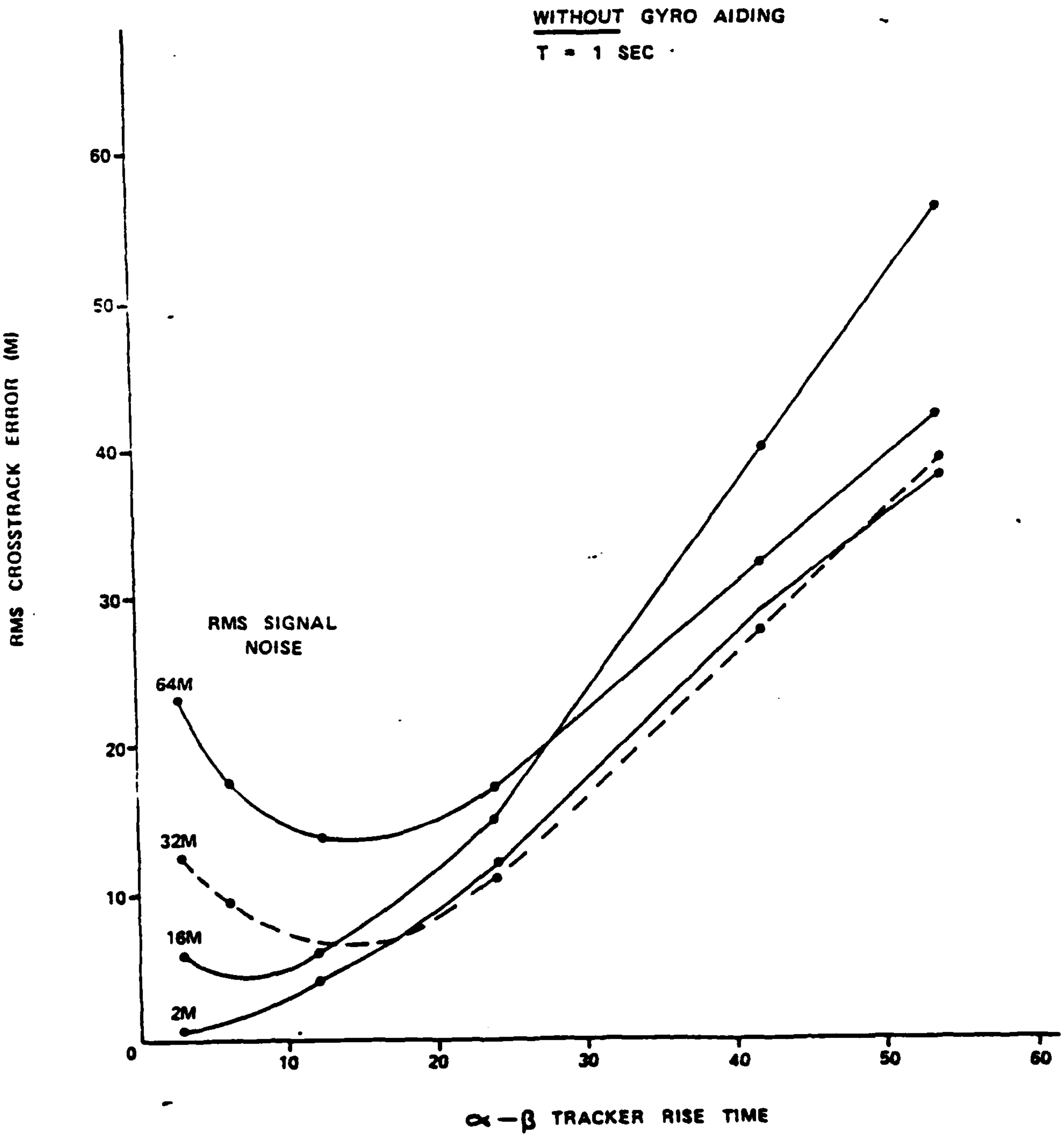

Figure A.9. RMS Crosstrack Error for α-β Trackers
30,000 dwt Tanker, 35 Degree Turn, 8 Knots

the actual ships track in Leg 2. As will be discussed in the next section, much of this lag behavior can be corrected through the addition of gyro aiding to the tracker.

The performance measures in Figures A.7 through A.9 show the rise time to be nearly equal for achieving minimum crosstrack error, course error, and rms crosstrack error. The optimum value to be used, however, is 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 m). Higher rise times, 10 to 20 seconds, seem appropriate for higher rms noise (32 to 64 m). This shift occurs principally as a function of the noise masking the tracker lag error for larger noise levels and lower rise times. Note that for very long rise times the errors asymptotically approach the tracker performance with 2 m noise. Thus in the limit, the errors caused by tracker lag dominate the noise errors. These effects can be observed in the individual track data shown in Figures B.1 through B.24 in Appendix B.

A special note should be made of the large course errors shown in Figure A.8. For moderate to large noise levels, the maximum course errors are quite large (i.e., in excess of 15 degrees). Such errors could severely degrade the effectiveness of a navigation display which displays this parameter directly or parameters derived therefrom (e.g., crosstrack velocity). As will be seen, gyro aiding significantly reduces the maximum crosstrack error.

<u>Addition of Gyro Aiding to $\alpha - \beta$ Trackers in a Navigation System for Ships</u>

The performance of the $\alpha - \beta$ trackers in the turn suggests that to achieve longer tracker rise times, the tracker performance in turns must be improved. Symptomatic of the long rise time conditions is the trackers' inability to rapidly detect the changing velocities. Yet in the turn, given the ship's turning rate, it is possible to reasonably estimate the velocity changes if it is assumed the ship is moving along a circular path with approximately a constant turn rate and a constant velocity. Consider the geometric relationships illustrated in Figure A.10. It is possible to derive the velocity changes for each sample interval according to the following relationships:

Estimated ship's velocity at sample interval n:

$$\hat{Y}_n = \left(\hat{X}_n^2 + \hat{Y}_n^2 \right)^{1/2} \qquad \text{(A-11)}$$

Estimated change in ship's velocity at sample interval n+1: (assuming small angle approximations)

$$\Delta\hat{V}_{n+1} = (\gamma/2)\,\hat{V}_n \qquad \text{(A-12)}$$

or for constant turn rate ($\hat{\theta}_n = \hat{\theta}_{n+1}$)

$$\Delta\hat{V}_{n+1} = (\hat{\theta}_{n+1}/2)\,T\,\hat{V}_n \qquad \text{(A-13)}$$

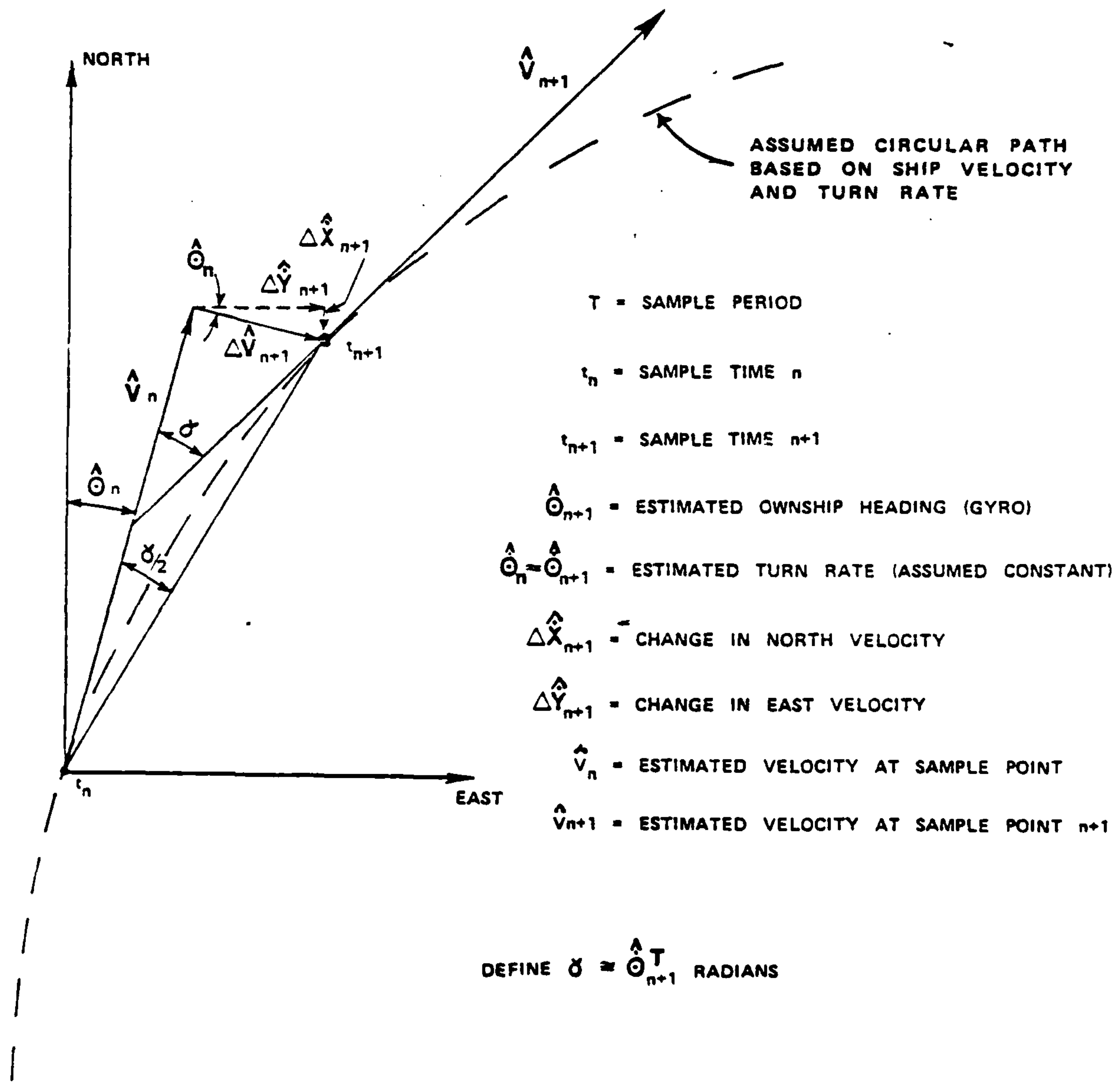

Figure A.10. Velocity Relationships for Ship Moving on a Circular Path (Constant Turn Rate)

Estimated change in ship's north velocities at sample interval n+1:

$$\Delta\hat{\dot{X}}_{n+1} = -(\hat{\dot{\theta}}_{n+1}/2)\, T\, \hat{V}_n \sin \hat{\theta}_{n+1} \qquad \text{(A-14)}$$

Estimated change in ship's east velocities at sample interval n+1:

$$\Delta\hat{\dot{Y}}_{n+1} = (\hat{\dot{\theta}}_{n+1}/2)\, T\, \hat{V}_n \cos \hat{\theta}_{n+1} \qquad \text{(A-15)}$$

As noted in the equations the current estimate of ownships heading ($\hat{\theta}_{n+1}$) and turn rate ($\hat{\dot{\theta}}_{n+1}$) are used to calculate the velocity changes. Ideally an average of the current estimates and the previous estimates could be used but since these variables change rather slowly, the introduced error is estimated to be small.

The velocities changes may be added directly to the tracker equations by replacing the previous estimated velocity with a sum of the previous estimated velocity and the changed velocities.

$$\hat{\dot{X}}_n \text{ becomes } (\hat{\dot{X}}_n + \Delta\hat{\dot{X}}_{n+1})$$

The gyro aided $\alpha - \beta$ tracker equations (equations A-1 through A-3) become:

$$\hat{X}_{n+1} = \hat{X}^1_{n+1} + \alpha\, (X_{n+1} - \hat{X}^1_{n+1}) \qquad \text{(A-16)}$$

$$\hat{\dot{X}}_{n+1} = (\hat{\dot{X}} + \Delta\hat{\dot{X}}_{n+1}) + \frac{\beta}{T}\, (X_{n+1} - \hat{X}^1_{n+1}) \qquad \text{(A-17)}$$

$$\hat{X}^1_{n+1} = \hat{X}_n + T\, (\hat{\dot{X}}_n + \Delta\hat{\dot{X}}_{n+1}) \qquad \text{(A-18)}$$

As will be seen in the analysis of the performance of this tracker, the assumption of constant turn rate and constant velocity is sufficiently in error that improvements can be made by changing a multiple of $\hat{\dot{\theta}}$ in the $\Delta\hat{\dot{X}}_{n+1}$ and $\Delta\hat{\dot{Y}}_{n+1}$ equations.

Implementation of the gyro-aiding filter was made as shown in Figure A-11. Equations A-16 through A-18 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.

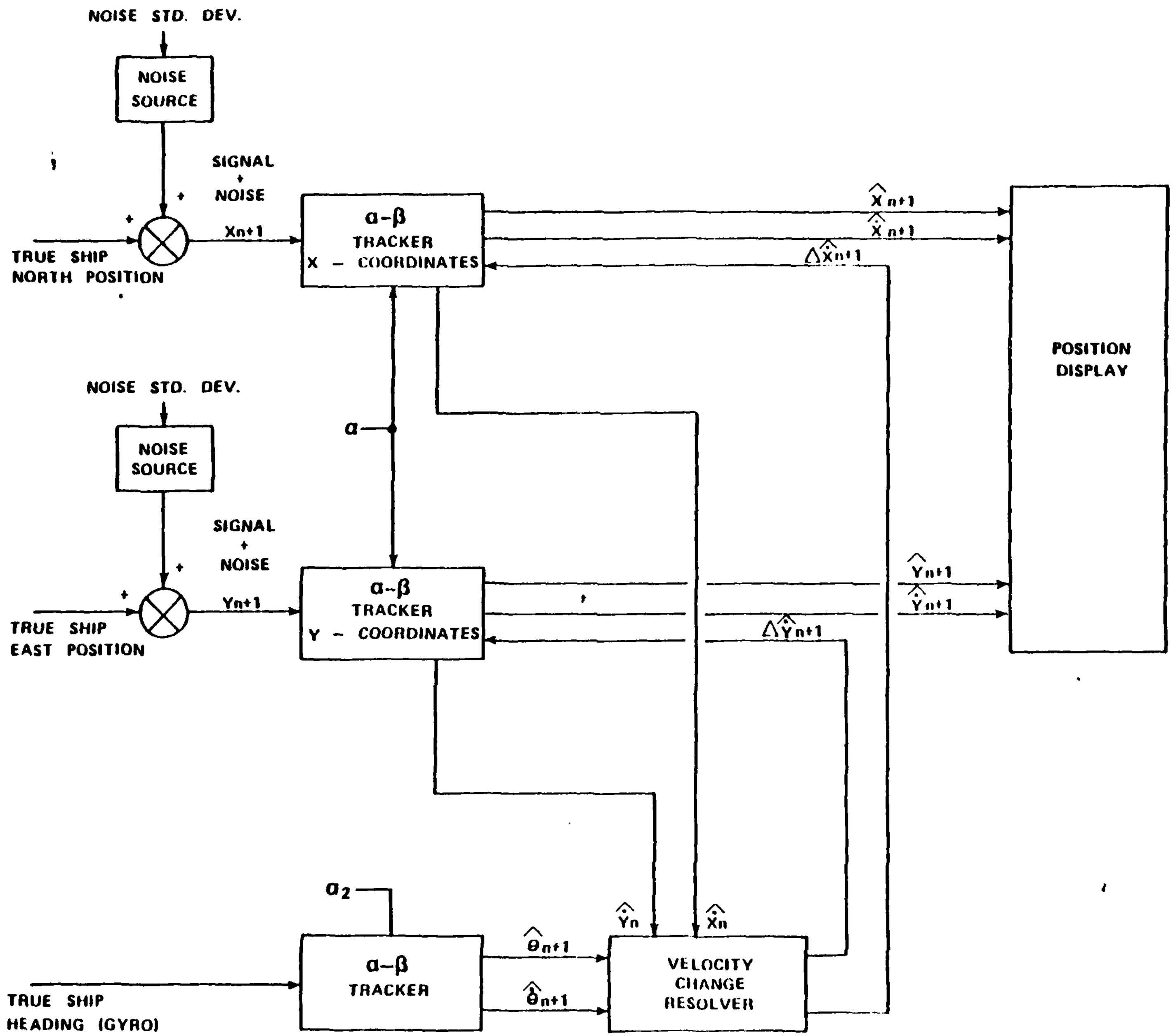

Figure A.11. Implementation Navigation System with Gyro Aiding

The initial analysis of gyro aiding sought to select an appropriate rise time for the gyro tracker an approximate multiples for the velocity change variables (equations A-14 and A-15). The baseline conditions selected were 32 m rms signal noise, with a 30 second rise time in the position trackers ($\alpha = 0.027$). The sample period was equal to 1 second. Figures A.12 and A.13 summarize the performance for these runs. As indicated, the 0.5 multiple of $\hat{\dot{\theta}}_{n+1}$ in the speed change equations (A-14 and A-15) proved to be limiting to the gyro aiding. By changing the multiple to 1.0 both the maximum crosstrack position error and maximum course error were reduced. Additionally, these data imply a rise time of between 2 and 4 seconds for the gyro tracker achieves a low valve for both maximum crosstrack error and maximum course error. 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 refine the multiple of $\hat{\dot{\theta}}_{n+1}$ in the speed change equations. Evaluation runs with zero rms noise were run. Maximum crosstrack error and maximum course error were evaluated. Figures A.14 and A.15 indicate the resultant performance. A multiple between 0.85 and 1.0 seem to minimize errors. The multiple of 0.85 was selected for all subsequent gyro aiding analyses. However, further investigation of the sensitivity of this multiple to ship size, turn angle, ship speed, rudder application, etc., is warranted.

The speed change equations were modified to be:

Estimated change in ship's north velocity at sample interval n+1

$$\Delta\hat{\dot{X}}_{n+1} = -(0.85\ \hat{\dot{\theta}}_{n+1})\ T\ \hat{V}_n \sin\hat{\theta}_{n+1} \qquad \text{(A-19)}$$

Estimated change in ship's east velocity at sample interval n+1

$$\Delta\hat{\dot{Y}}_{n+1} = (0.85\ \hat{\dot{\theta}}_{n+1})\ T\ \hat{V}_n \cos\ \hat{\theta}_{n+1} \qquad \text{(A-20)}$$

Equations A-16 through A-18 remained unchanged. Equations A-16 through A-20 were implemented for the gyro aiding tracking system in future RA-2 experiments.

Performance of α-β Trackers with Gyro Aiding

The effectiveness of gyro aiding was evaluated by applying the new tracker configurations to the 30,000 dwt tanker executing a 35-degree turn at 8 knots. Figures A.16 and A.17 show the tracks of the ship and α - β trackers with and without gyro aiding. The rms noise was 32 m (105.6 ft) for both runs, tracker rise time was 42 seconds ($\alpha = 0.019$) and T = 1 sec. The rather dramatic reduction in tracker error through the turn results in a reduced maximum crosstrack error, a reduction in the maximum course error and a reduction in rms crosstrack error.

Figures A.18, A.19, and A.20 summarize the gyro aided tracker performance in the 35-degree turn for alternate levels of signal noise and position tracker rise times.

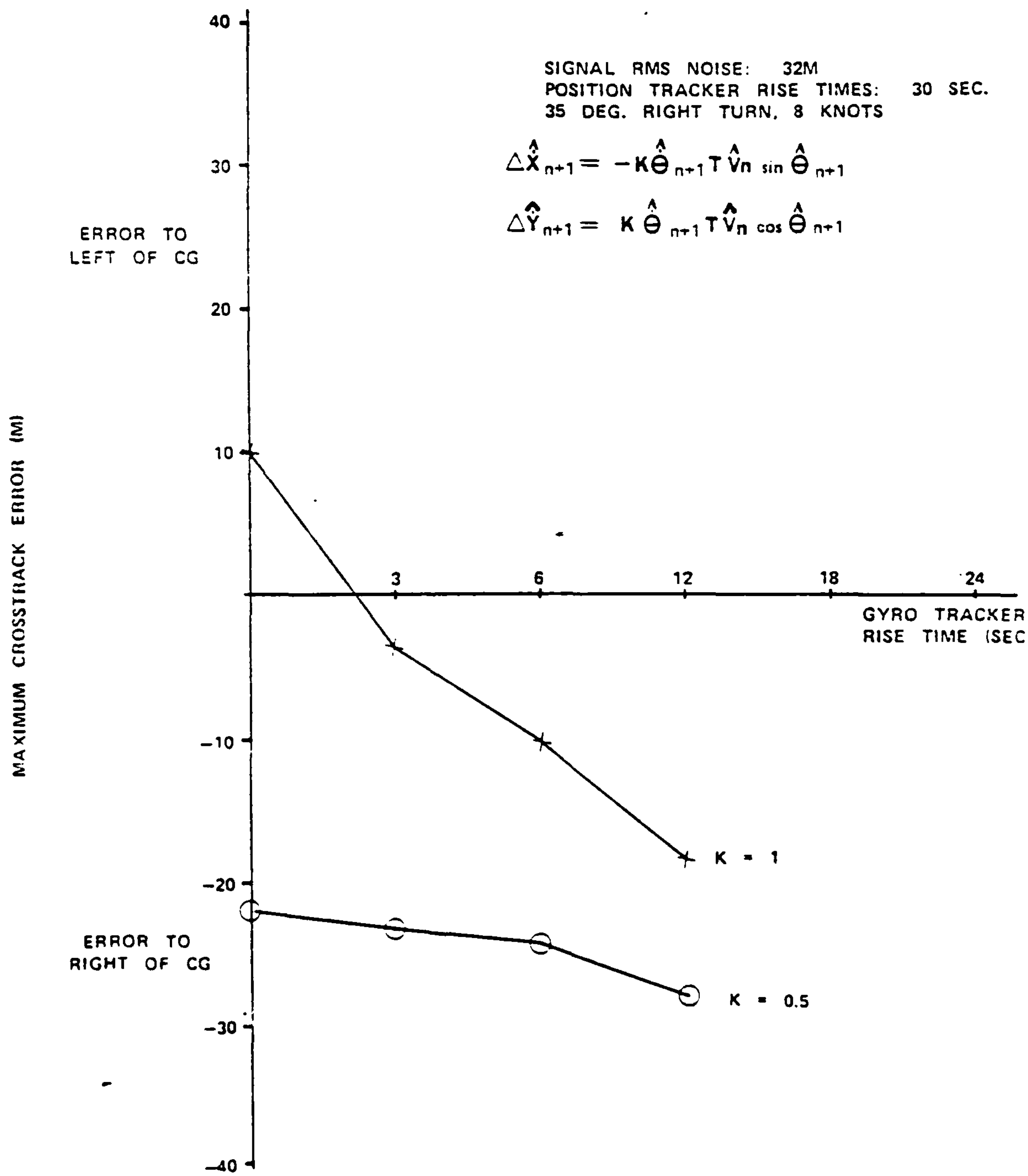

Figure A.12. Selection of Gyro Tracker Rise Time Based on Maximum Crosstrack Error

AD-A106 941 ECLECTECH ASSOCIATES INC NORTH STONINGTON CT F/G 17/7
SIMULATOR EVALUATION OF ELECTRONIC RADIO AIDS TO NAVIGATION DIS--ETC(U)
JAN 81 R . COOPER, K L MARINO, W R BERTSCHE DOT-CG-835285-A
UNCLASSIFIED EA-80-U-86 NL

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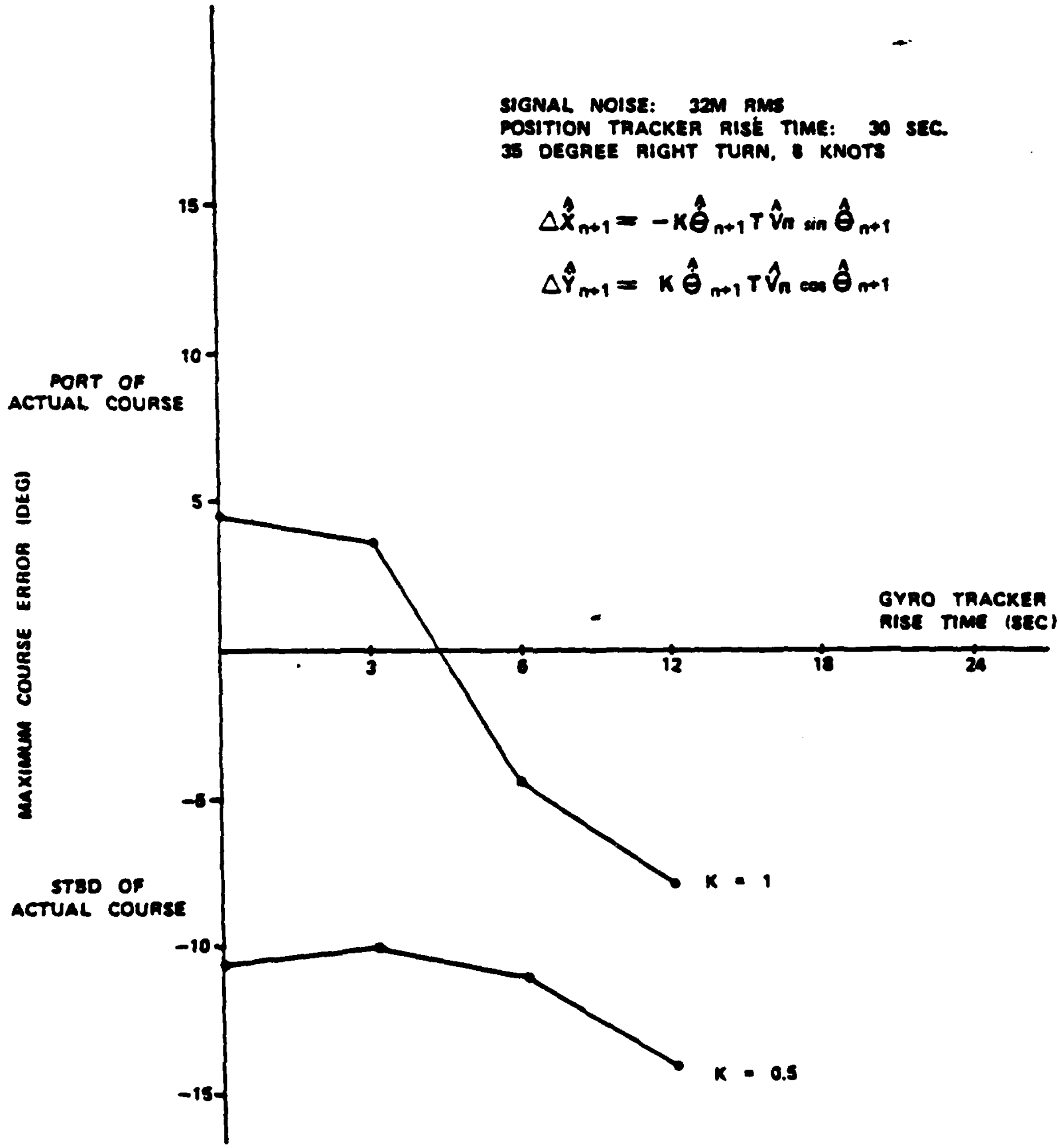


Figure A.13. Selection of Gyro Tracker Rise Time Based on Maximum Crosstrack Error

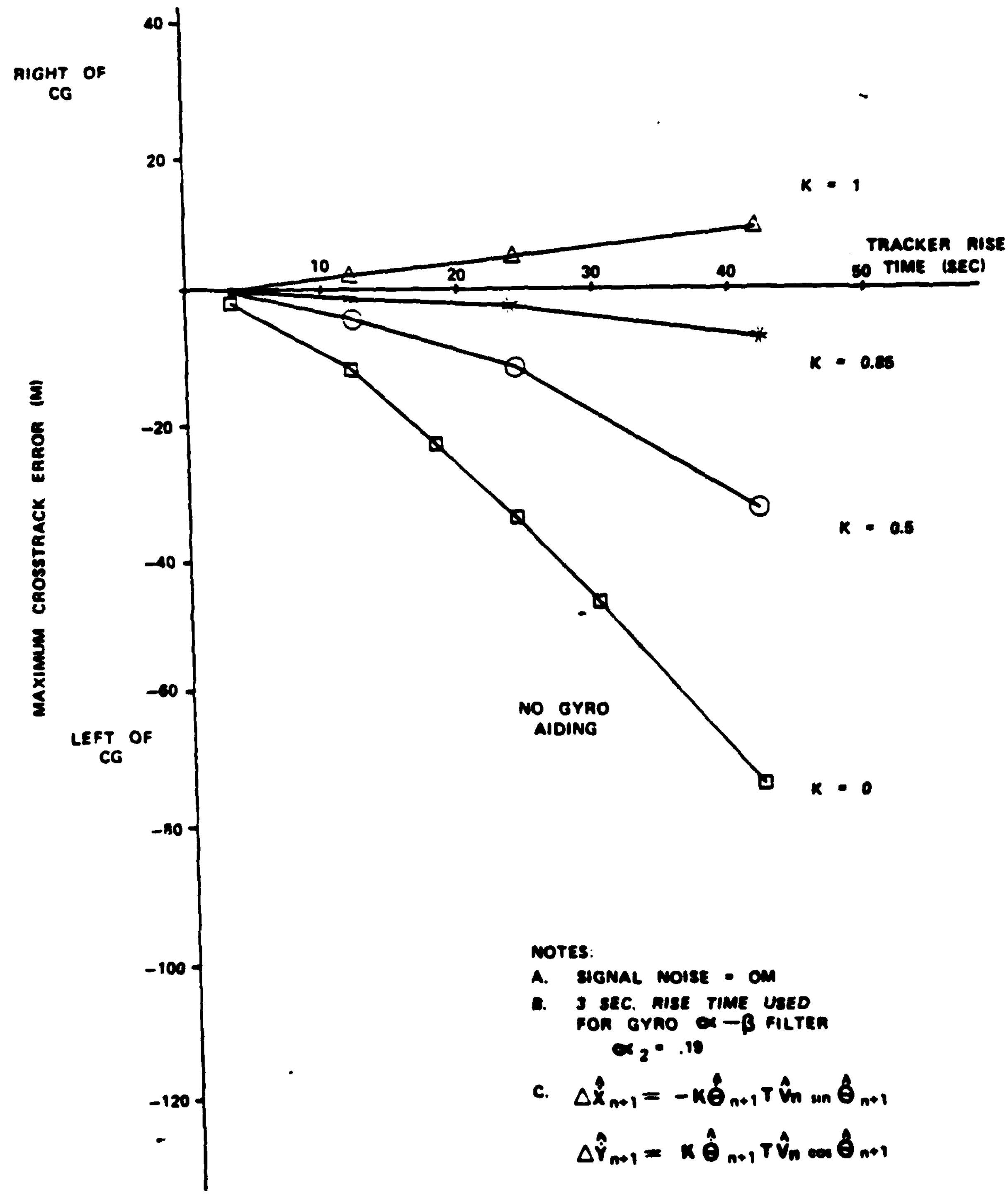


Figure A.14. Maximum Crosstrack Position Error Following a Right 35 Degree Turn, 30,000 dwt Tanker

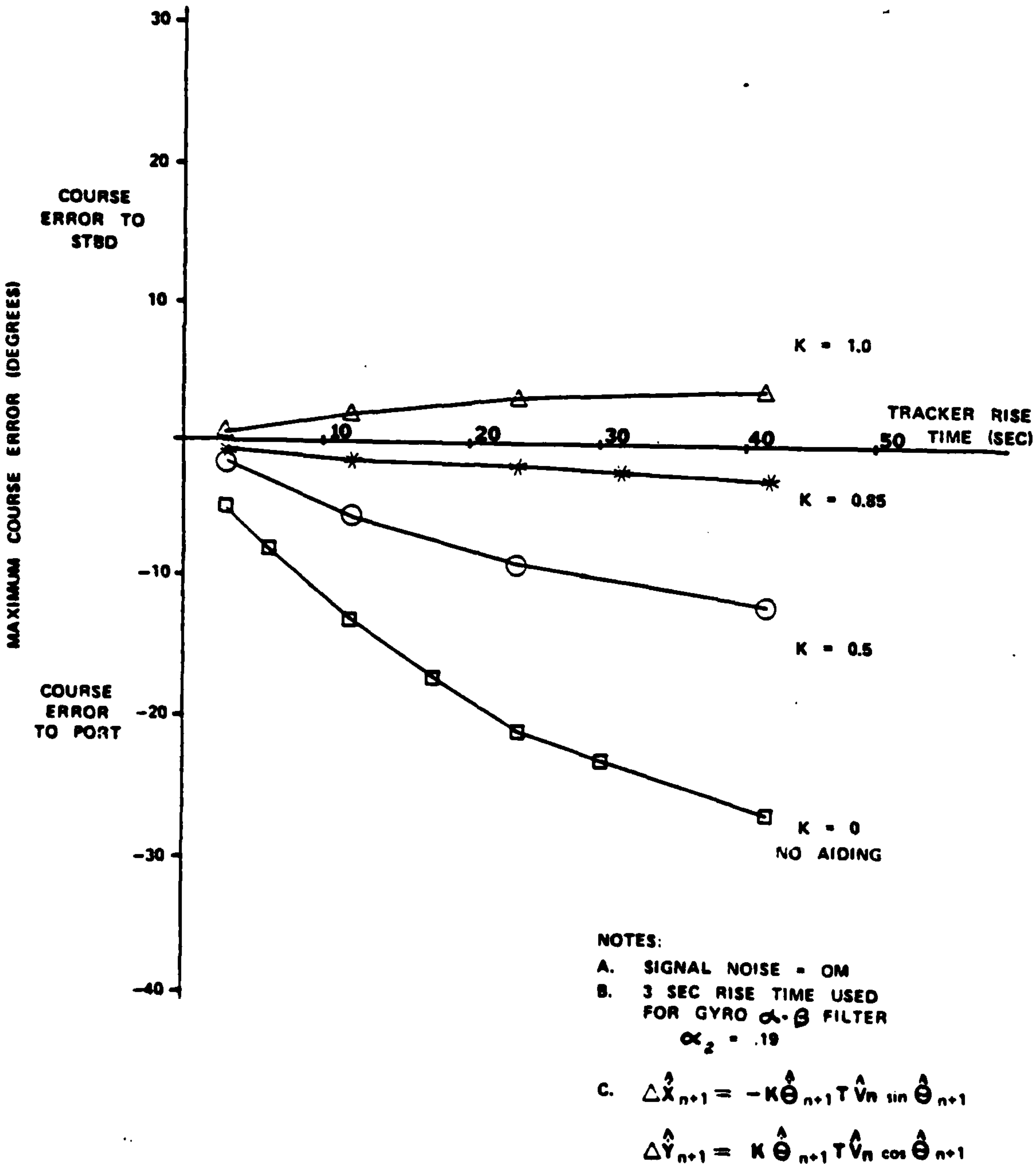


Figure A.15. Maximum Course Error Following a Right 35 Degree Turn
30,000 dwt Tanker

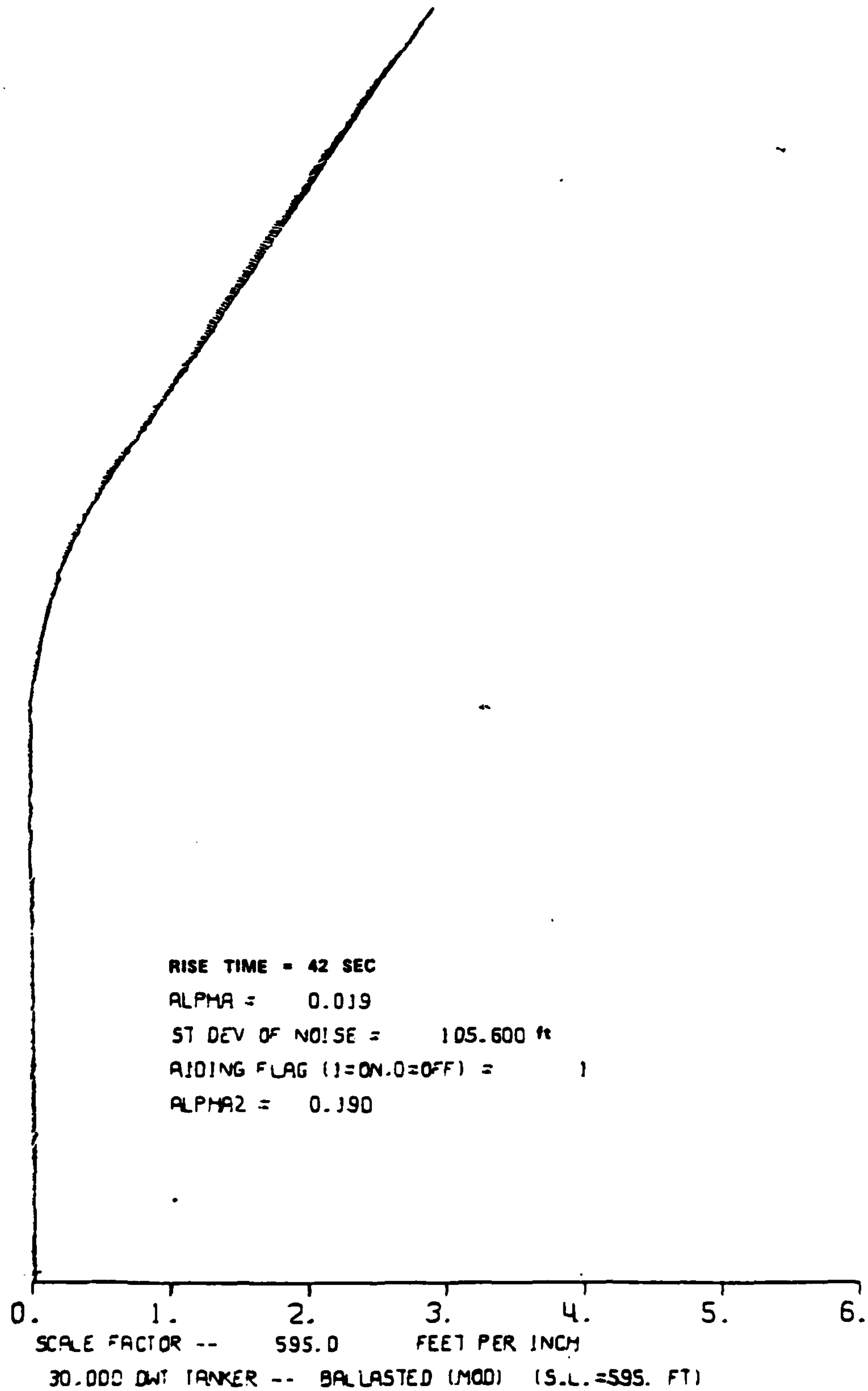


Figure A.16. α - β Tracker Performance With Gyro Aiding, Rise Time 42 Seconds, 30,000 dwt Ship, 35 Degree Turn, 8 Knots

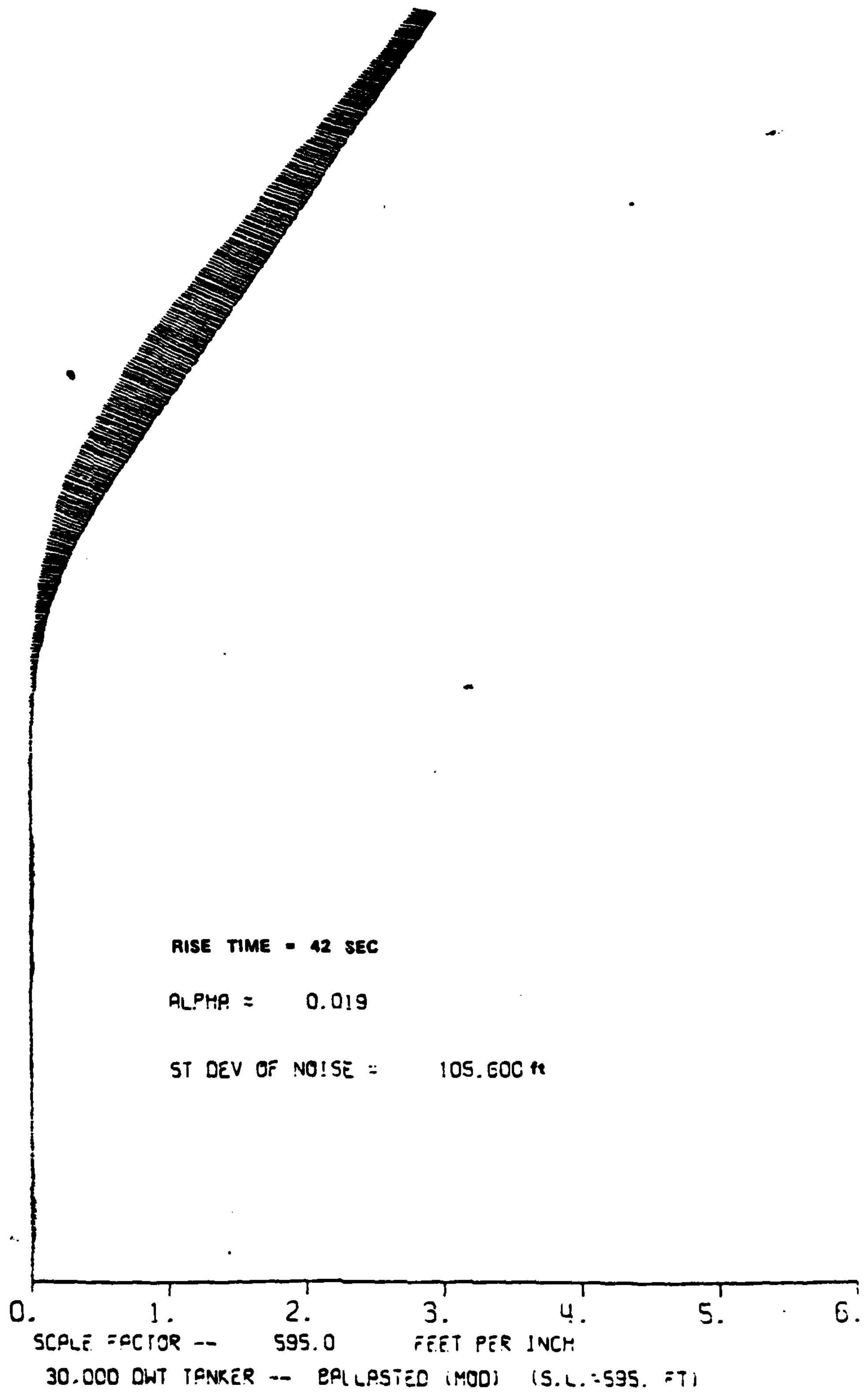


Figure A.17. α-β Tracker Performance Without Gyro Aiding Rise Time 42 Seconds, 30,000 dwt Ship, 35 Degree Turn, 8 Knots

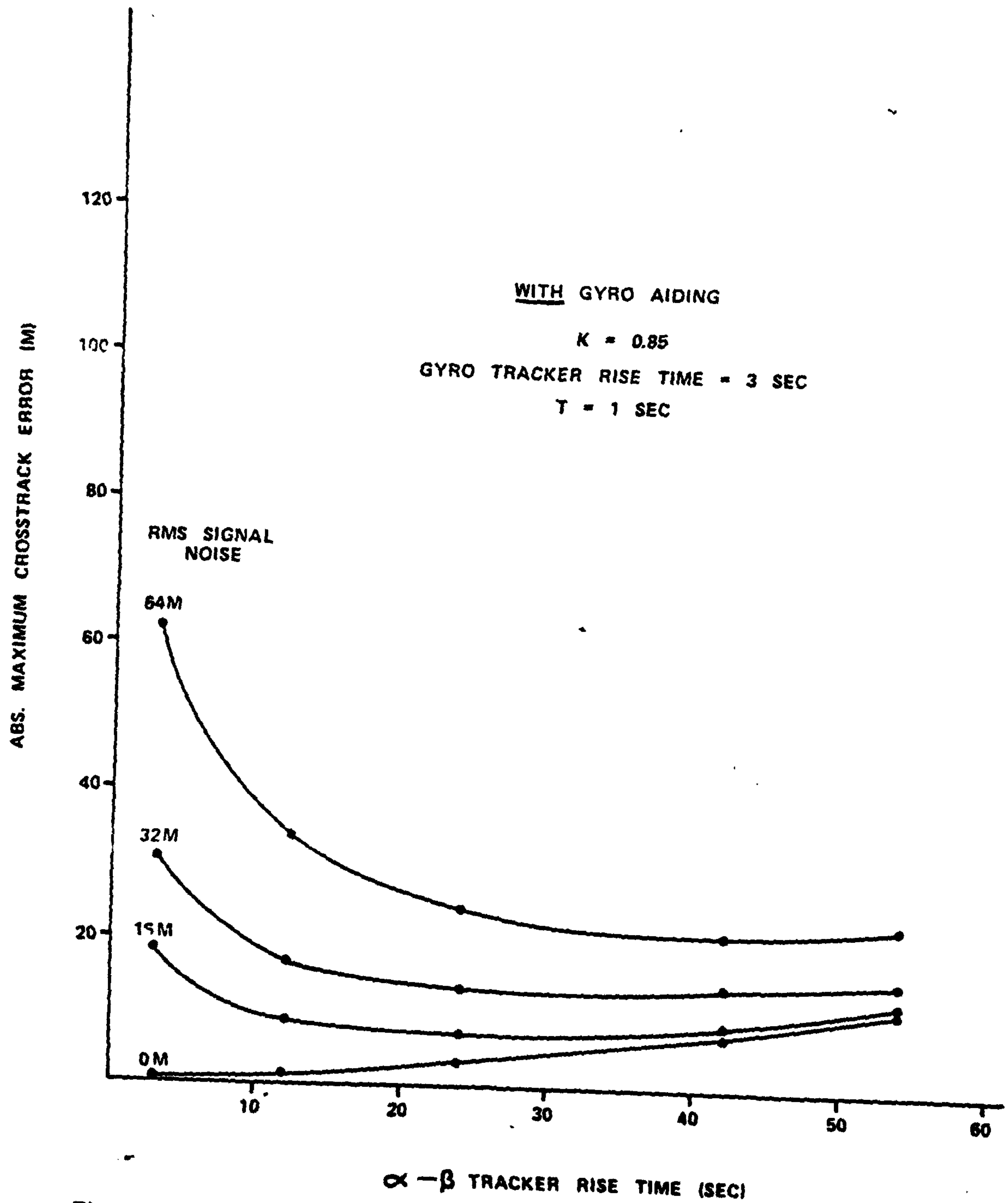


Figure A.18. Absolute Value of the Maximum Crosstrack Position Error for α- β Trackers With Gyro Aiding, 30,000 dwt Tanker, 35 Degree Turn, 8 Knots

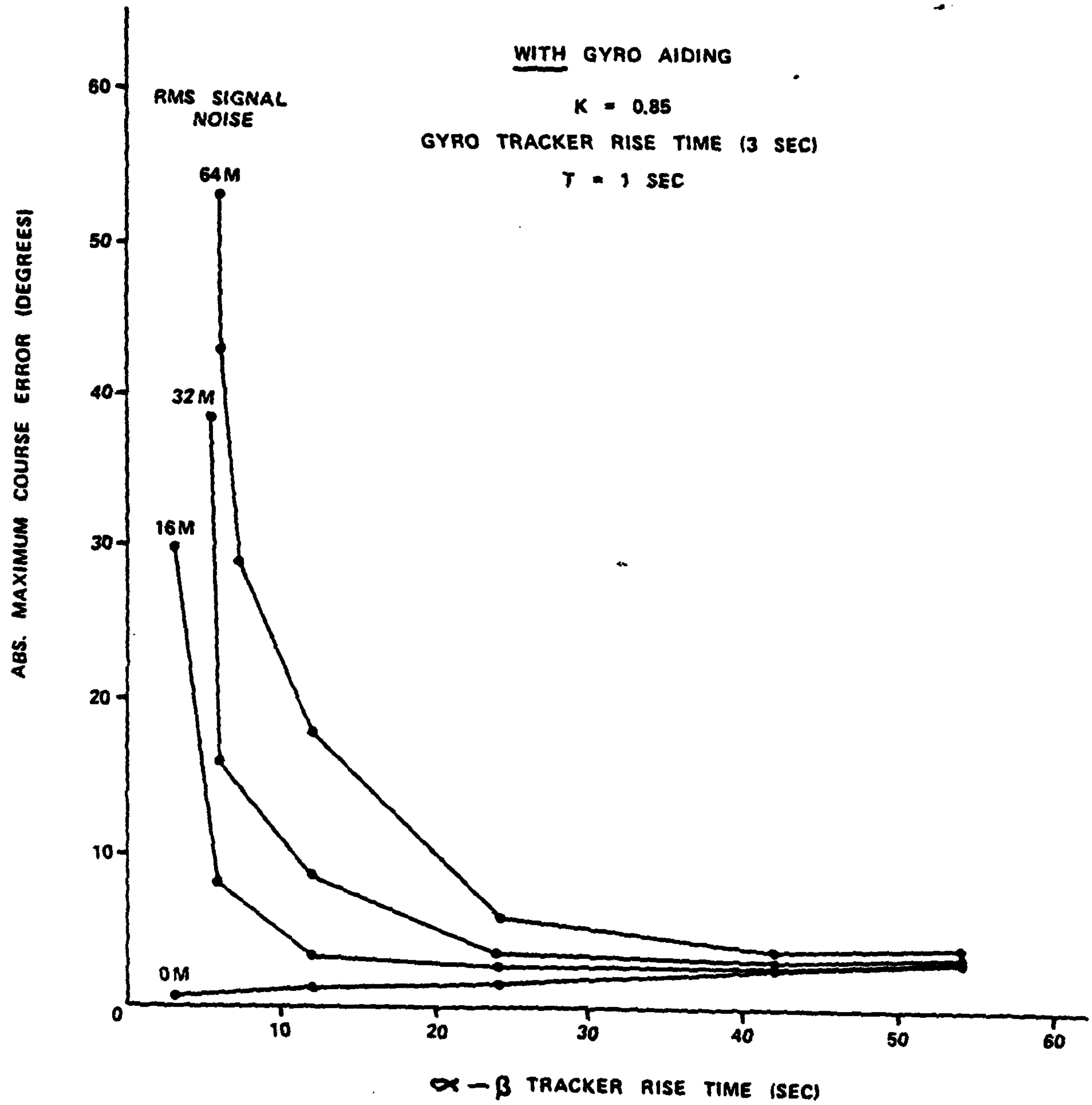


Figure A.19. Absolute Value of a Course Error for α- β Trackers <u>With</u> Gyro Aiding, 30,000 dwt Tanker, 35 Degree Turn, 8 Knots

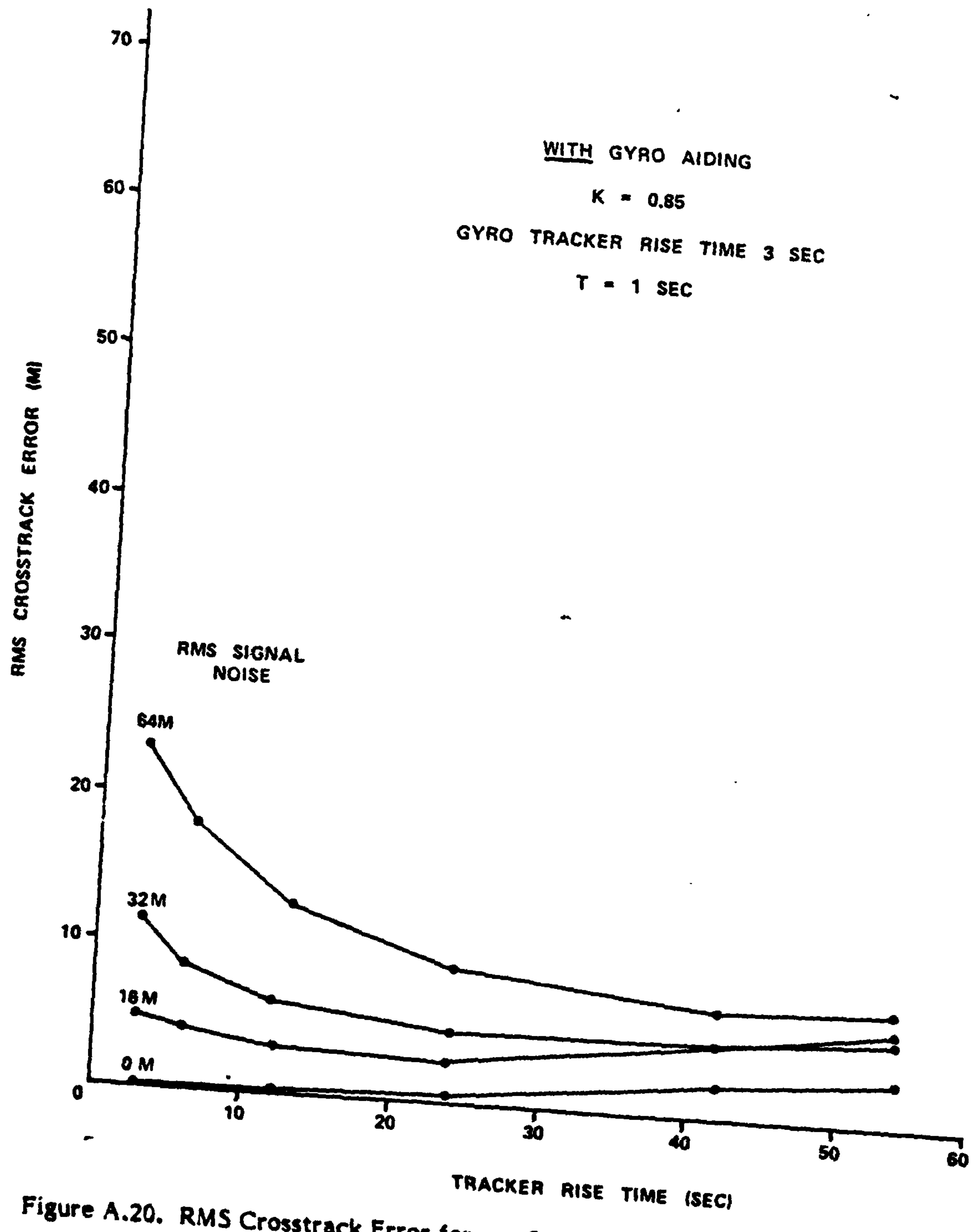


Figure A.20. RMS Crosstrack Error for α-β Trackers, With Gyro Aiding
30,000 dwt Tanker, 35 Degree Turn, 8 Knots

Rise times which achieve minimum errors seem to fall between 20 and 42 seconds (compared to 2 to 20 seconds for the unaided trackers). Interestingly, the minimum values appear to be less sensitive to the value of rise time as a function of noise level. A rise time of 36 seconds seems to be a good choice for signal noise 2 m to 64 m.

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. Data in Figure A.19 show that even with 64 m rms noise the maximum course error is reduced to under 4 degrees. This improvement, however, must be viewed with some caution since review of the individual run data showed course error to be biased to the right or left for several minutes. Such a long-term bias, even small, might cause a piloting problem.

The individual track plots for the gyro aiding analyses appear in Figures B.25 through B.48 in Appendix B. Grouped by rms signal noise level, improved performance with longer rise times is evident. These figures, however, indicate one trend which must be considered. The position trackers exhibited a potential instability for large rise times. Consider Figure B.30, 0 rms noise and 54 second rise time. In this plot the tracker error appears to be growing at the end of leg 2. No formal analysis of this tendency was performed, but before practical implementation of gyro aided filters is attempted, a more thorough analysis of this phenomenon should be made.

APPENDIX B

α - β TRACKER PERFORMANCE DATA WITH AND WITHOUT GYRO AIDING

B1. INTRODUCTION

The performance of the α- β 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 presented in Appendix A. Position tracker rise times of 3, 6, 12, 24, 42, and 54 seconds were evaluated for each condition. The individual track plots appear in the designated figures. Tracker sample time was T = 1 second.

<u>α - β Trackers Without Gyro Aiding</u>

rms noise = 2 m (6.6 ft)	Figures B1 - B6
rms noise = 16 m (52.8 ft)	Figures B7 - B12
rms noise = 32 m (105.6 ft)	Figures B13 - B18
rms noise = 64 m (211.2 ft)	Figures B19 - B24

<u>α - β Trackers With Gryo Aiding</u> (Gryo tracker rise time 3 seconds

$$\Delta\hat{\hat{X}}_{n+1} = (-0.85\ \hat{\hat{\theta}}_{n+1})\ T\ \hat{V}_n\ \sin\hat{\theta}_{n+1}$$

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

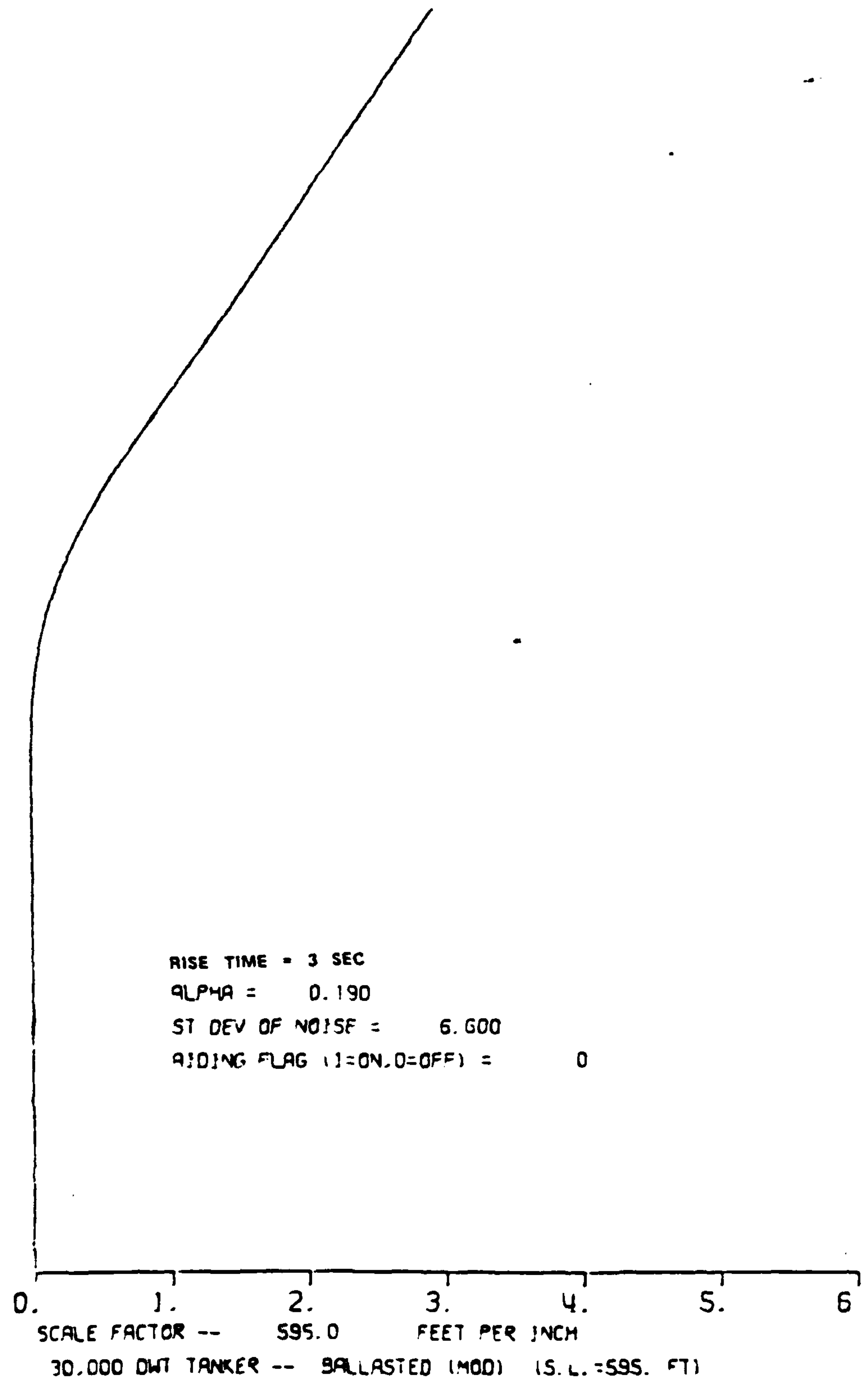
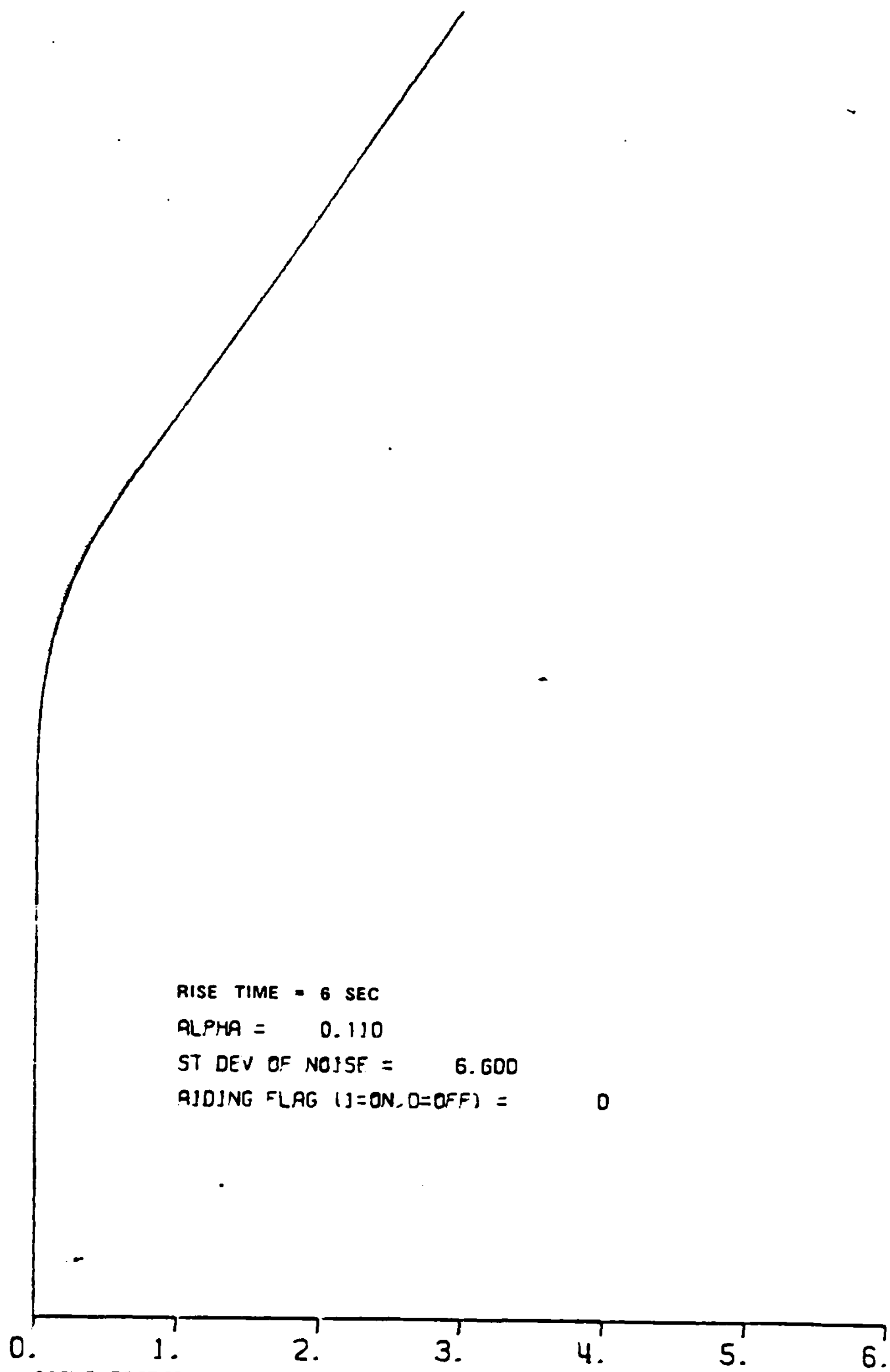

RISE TIME = 3 SEC
ALPHA = 0.190
ST DEV OF NOISE = 6.600
AIDING FLAG (1=ON,0=OFF) = 0
0.
1.
2.
3.
4.
5.
6
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.1



SCALE FACTOR -- 595.0 FEET PER INCH

30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.2

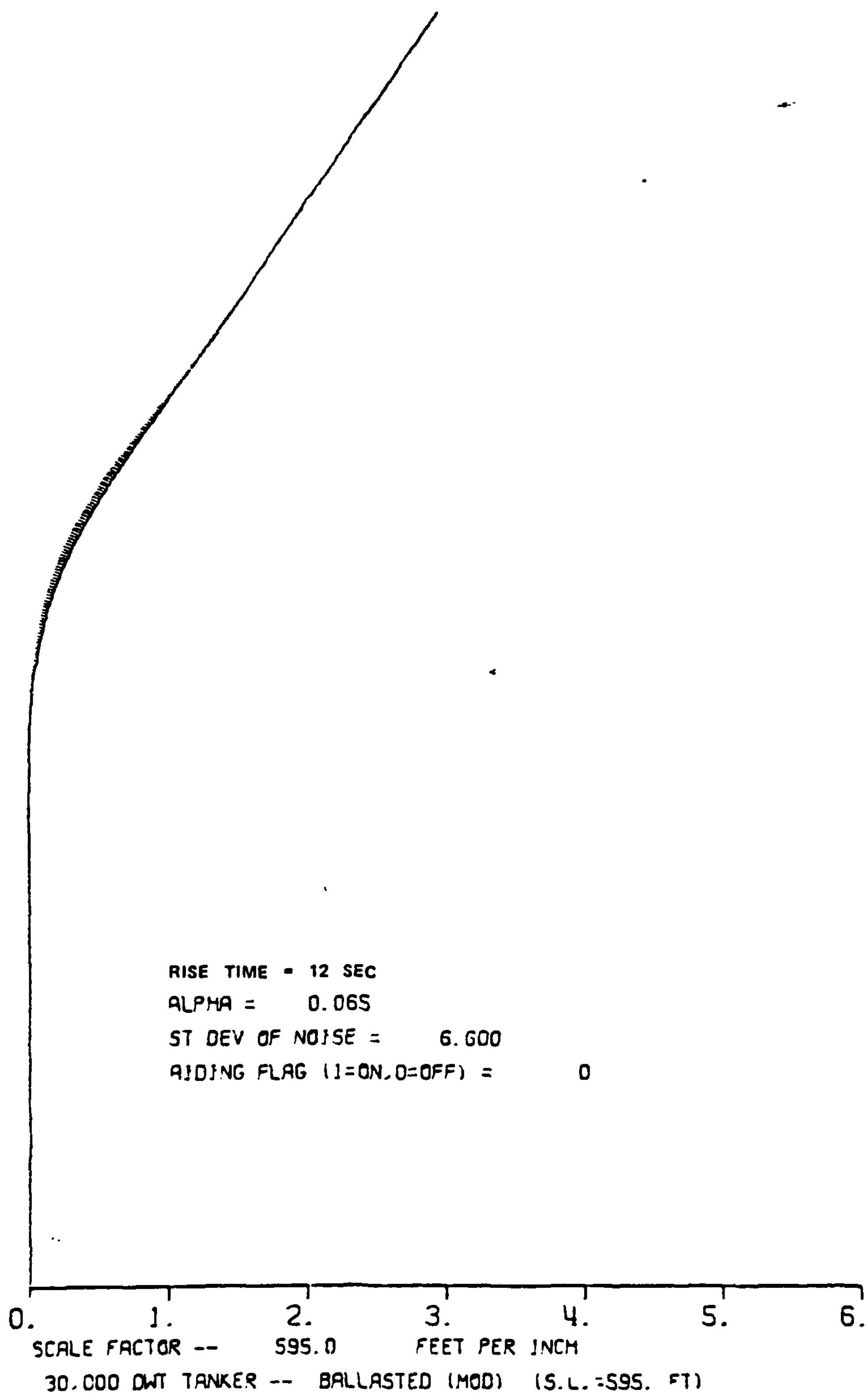

RISE TIME = 12 SEC
ALPHA = 0.065
ST DEV OF NOISE = 6.600
AIDING FLAG (1=ON,0=OFF) = 0
0. 1. 2. 3. 4. 5. 6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.3

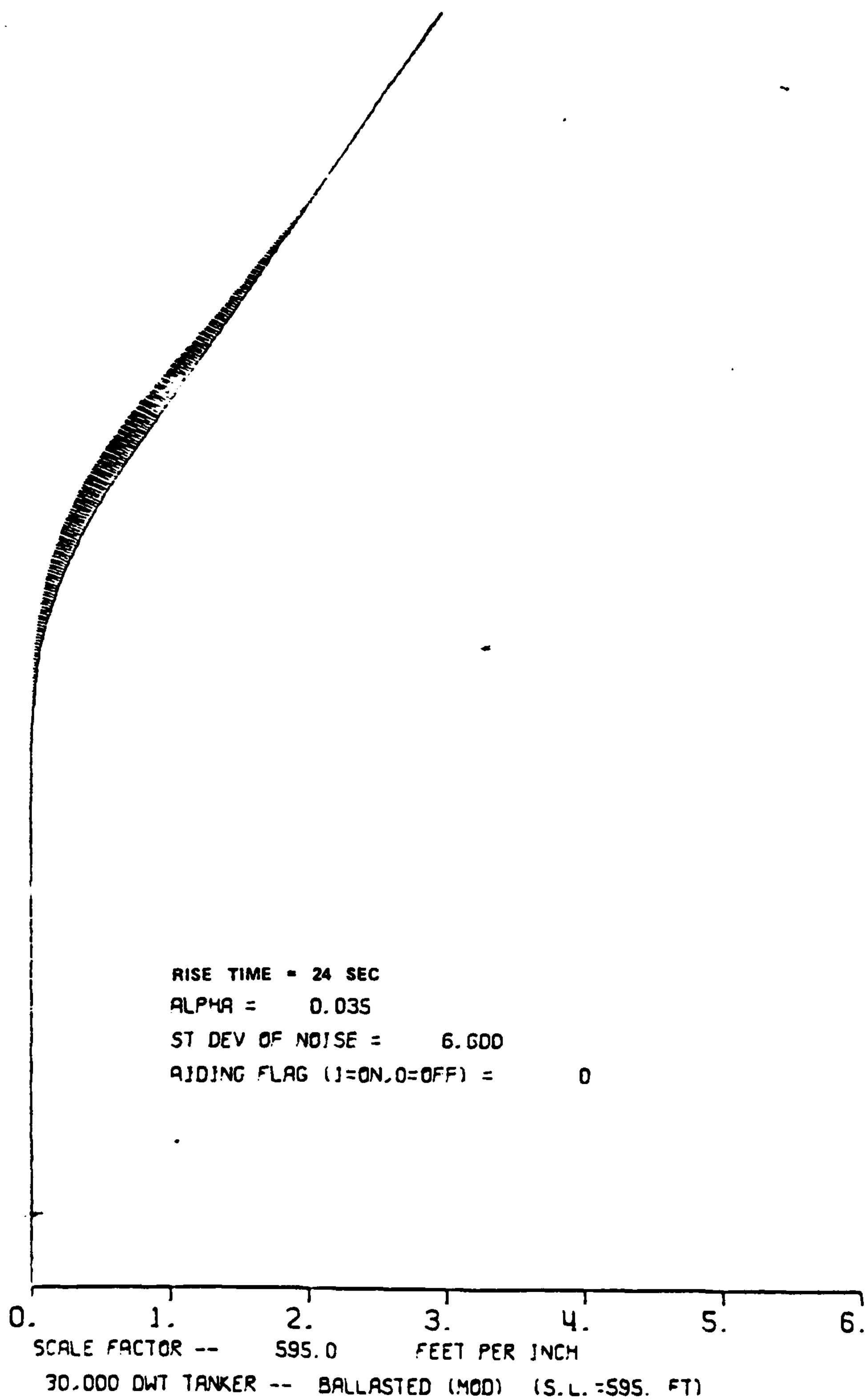
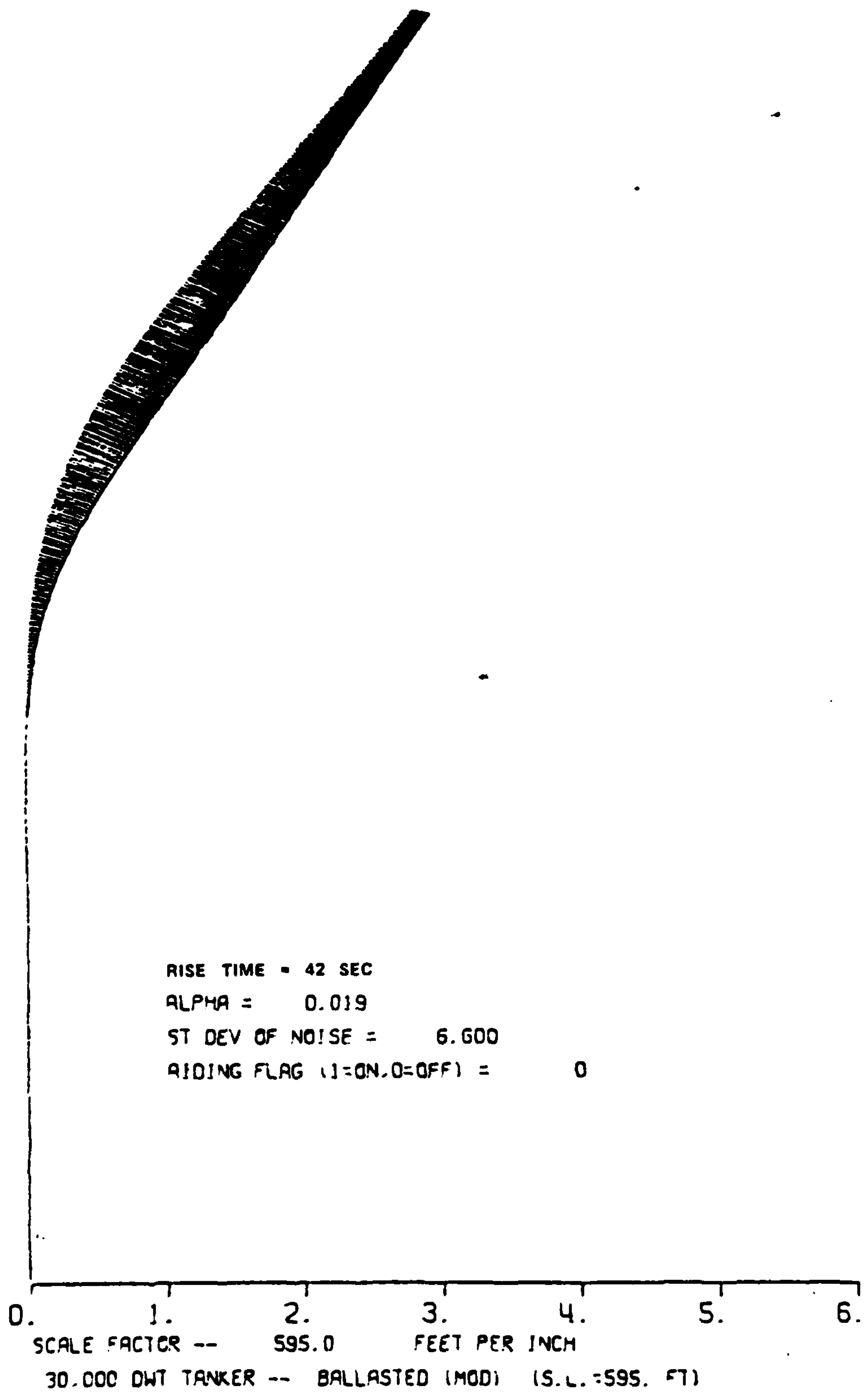

RISE TIME = 24 SEC
ALPHA = 0.035
ST DEV OF NOISE = 6.600
AIDING FLAG (1=ON,0=OFF) = 0
0. 1. 2. 3. 4. 5. 6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.4



RISE TIME = 42 SEC
ALPHA = 0.019
ST DEV OF NOISE = 6.600
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 B.5

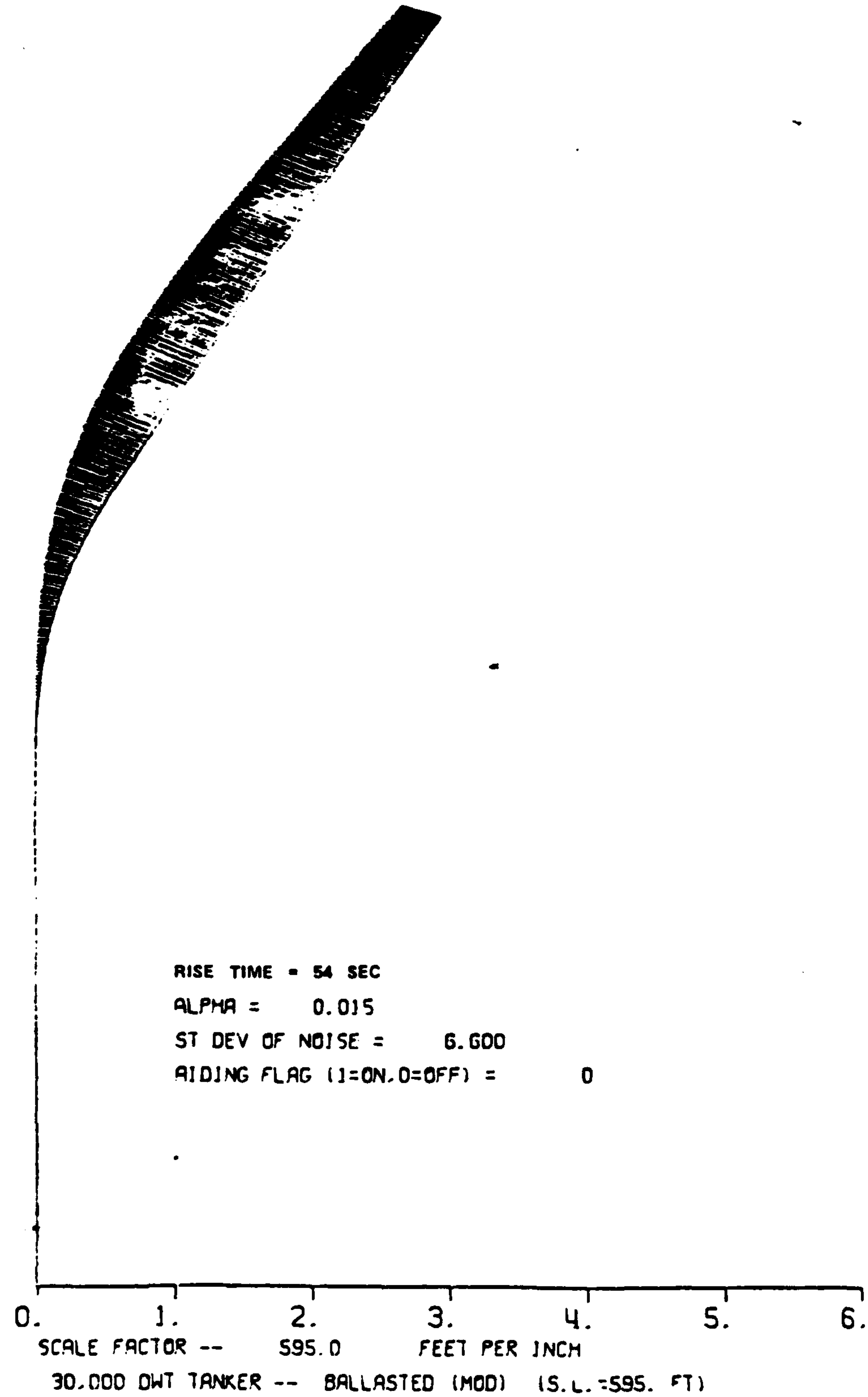

RISE TIME = 54 SEC
ALPHA = 0.015
ST DEV OF NOISE = 6.600
AIDING FLAG (1=ON,0=OFF) = 0
0. 1. 2. 3. 4. 5. 6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.6

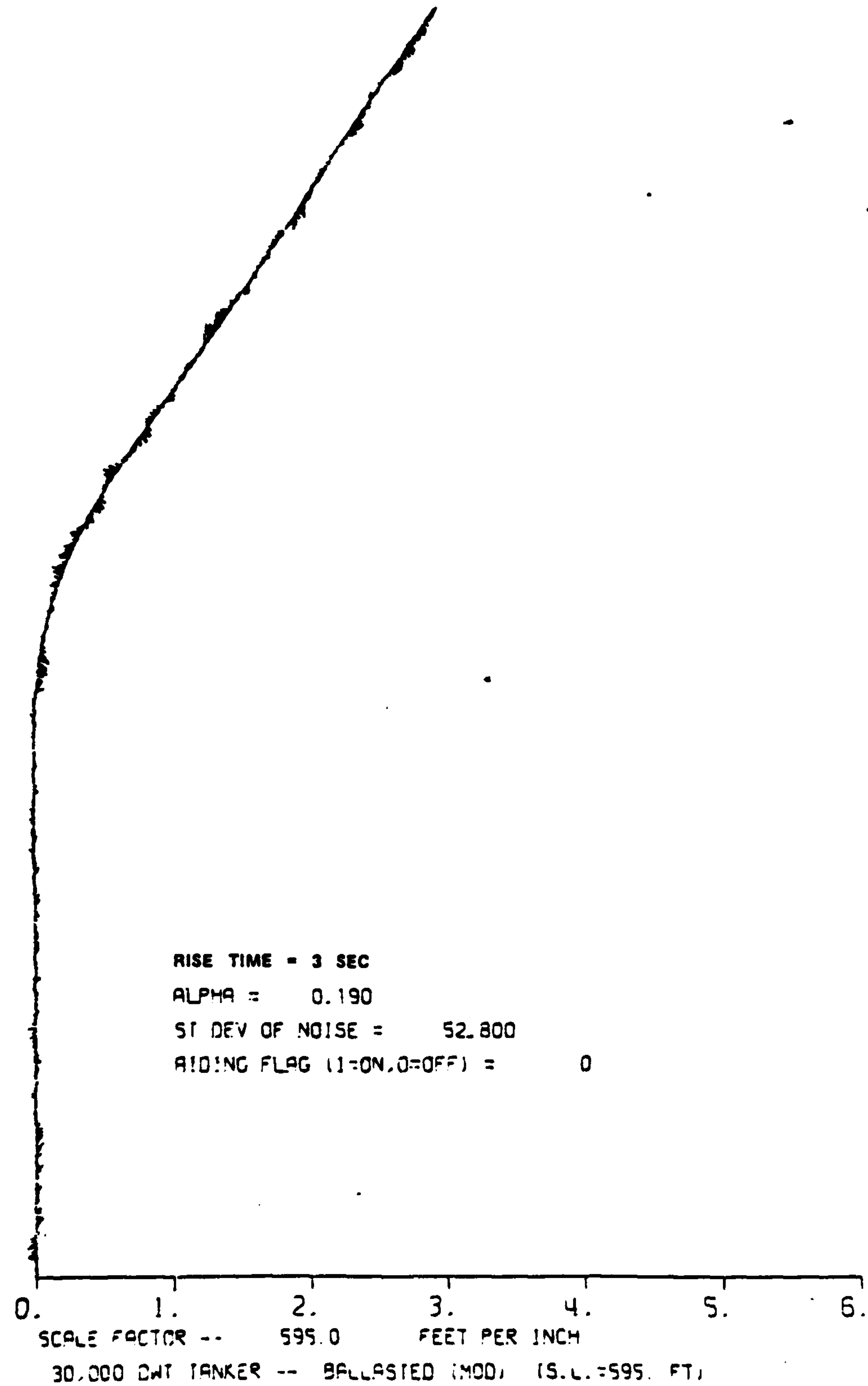

RISE TIME = 3 SEC
ALPHA = 0.190
ST DEV OF NOISE = 52.800
RIDING FLAG (1=ON,0=OFF) = 0
0. 1. 2. 3. 4. 5. 6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.7

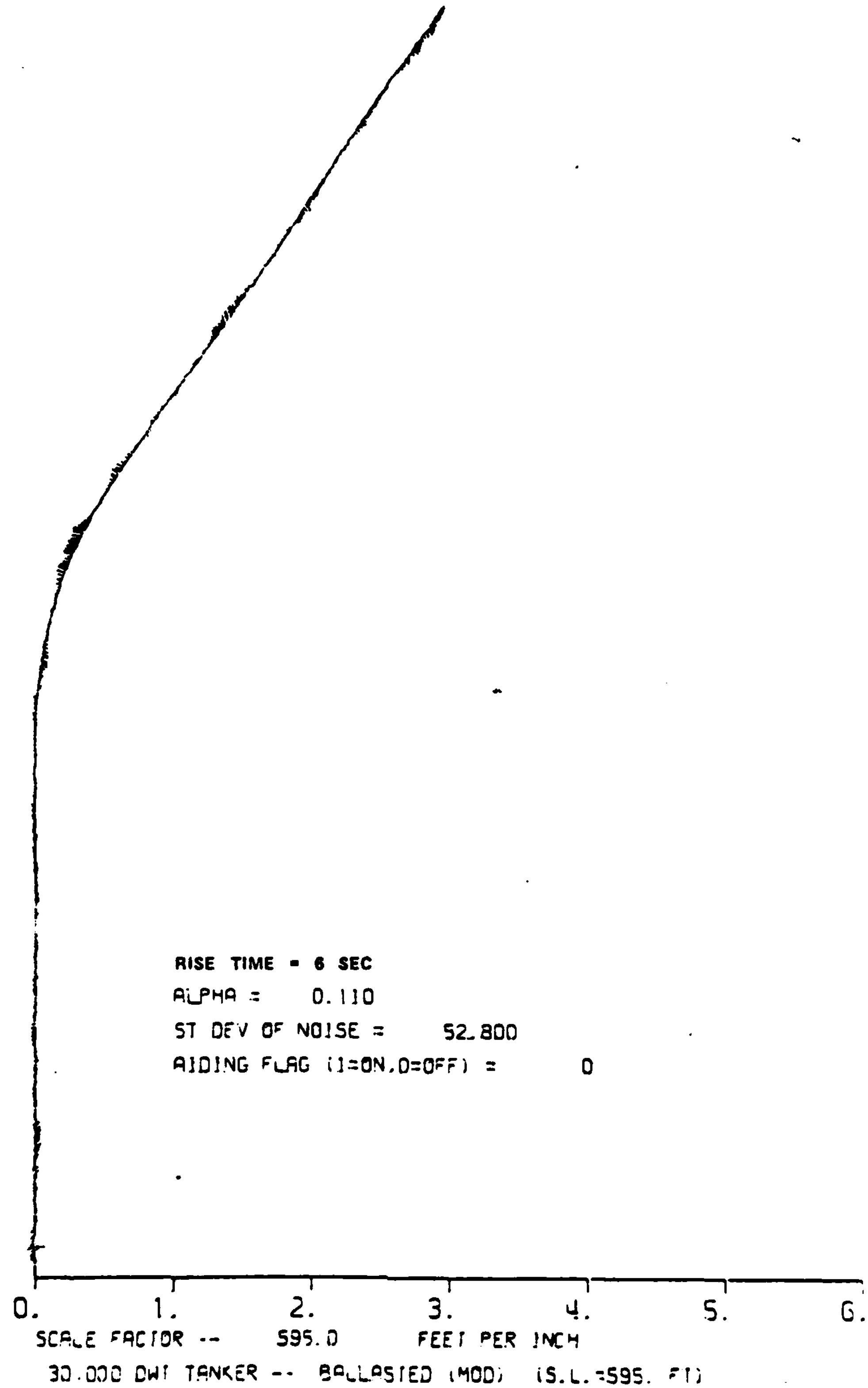

RISE TIME = 6 SEC
ALPHA = 0.110
ST DEV OF NOISE = 52.800
AIDING FLAG (1=ON,0=OFF) = 0
0. 1. 2. 3. 4. 5. 6.
SCALE FACTOR -- 595.0 FEET PER INCH
30.000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.8

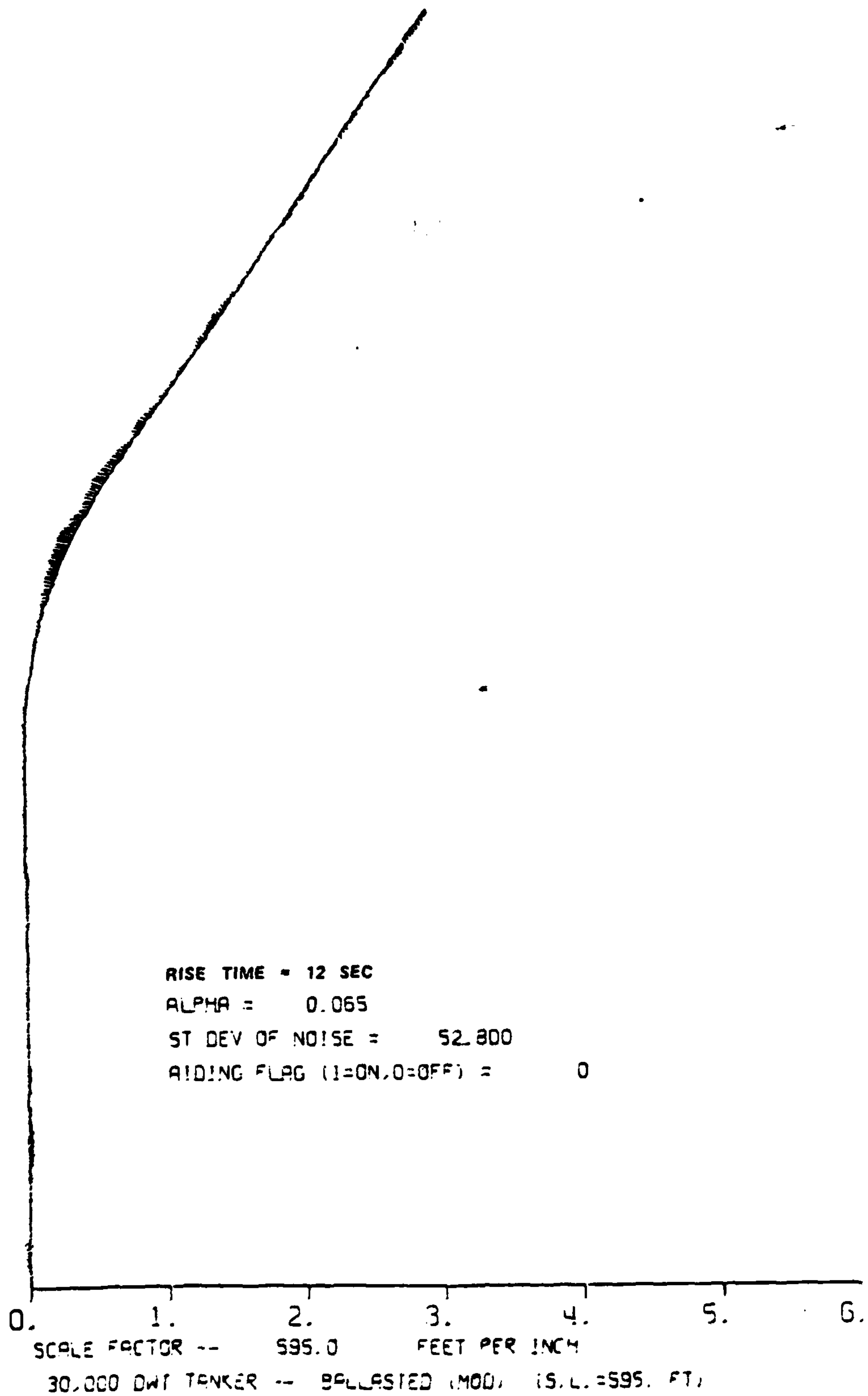

RISE TIME = 12 SEC
ALPHA = 0.065
ST DEV OF NOISE = 52.800
AIDING FLAG (1=ON,0=OFF) = 0
0.
1.
2.
3.
4.
5.
6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.9

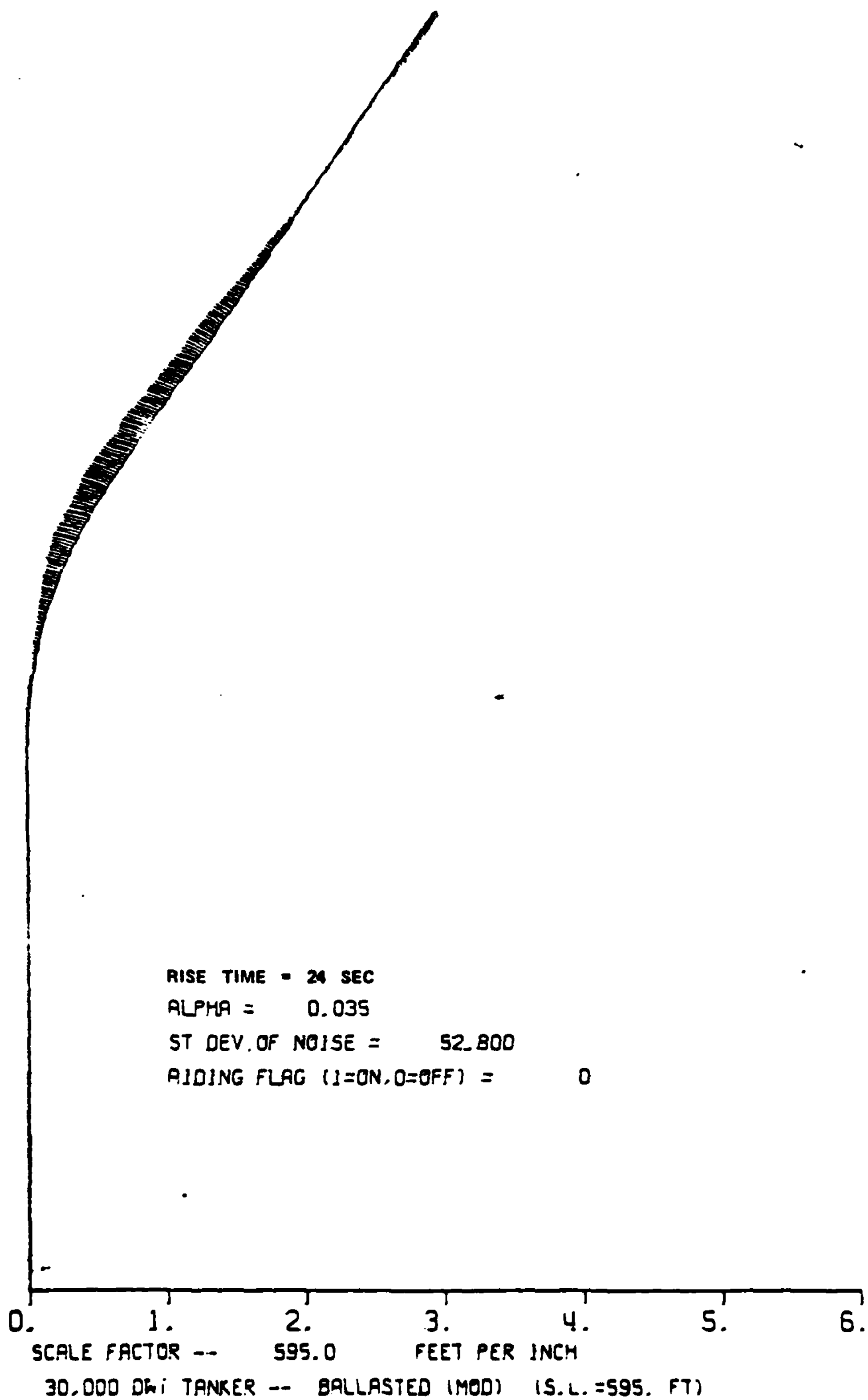

RISE TIME = 24 SEC
ALPHA = 0.035
ST DEV.OF NOISE = 52.800
AIDING FLAG (1=ON,0=OFF) = 0
0.
1.
2.
3.
4.
5.
6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.10

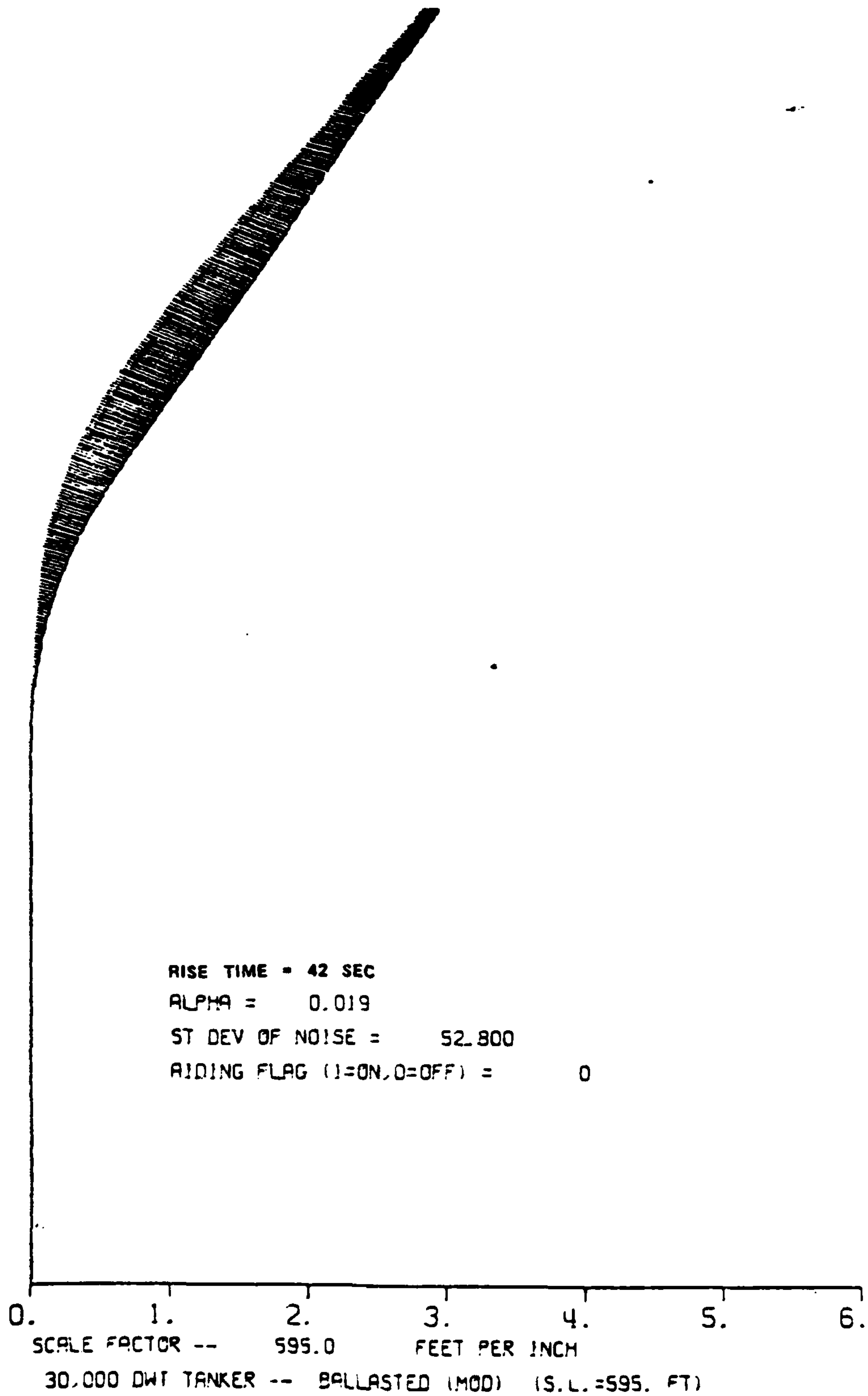

RISE TIME = 42 SEC
ALPHA = 0.019
ST DEV OF NOISE = 52.800
AIDING FLAG (1=ON,0=OFF) = 0
0.
1.
2.
3.
4.
5.
6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.11

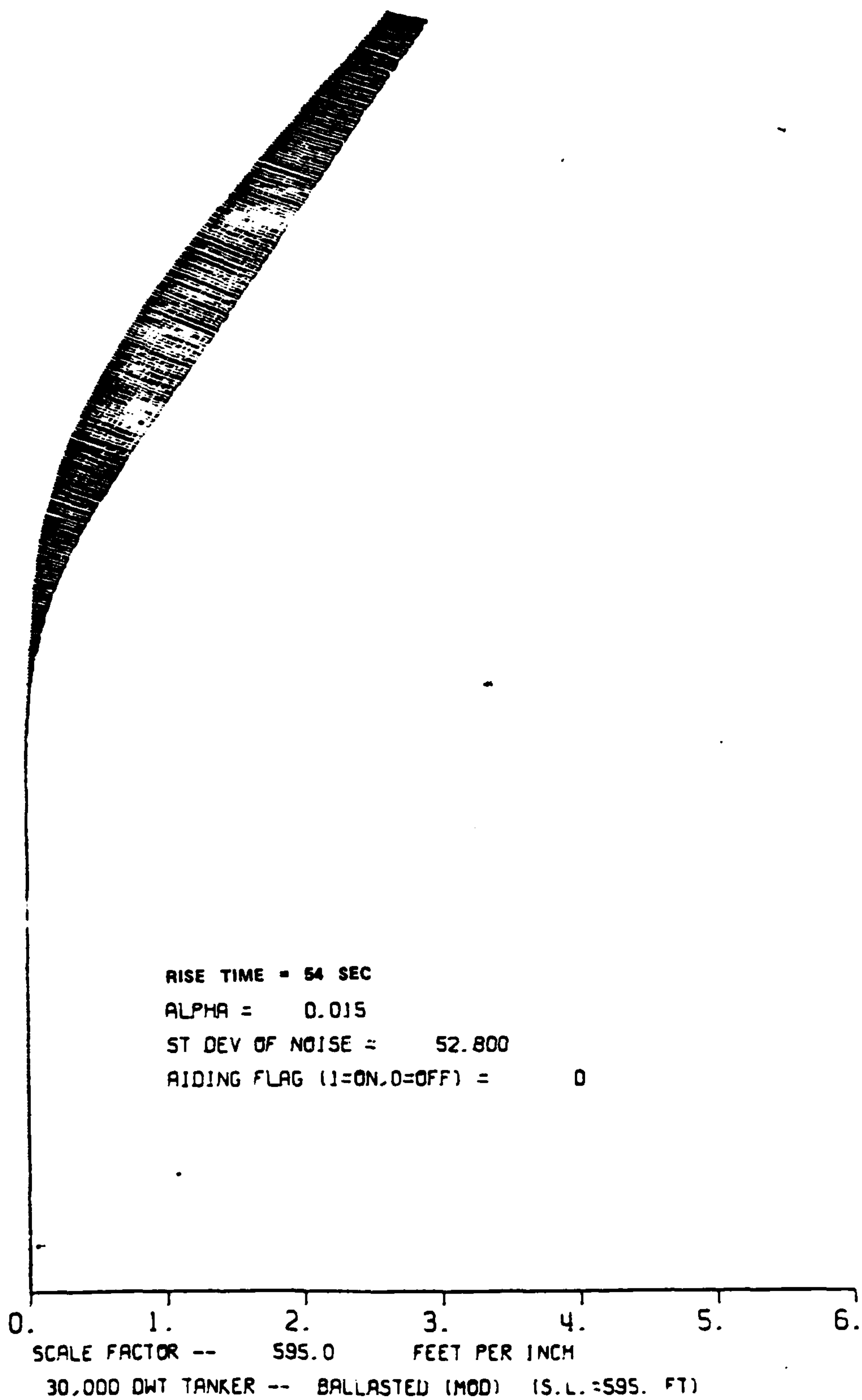
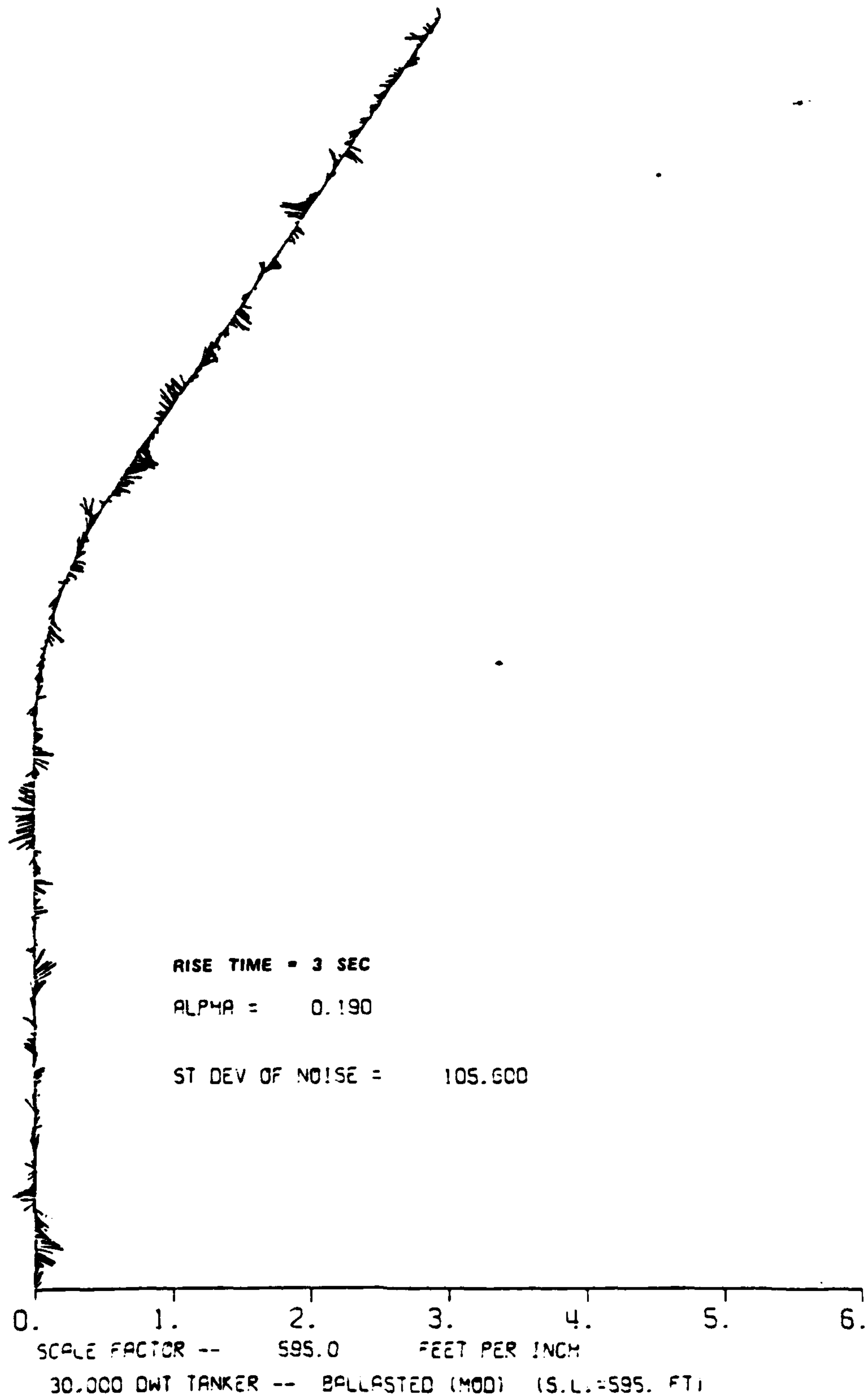
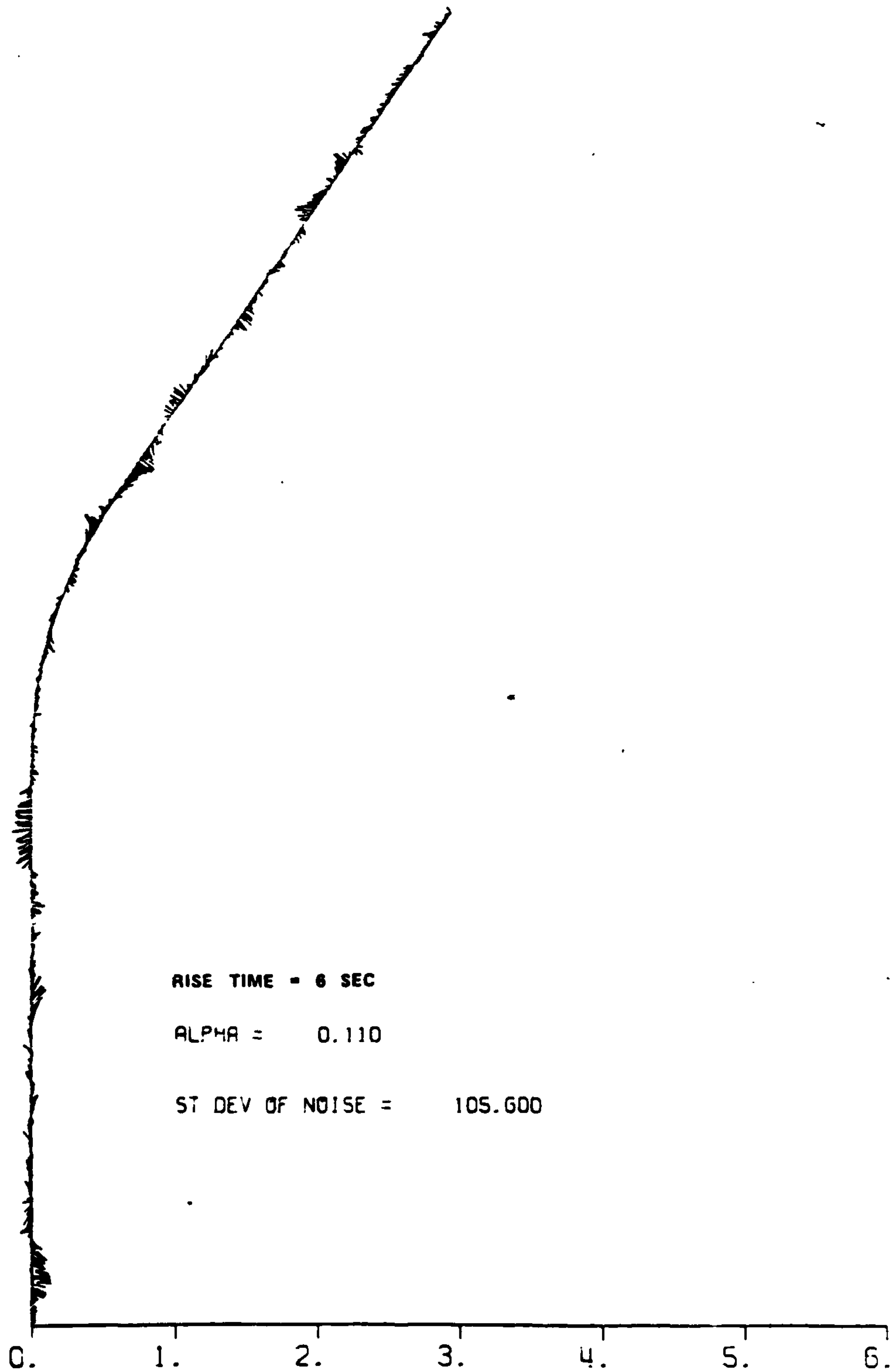

RISE TIME = 54 SEC
ALPHA = 0.015
ST DEV OF NOISE = 52.800
AIDING FLAG (1=ON,0=OFF) = 0
0.
1.
2.
3.
4.
5.
6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.12



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

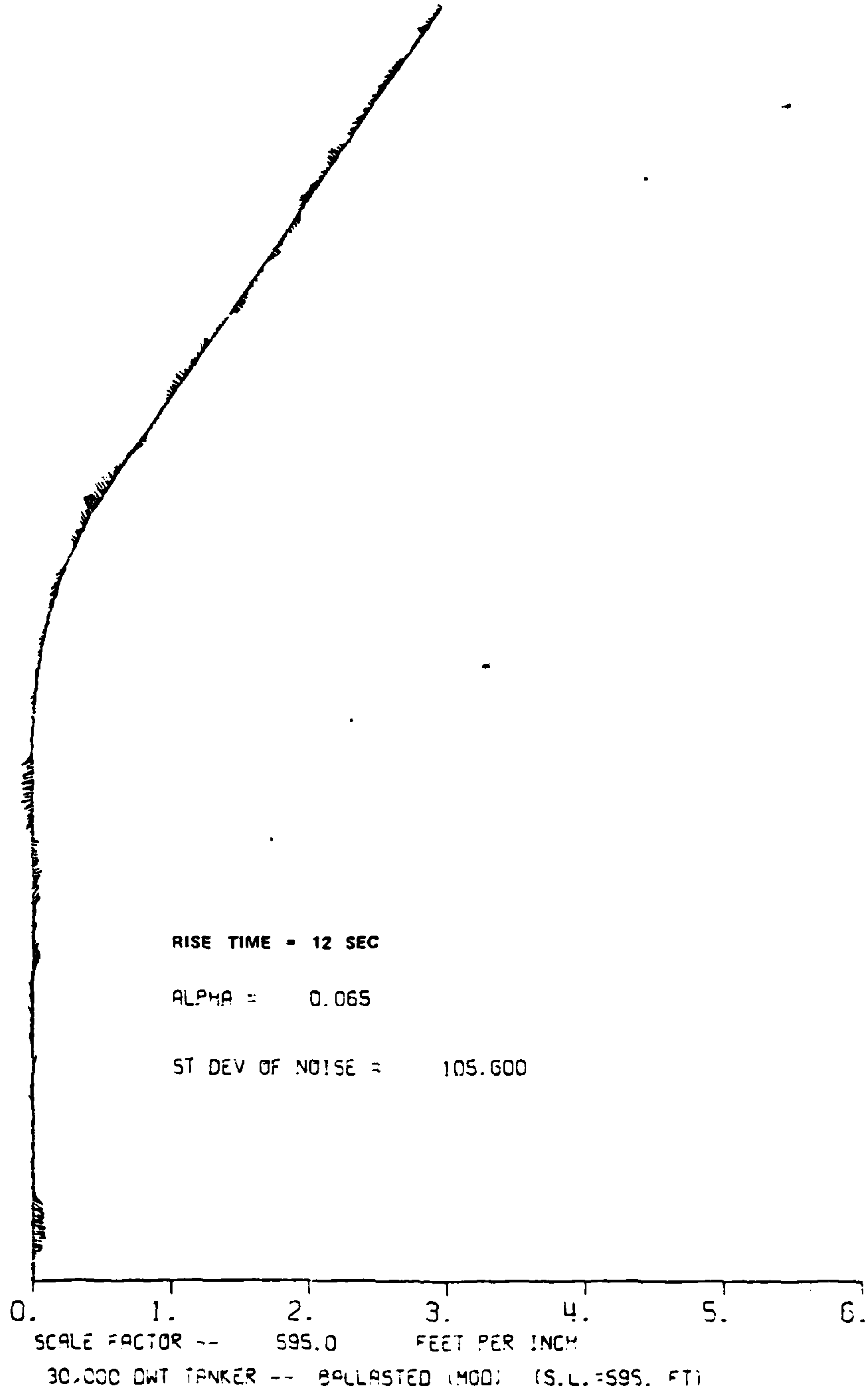
Figure B.13



SCALE FACTOR -- 595.0 FEET PER INCH

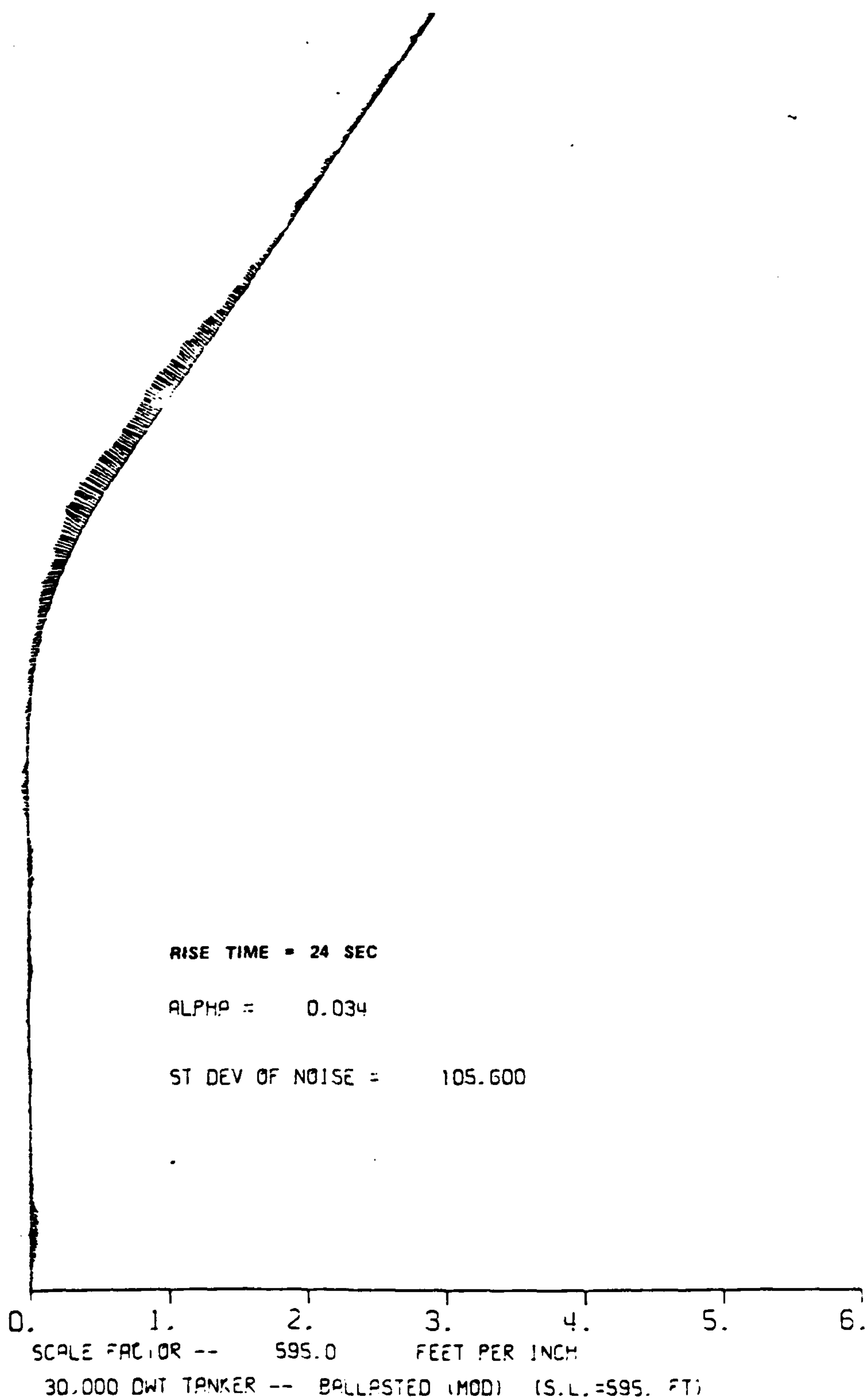
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.14



RISE TIME = 12 SEC
ALPHA = 0.065
ST DEV OF NOISE = 105.600
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 B.15


RISE TIME = 24 SEC
ALPHA = 0.034
ST DEV OF NOISE = 105.600
0.
1.
2.
3.
4.
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6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.16

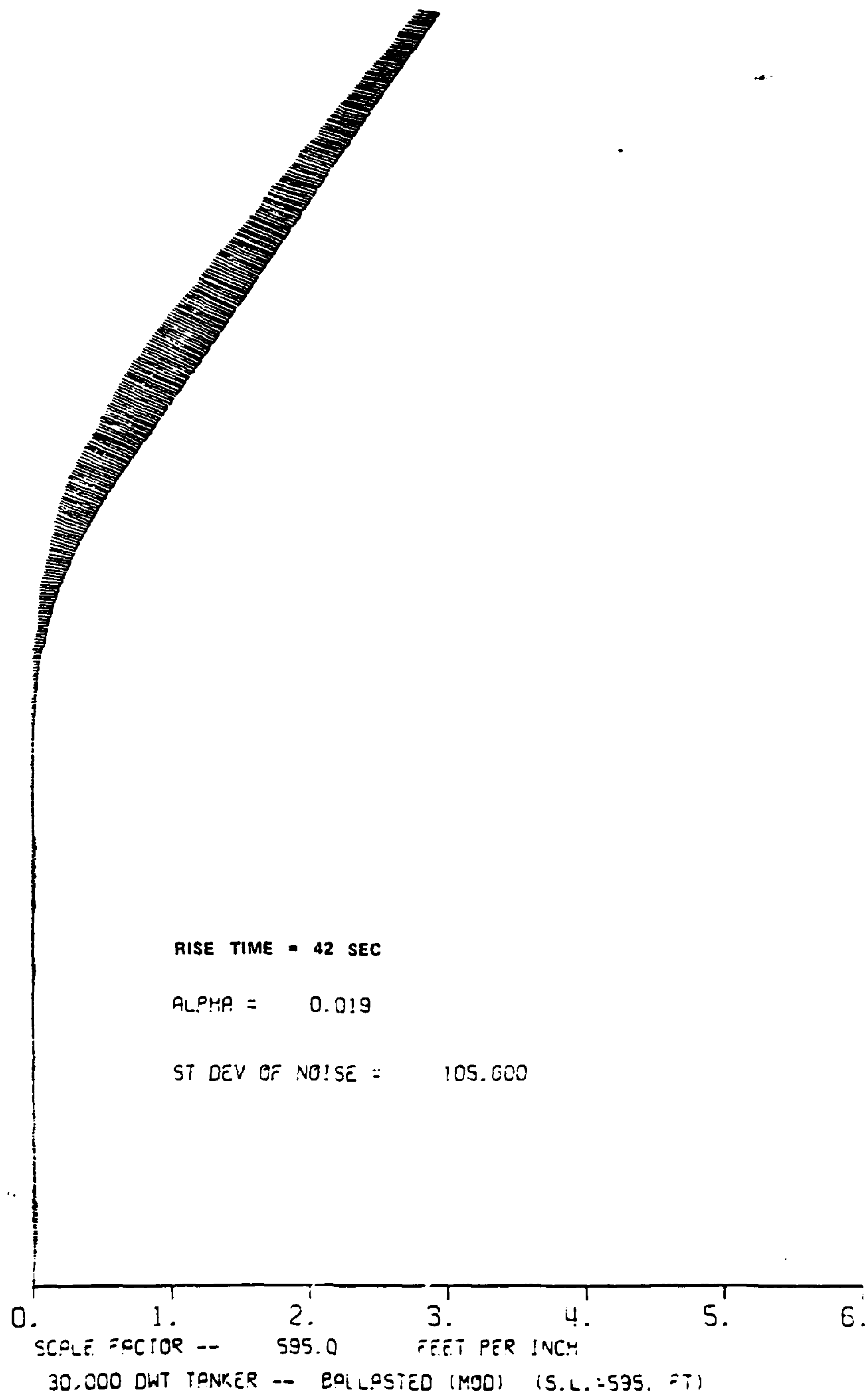
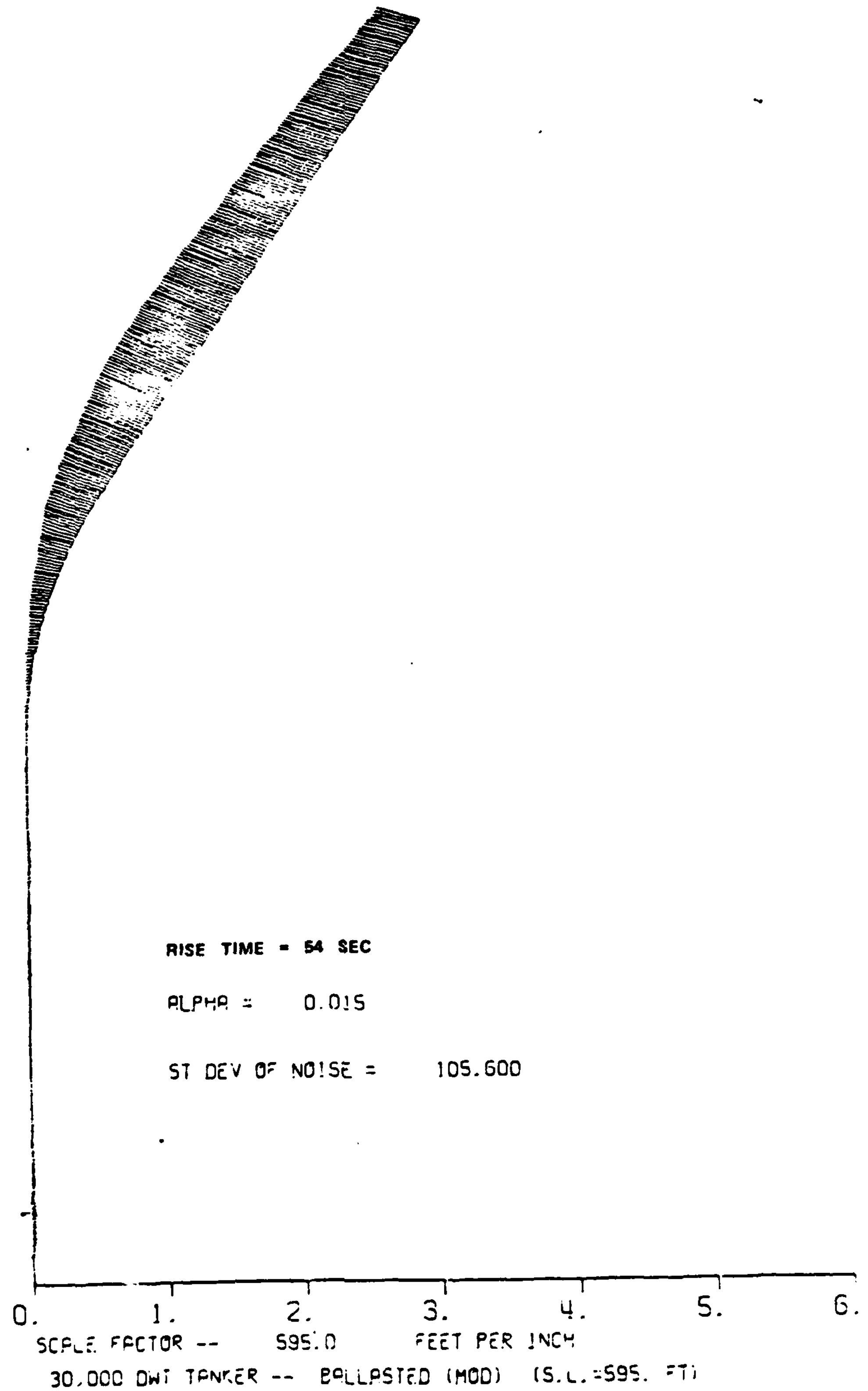
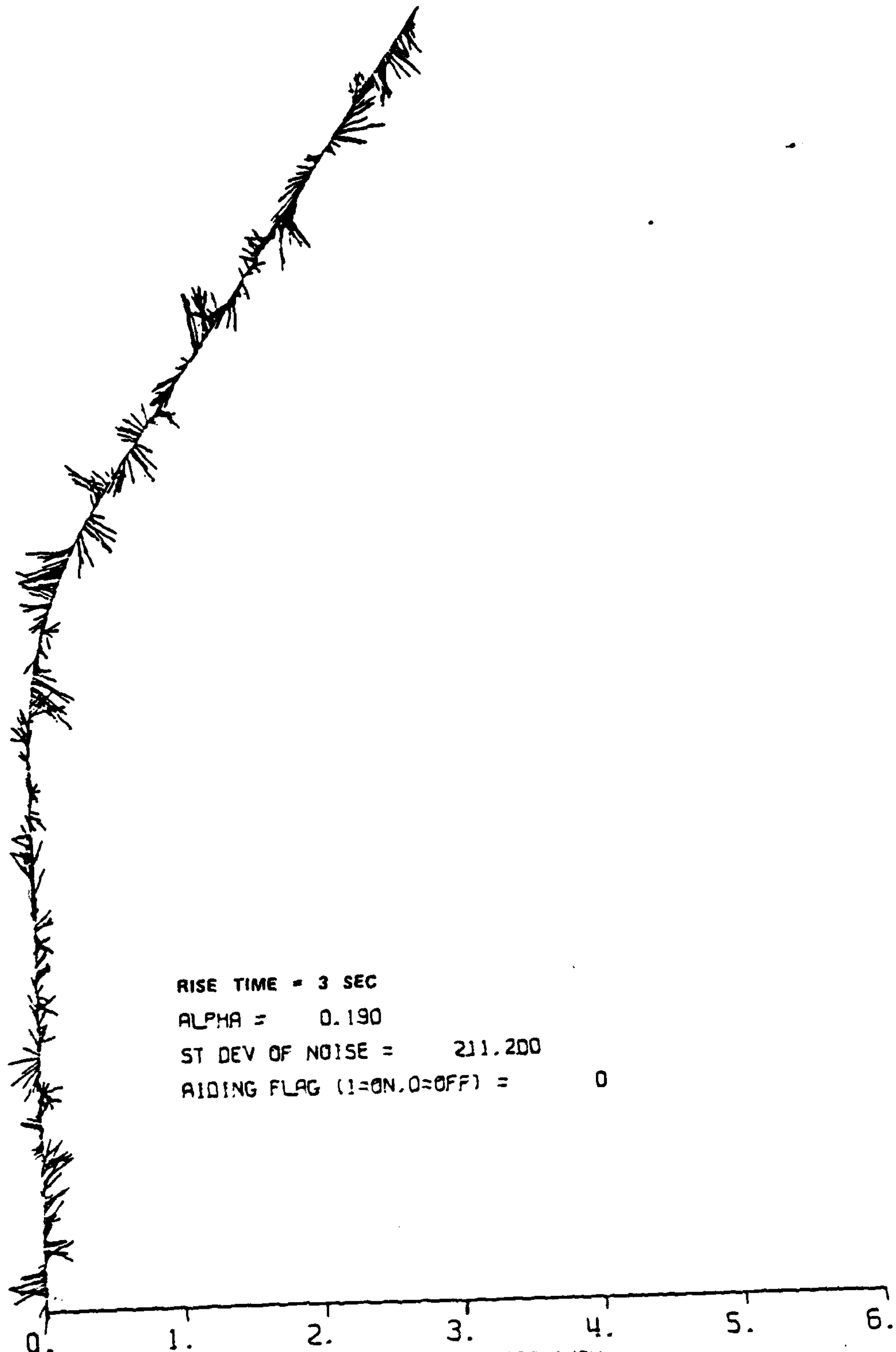

RISE TIME = 42 SEC
ALPHA = 0.019
ST DEV OF NOISE = 105.000
0.
1.
2.
3.
4.
5.
6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.17



RISE TIME = 54 SEC
ALPHA = 0.015
ST DEV OF NOISE = 105.600
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 B.18



SCALE FACTOR -- 595.0 FEET PER INCH

30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.19

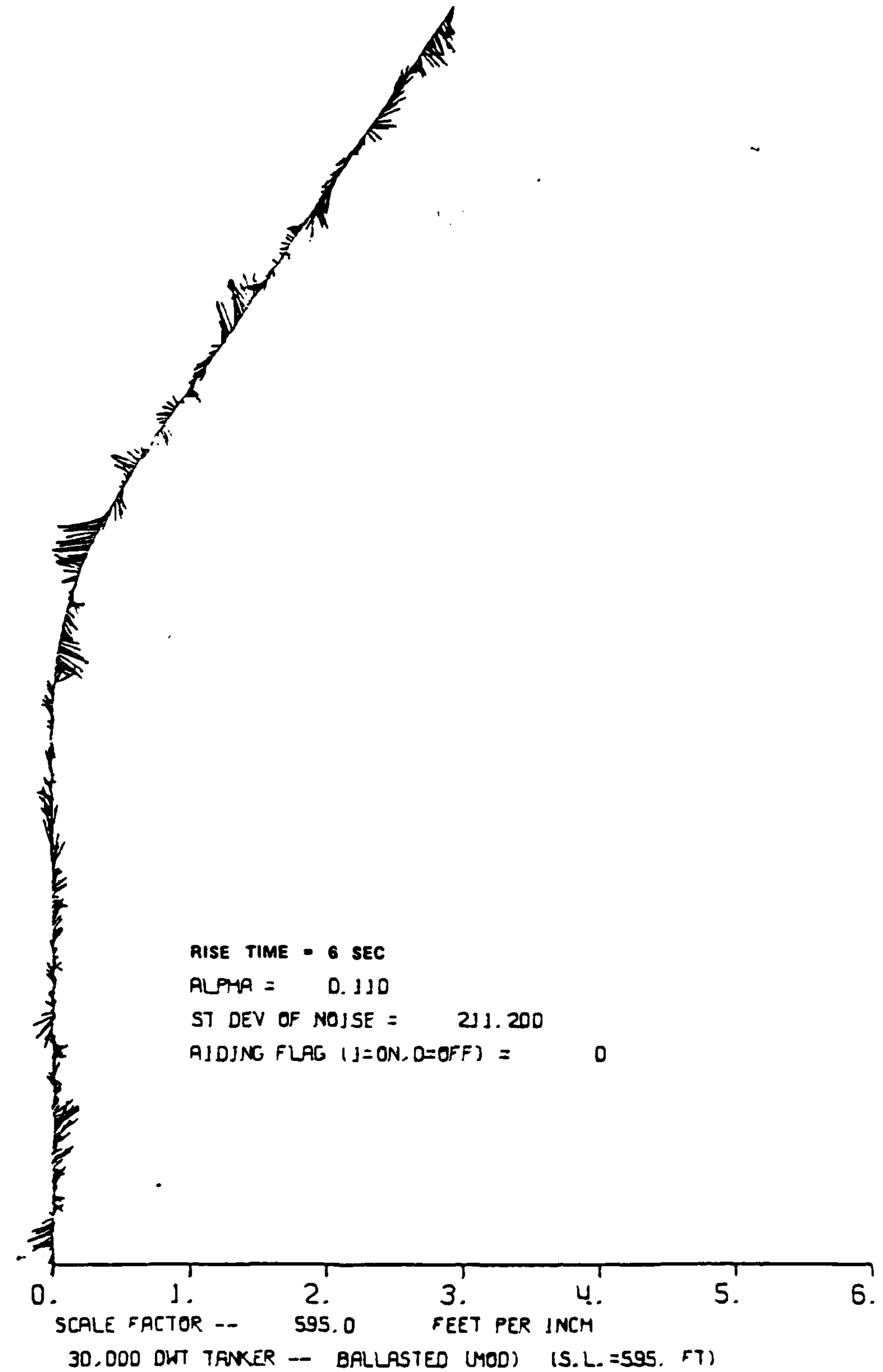

RISE TIME = 6 SEC
ALPHA = 0.110
ST DEV OF NOISE = 211.200
AIDING FLAG (1=ON,0=OFF) = 0
0. 1. 2. 3. 4. 5. 6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.20

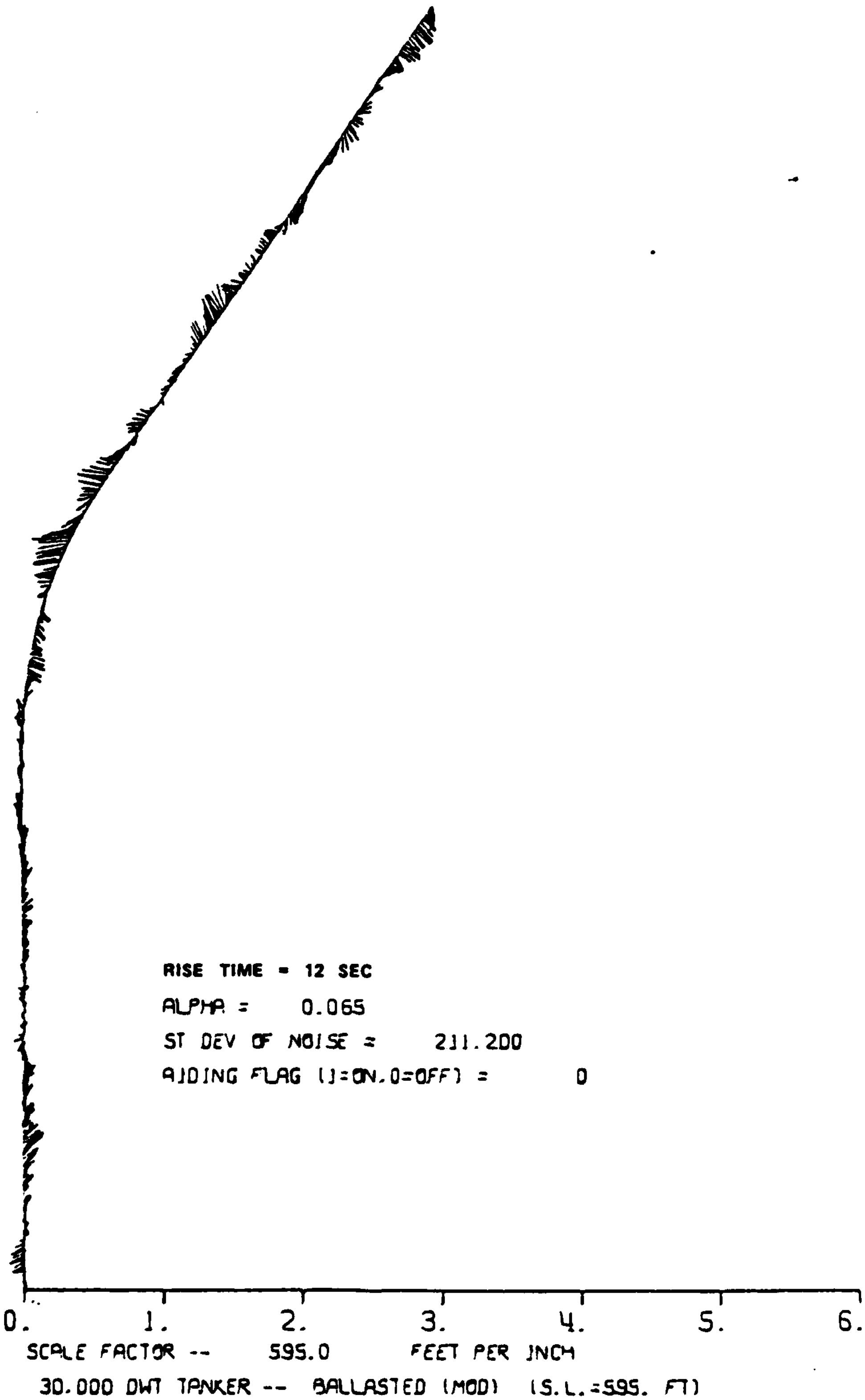

RISE TIME = 12 SEC
ALPHA = 0.065
ST DEV OF NOISE = 211.200
AIDING FLAG (1=ON,0=OFF) = 0
0.
1.
2.
3.
4.
5.
6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.21

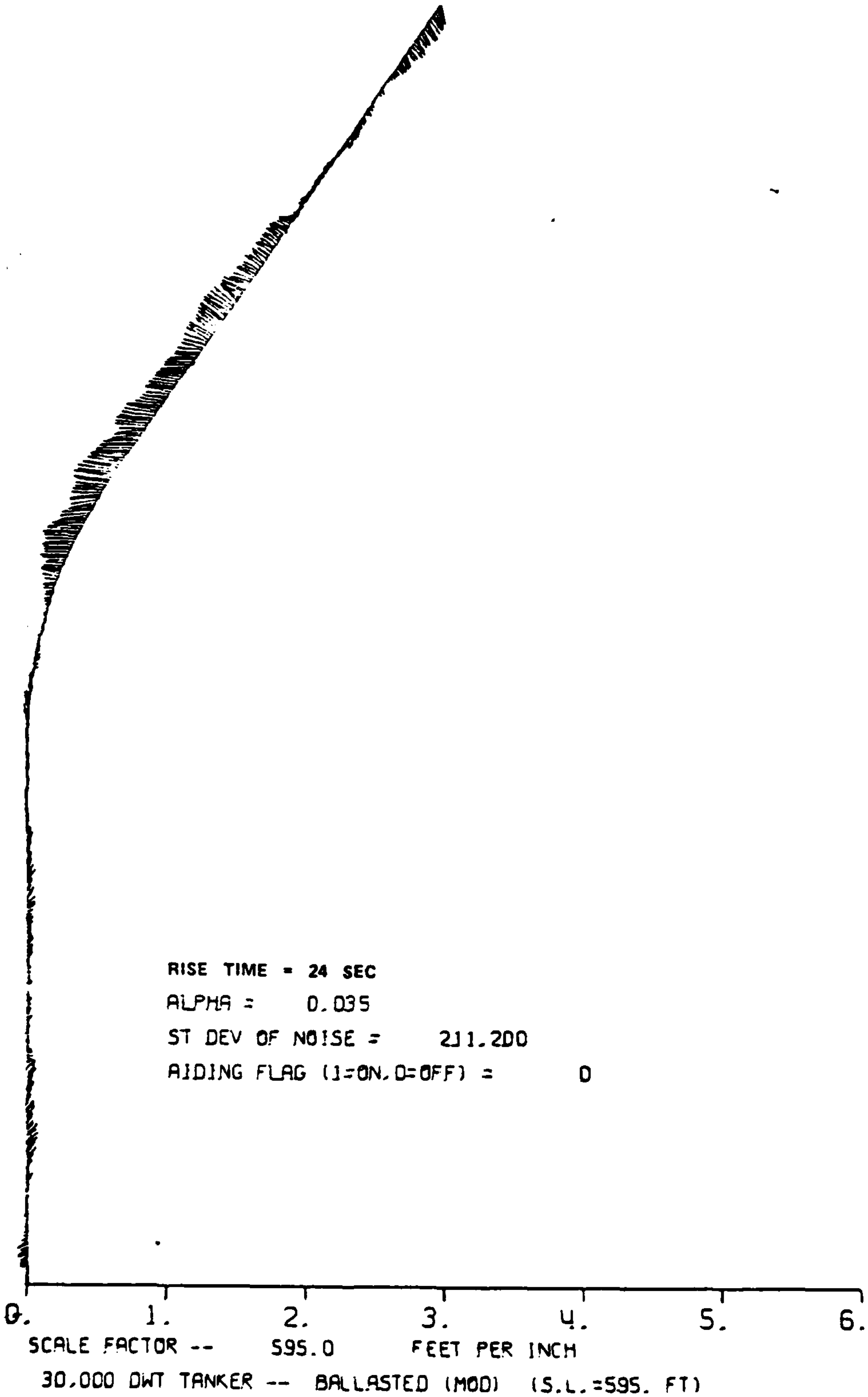

RISE TIME = 24 SEC
ALPHA = 0.035
ST DEV OF NOISE = 211.200
AIDING FLAG (1=ON,0=OFF) = 0
0. 1. 2. 3. 4. 5. 6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.22

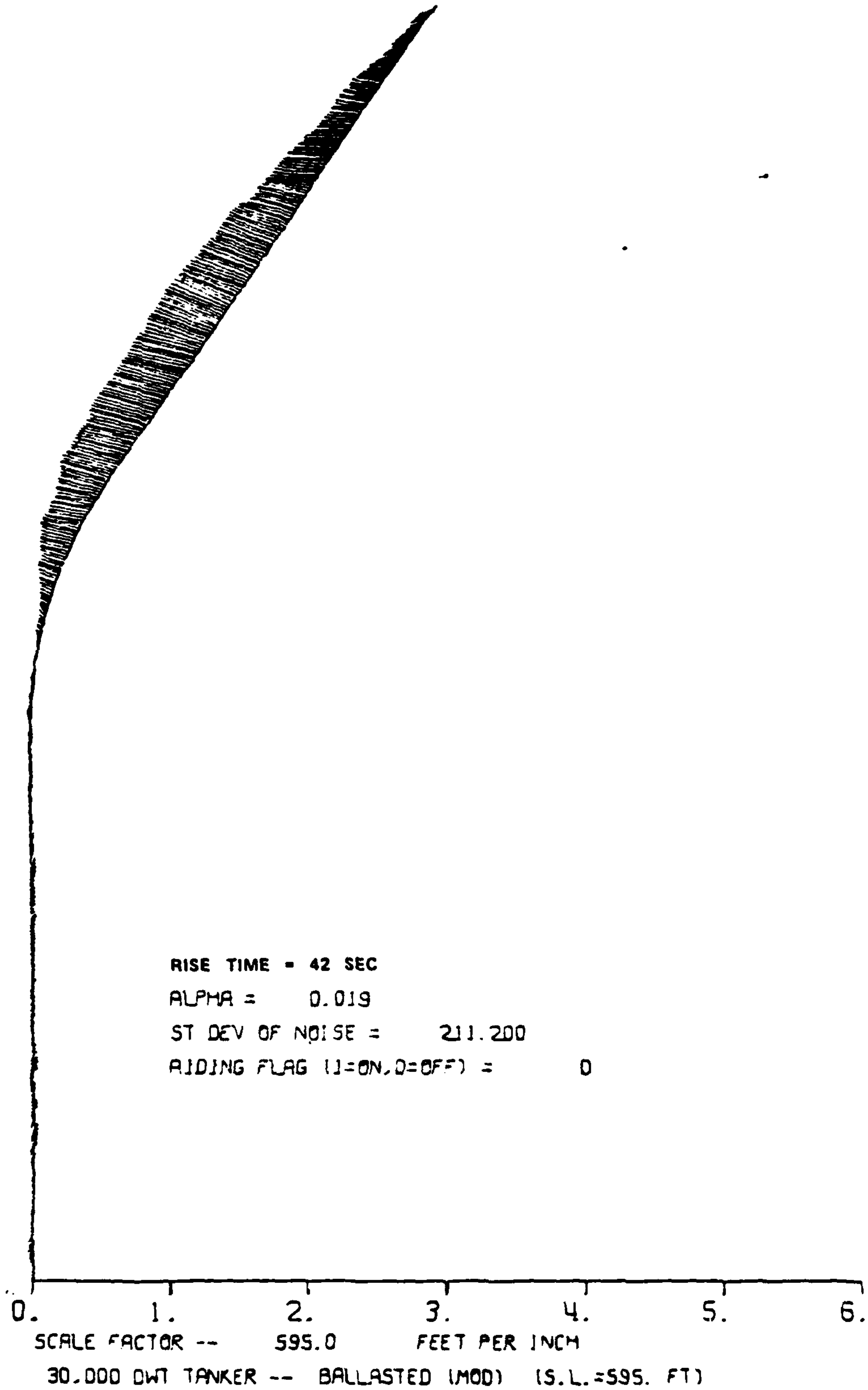

RISE TIME = 42 SEC
ALPHA = 0.019
ST DEV OF NOISE = 211.200
AIDING FLAG (1=ON,0=OFF) = 0
0. 1. 2. 3. 4. 5. 6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.23

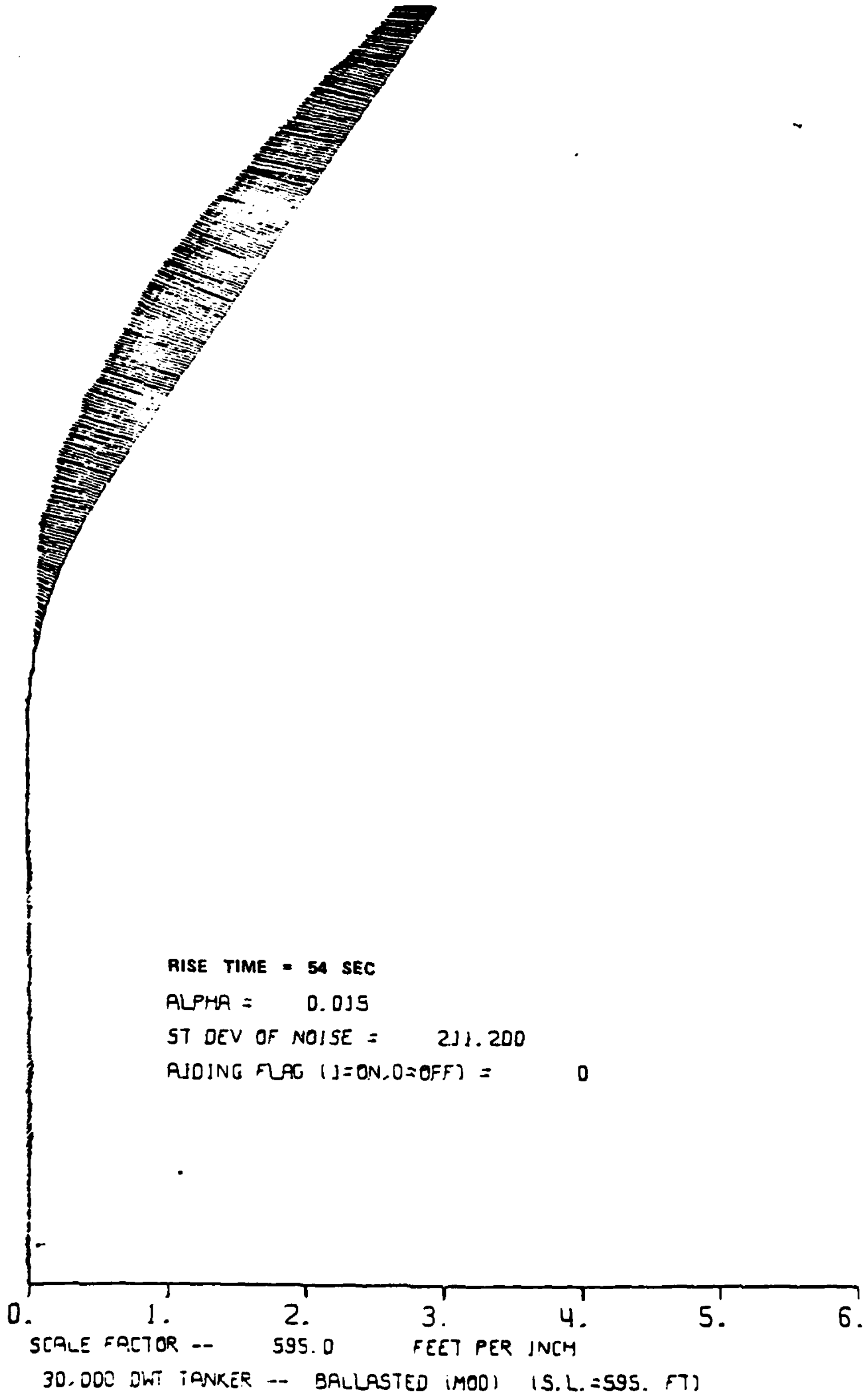
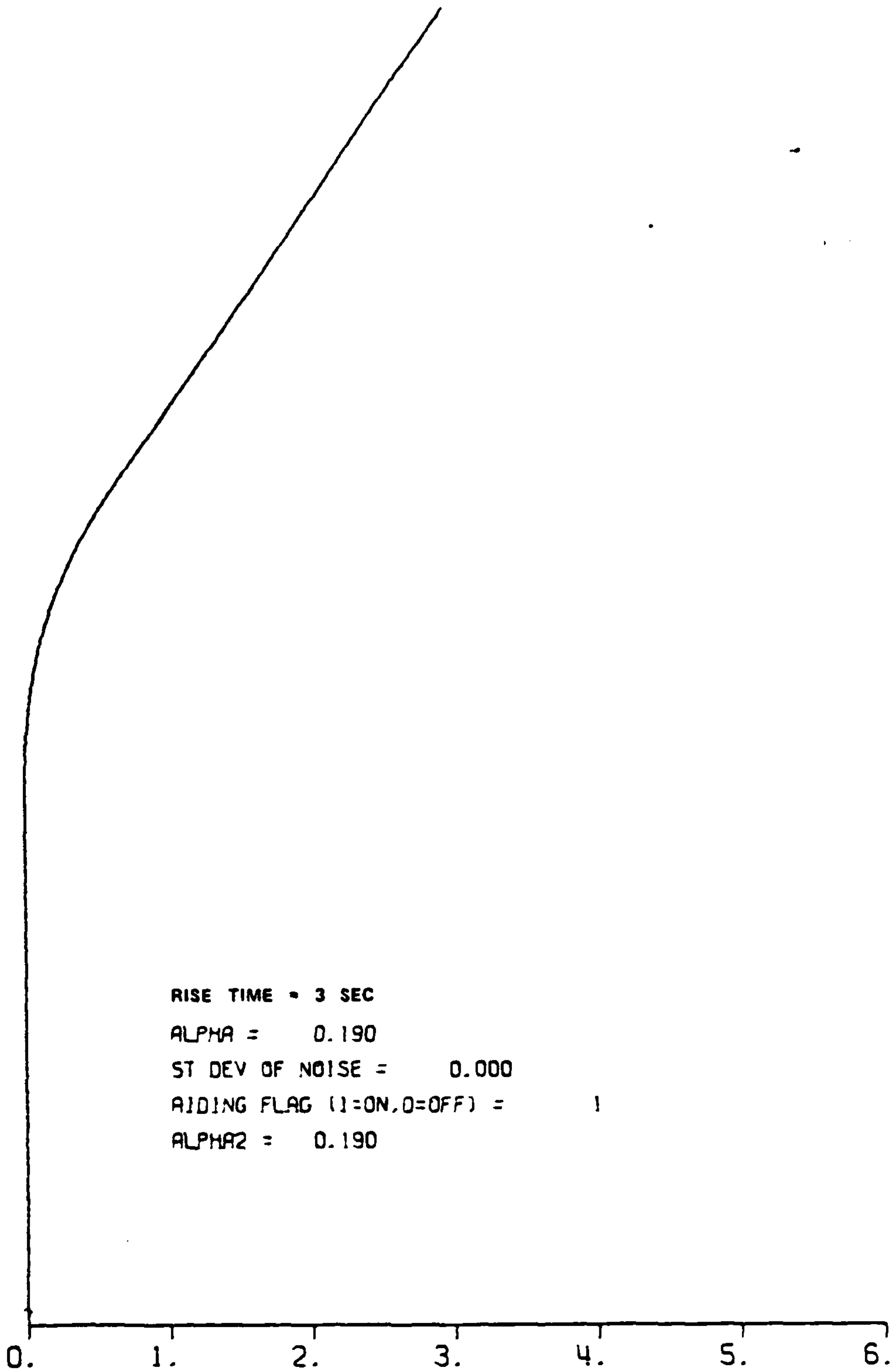

RISE TIME = 54 SEC
ALPHA = 0.015
ST DEV OF NOISE = 211.200
AIDING FLAG (1=ON,0=OFF) = 0
0. 1. 2. 3. 4. 5. 6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.24



SCALE FACTOR -- 595.0 FEET PER INCH

30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.25

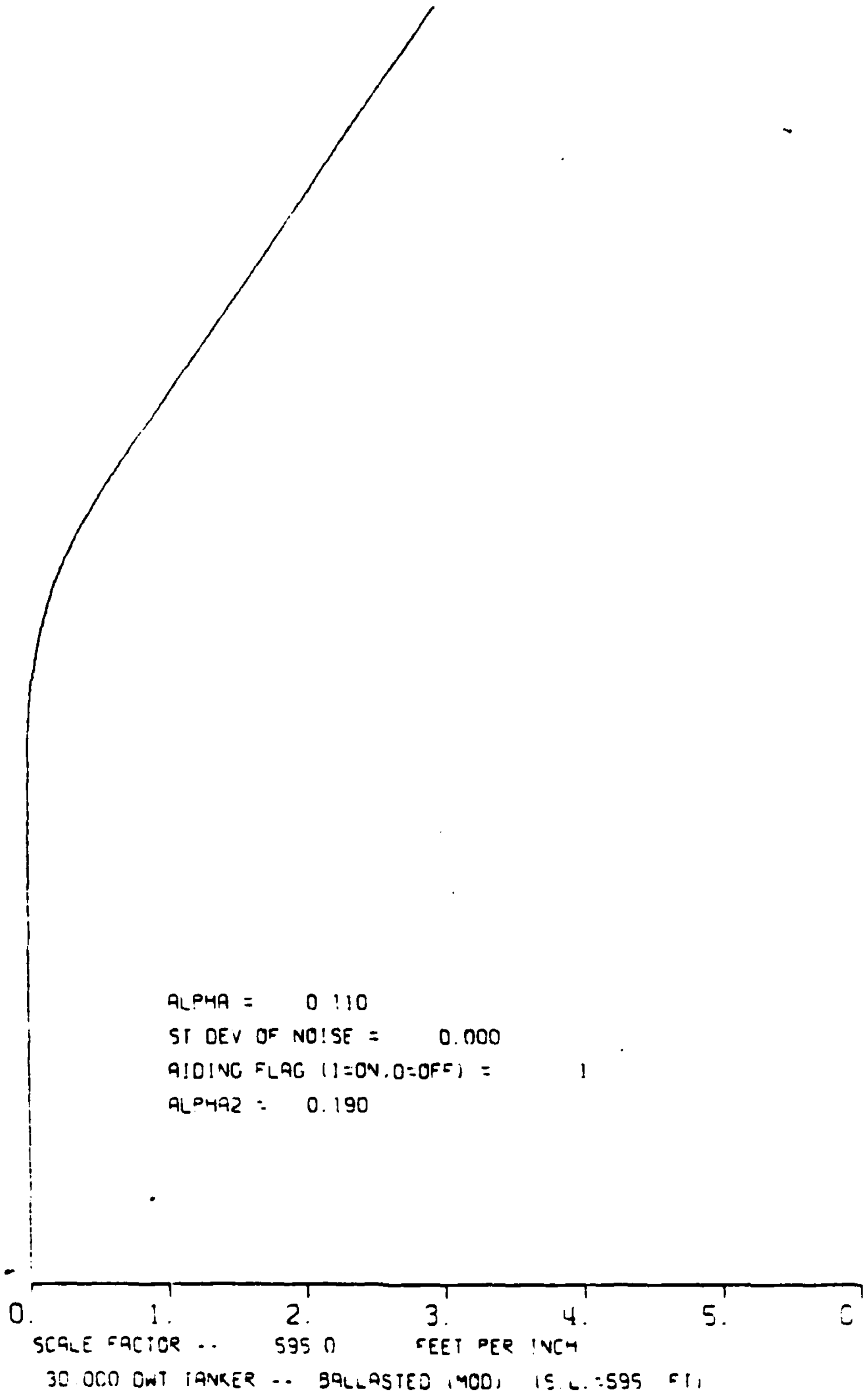
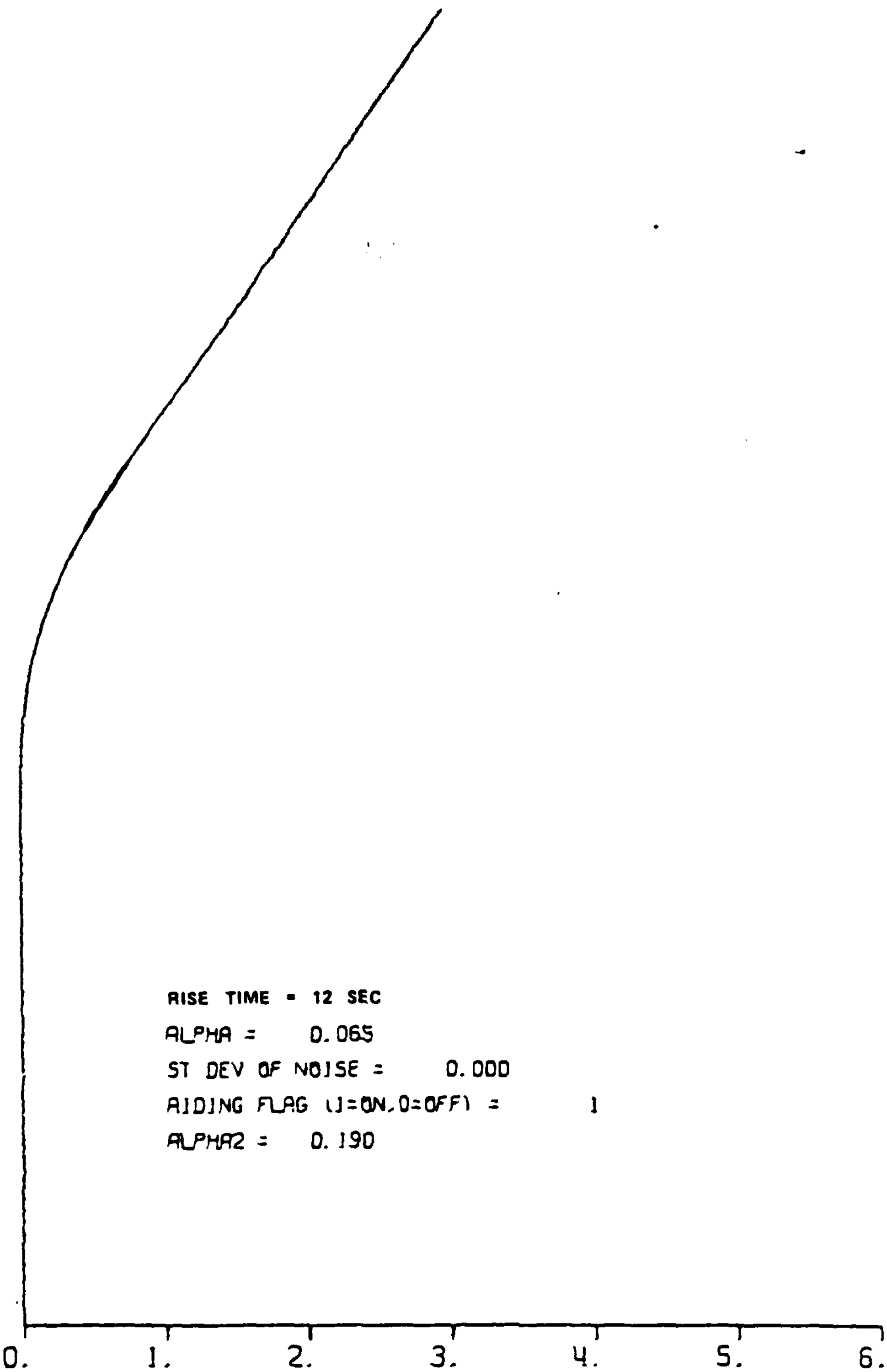

ALPHA = 0.110
ST DEV OF NOISE = 0.000
AIDING FLAG (1=ON,0=OFF) = 1
ALPHA2 = 0.190
0.
1.
2.
3.
4.
5.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595 FT)

Figure B.26



SCALE FACTOR -- 595.0 FEET PER INCH

30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.27

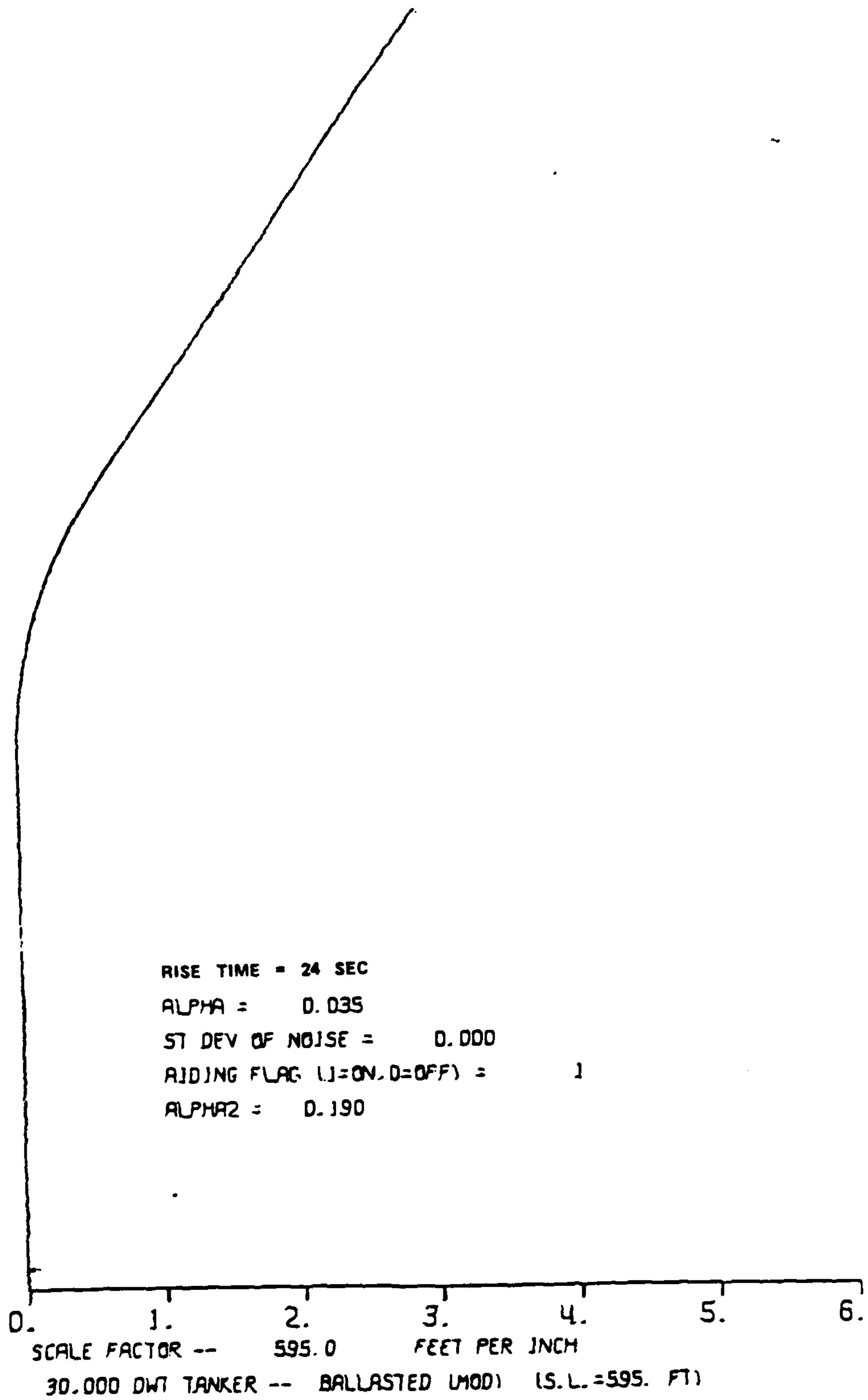

RISE TIME = 24 SEC
ALPHA = 0.035
ST DEV OF NOISE = 0.000
AIDING FLAG (1=ON, 0=OFF) = 1
ALPHA2 = 0.190
0.
1.
2.
3.
4.
5.
6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.28

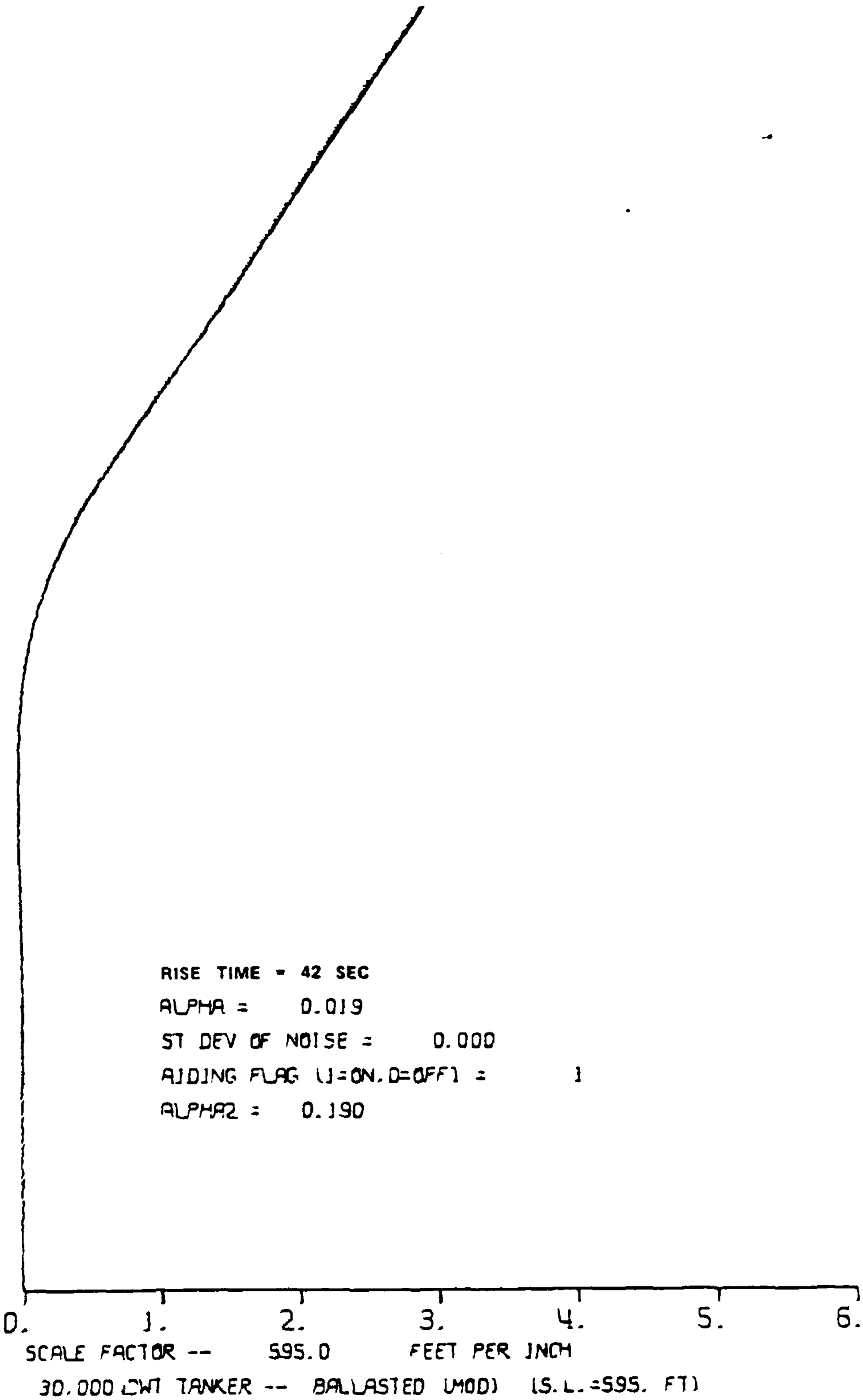
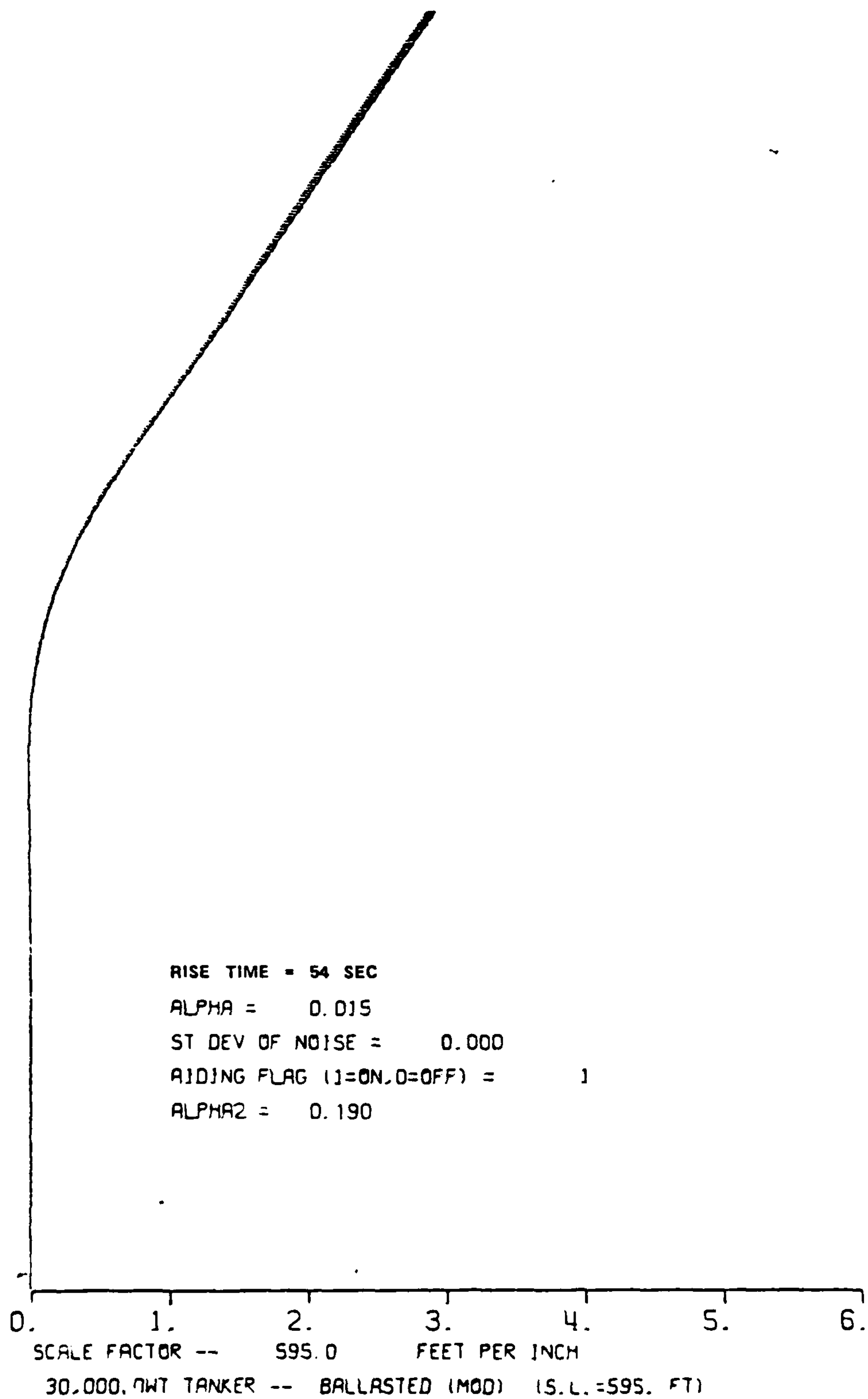

RISE TIME = 42 SEC
ALPHA = 0.019
ST DEV OF NOISE = 0.000
AIDING FLAG (1=ON,0=OFF) = 1
ALPHA2 = 0.190
0.
1.
2.
3.
4.
5.
6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.29



RISE TIME = 54 SEC
ALPHA = 0.015
ST DEV OF NOISE = 0.000
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 B.30

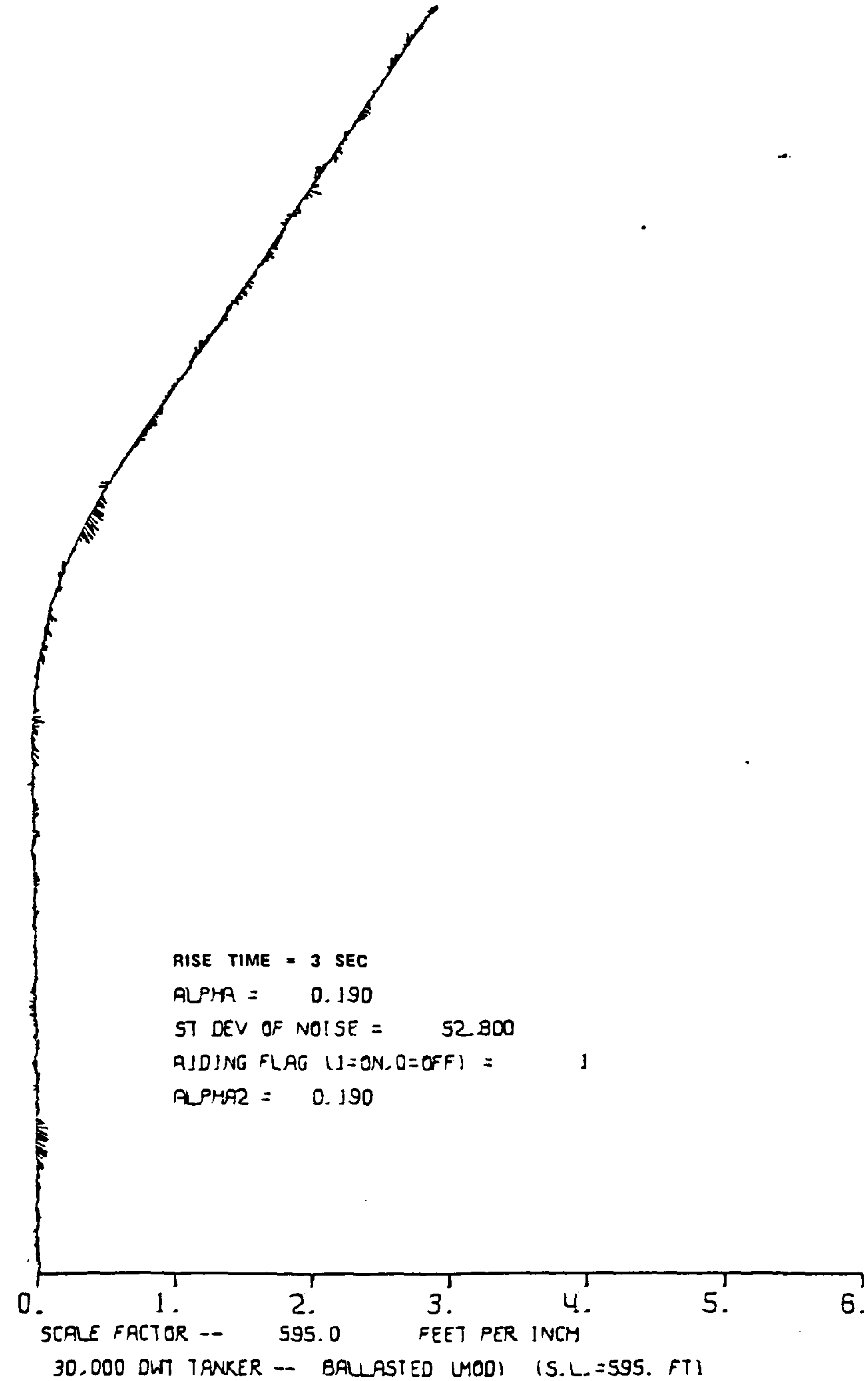

RISE TIME = 3 SEC
ALPHA = 0.190
ST DEV OF NOISE = 52.800
AIDING FLAG (1=ON,0=OFF) = 1
ALPHA2 = 0.190
0. 1. 2. 3. 4. 5. 6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.31

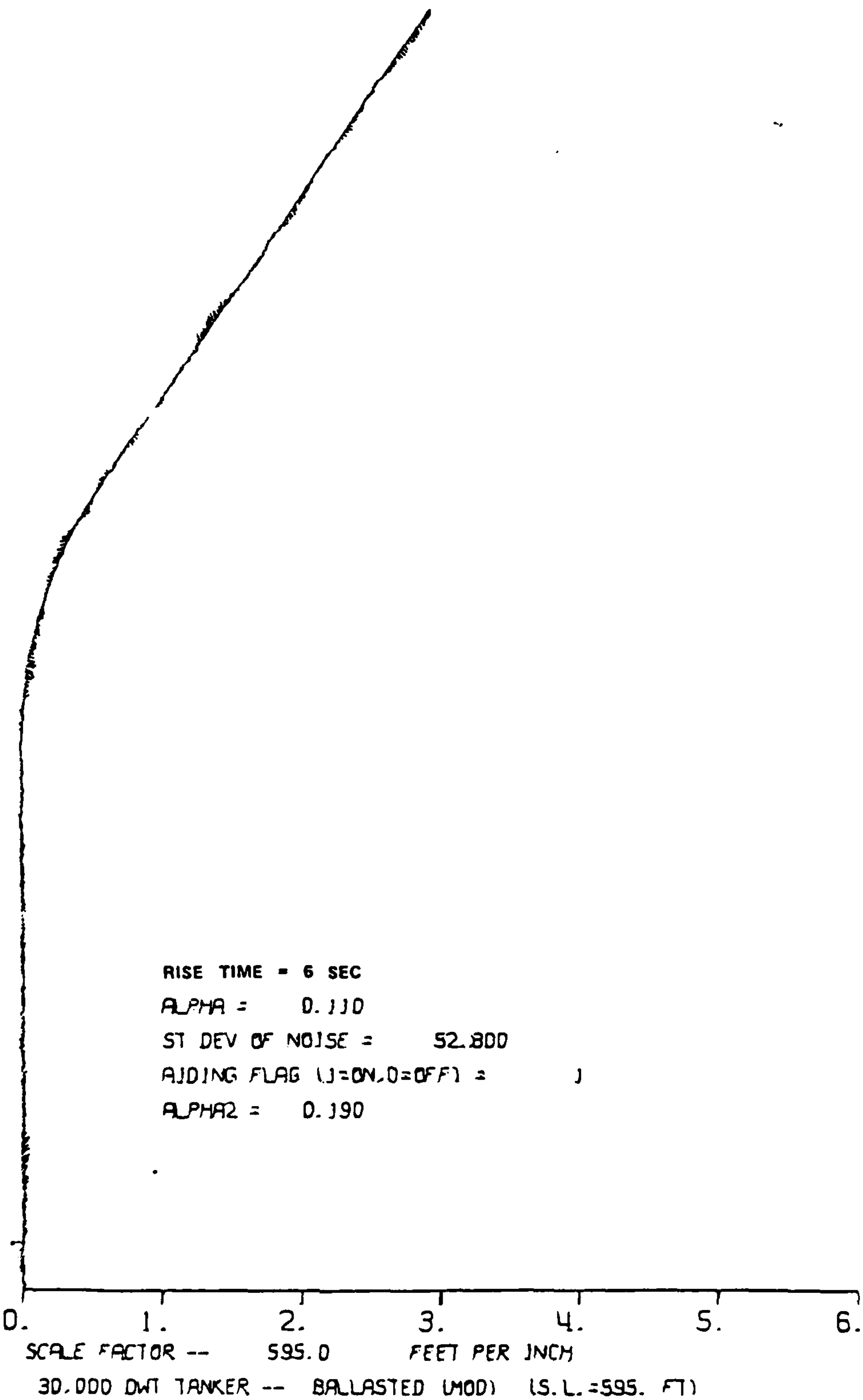
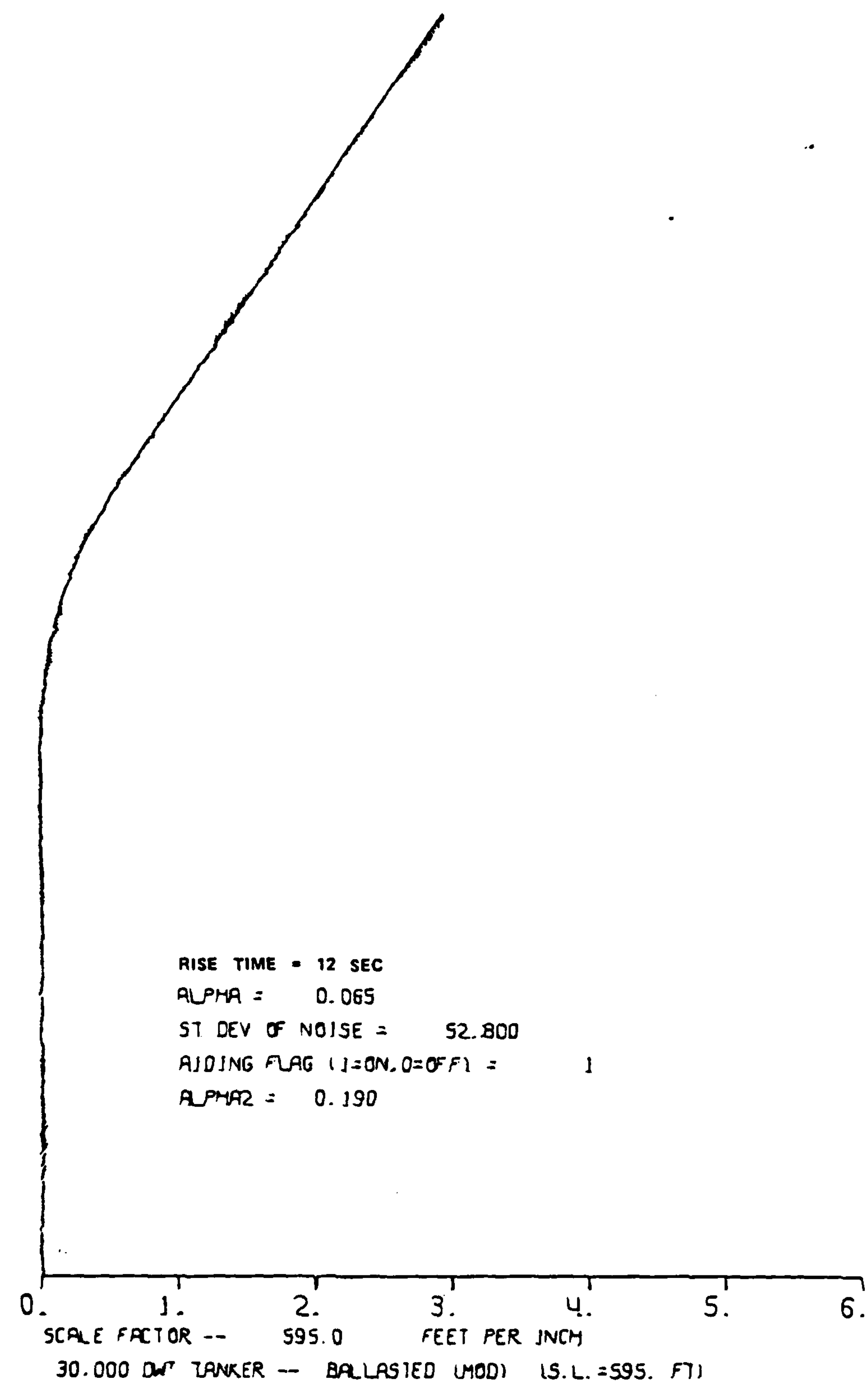

RISE TIME = 6 SEC
ALPHA = 0.110
ST DEV OF NOISE = 52.800
AIDING FLAG (1=ON,0=OFF) = 1
ALPHA2 = 0.190
0.
1.
2.
3.
4.
5.
6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.32



RISE TIME = 12 SEC
ALPHA = 0.065
ST DEV OF NOISE = 52.800
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 B.33

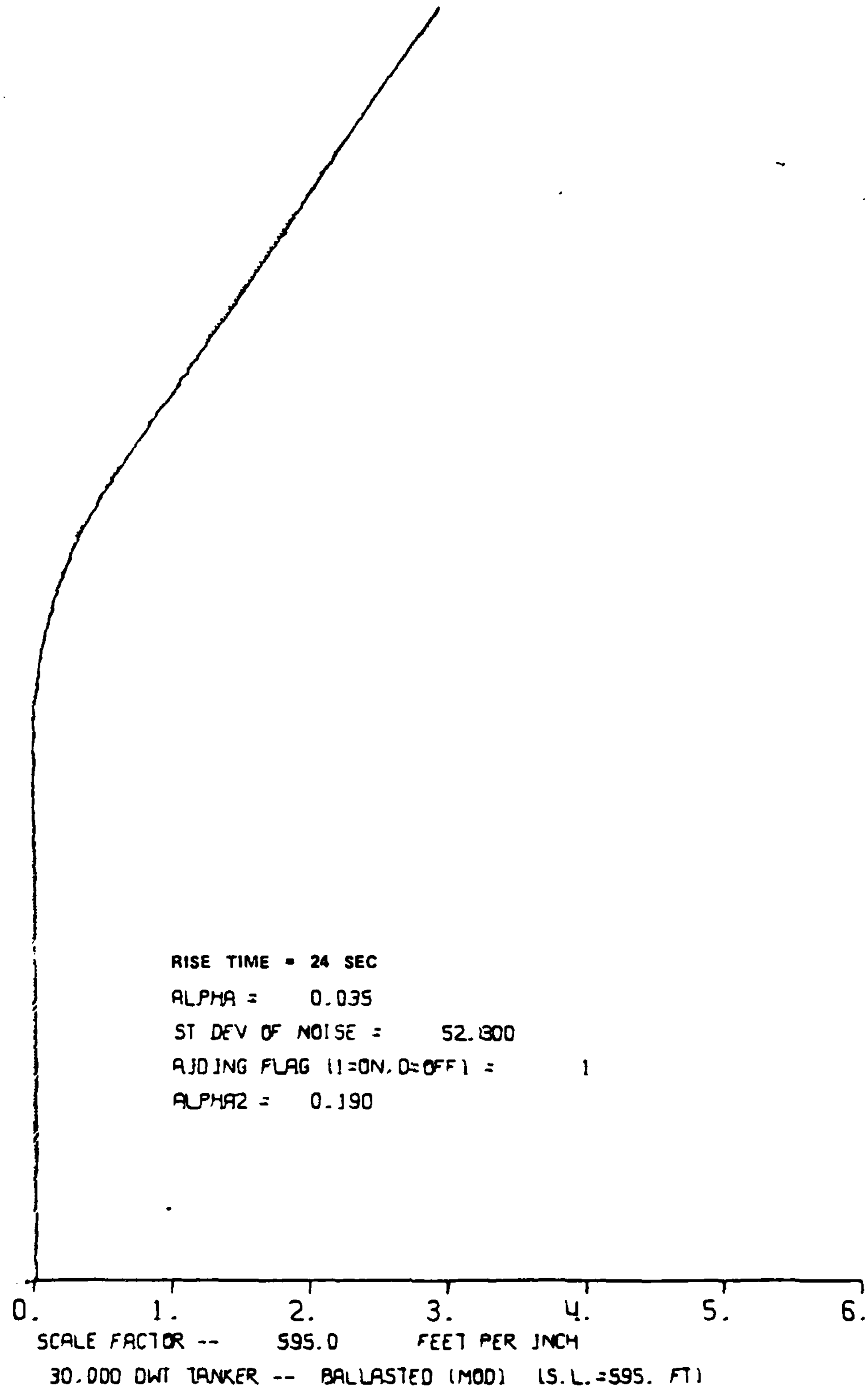
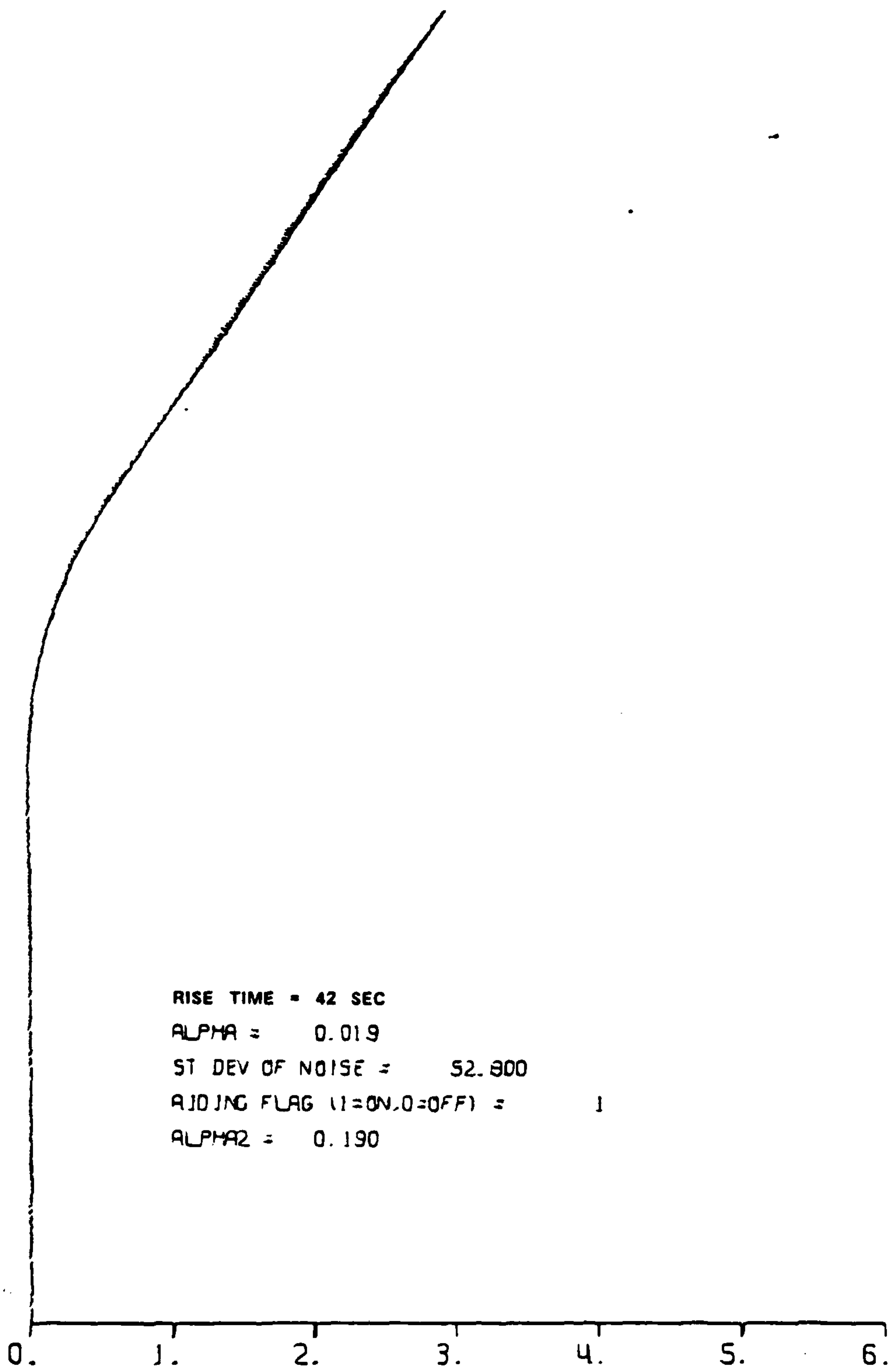

RISE TIME = 24 SEC
ALPHA = 0.035
ST DEV OF NOISE = 52.800
AIDING FLAG (1=ON, 0=OFF) = 1
ALPHA2 = 0.190
0.
1.
2.
3.
4.
5.
6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.34



SCALE FACTOR -- 595.0 FEET PER INCH

30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.35

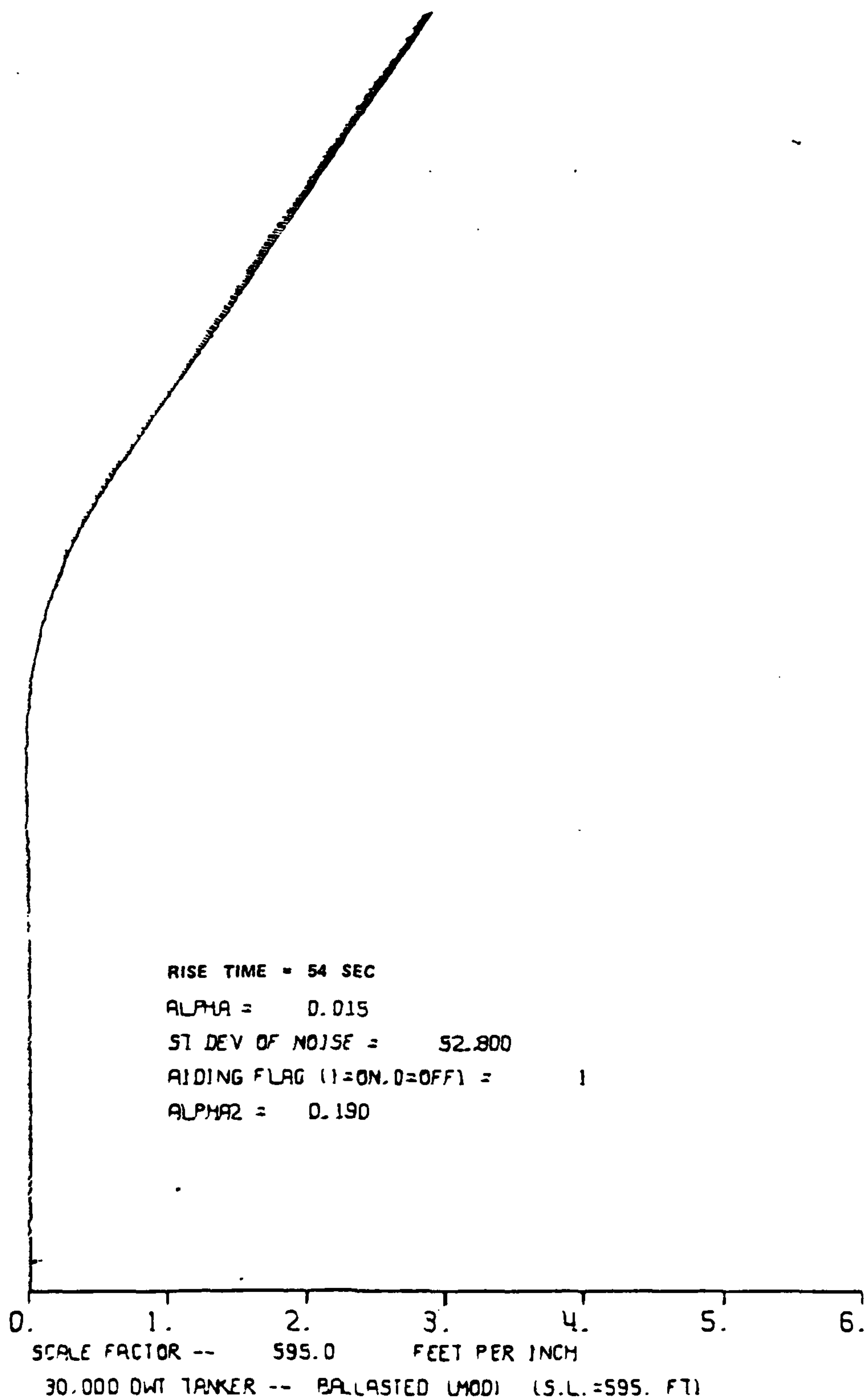

RISE TIME = 54 SEC
ALPHA = 0.015
ST DEV OF NOISE = 52.800
AIDING FLAG (1=ON, 0=OFF) = 1
ALPHA2 = 0.190
0. 1. 2. 3. 4. 5. 6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.36

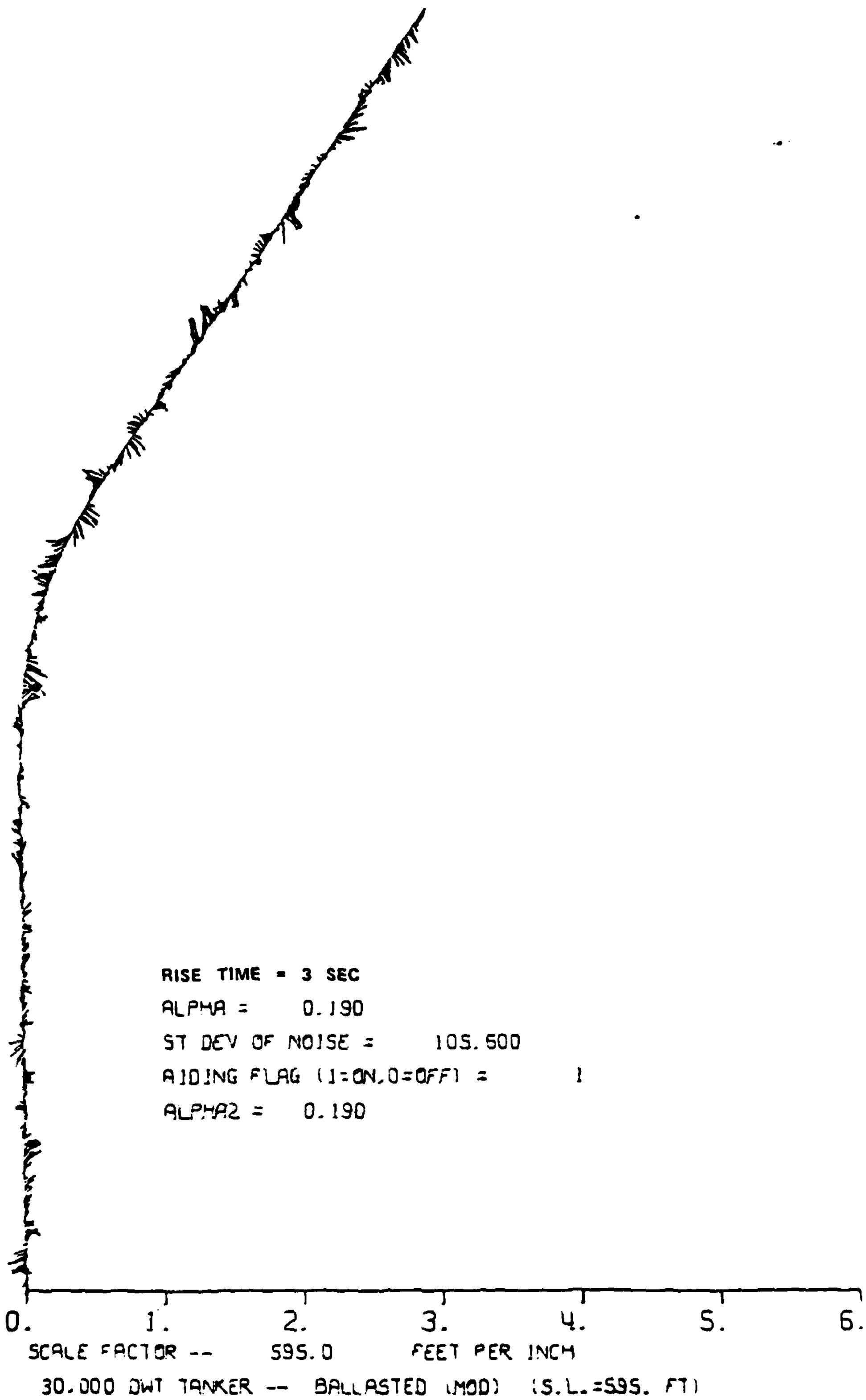
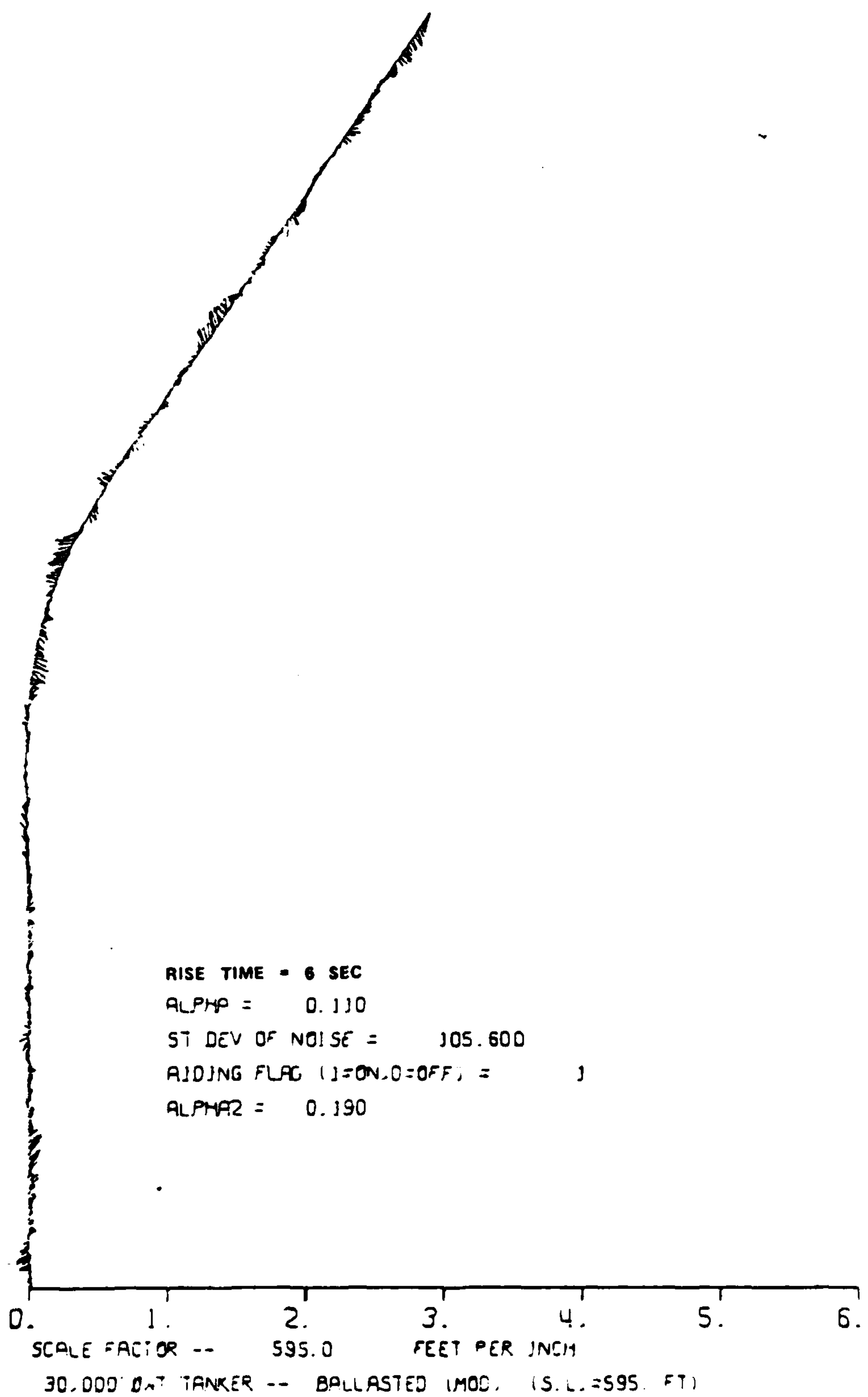
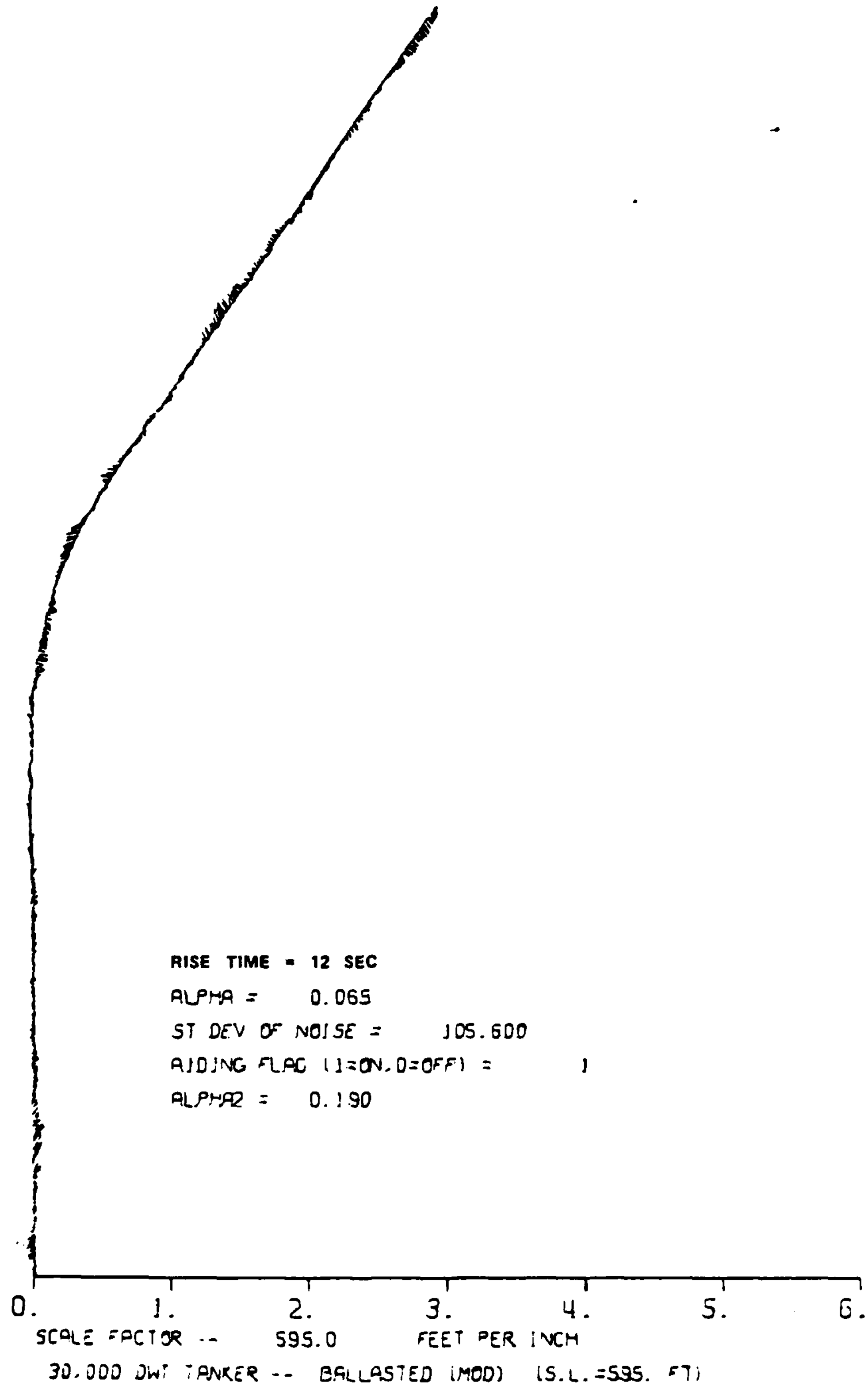

RISE TIME = 3 SEC
ALPHA = 0.190
ST DEV OF NOISE = 105.600
AIDING FLAG (1=ON,0=OFF) = 1
ALPHA2 = 0.190
0.
1.
2.
3.
4.
5.
6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.37



RISE TIME = 6 SEC
ALPHA = 0.110
ST DEV OF NOISE = 105.600
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 B.38



RISE TIME = 12 SEC
ALPHA = 0.065
ST DEV OF NOISE = 105.600
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 B.39

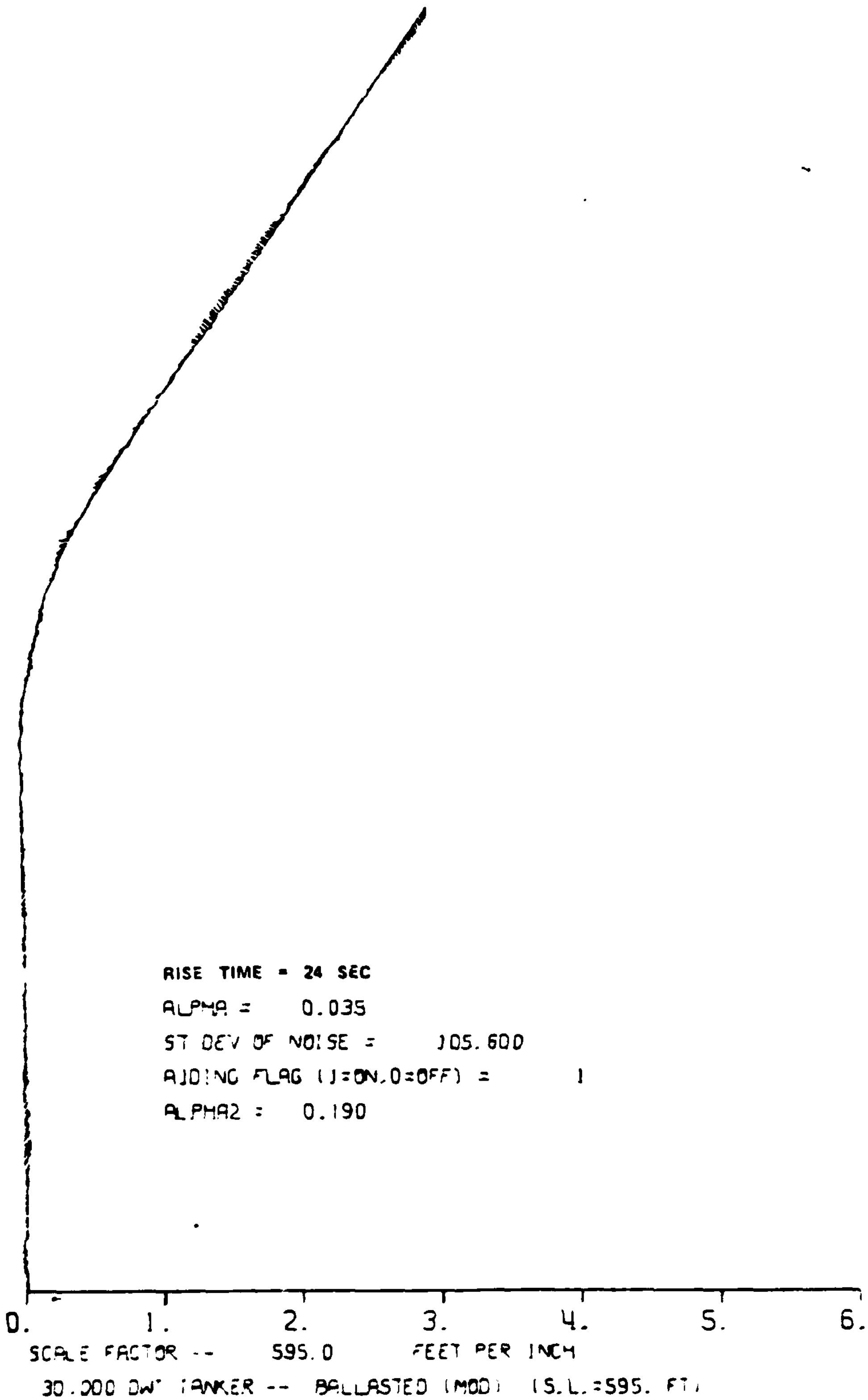
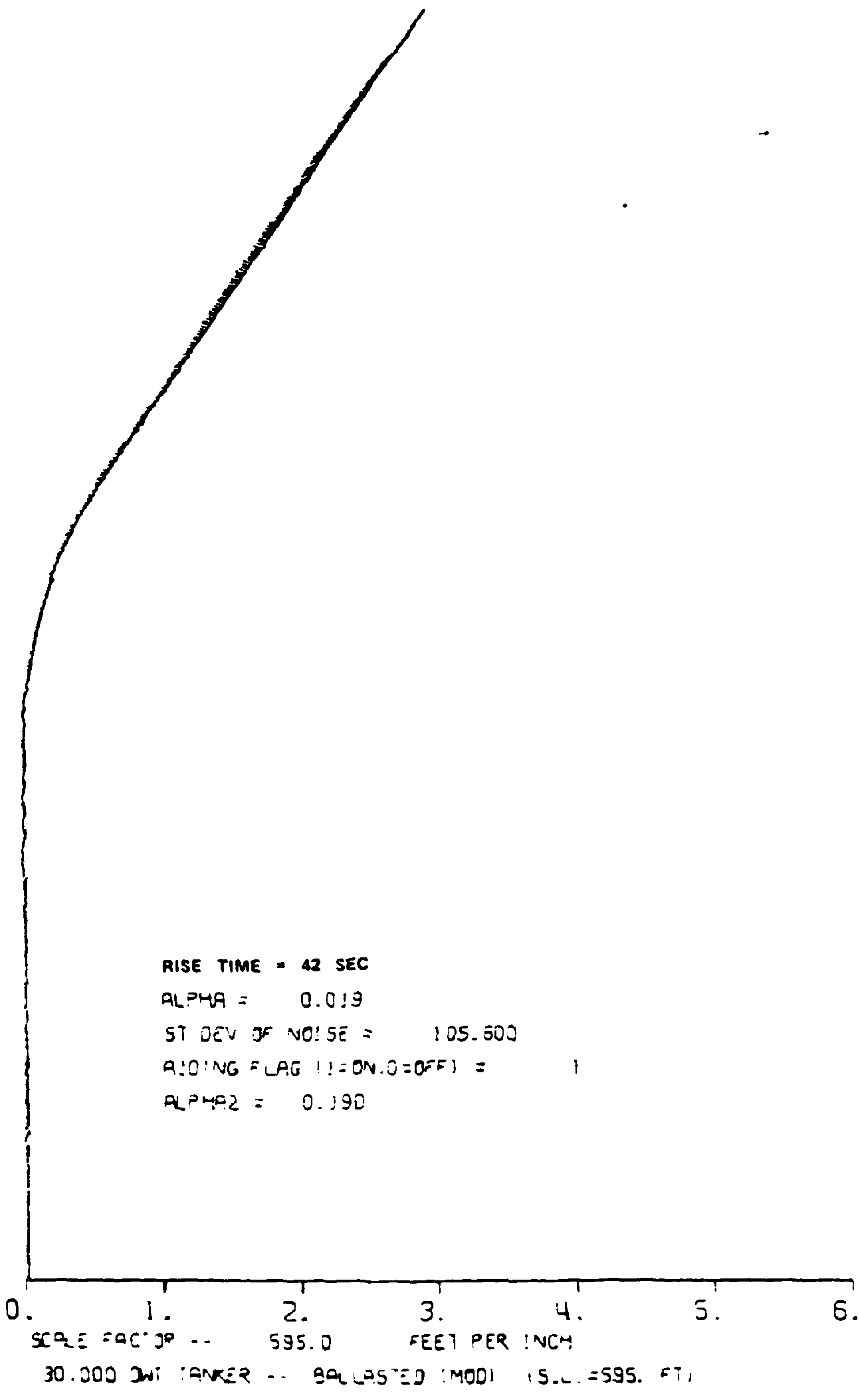

RISE TIME = 24 SEC
ALPHA = 0.035
ST DEV OF NOISE = 105.600
AIDING FLAG (1=ON,0=OFF) = 1
ALPHA2 = 0.190
0.
1.
2.
3.
4.
5.
6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.40



RISE TIME = 42 SEC
ALPHA = 0.019
ST DEV OF NOISE = 105.600
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 B.41

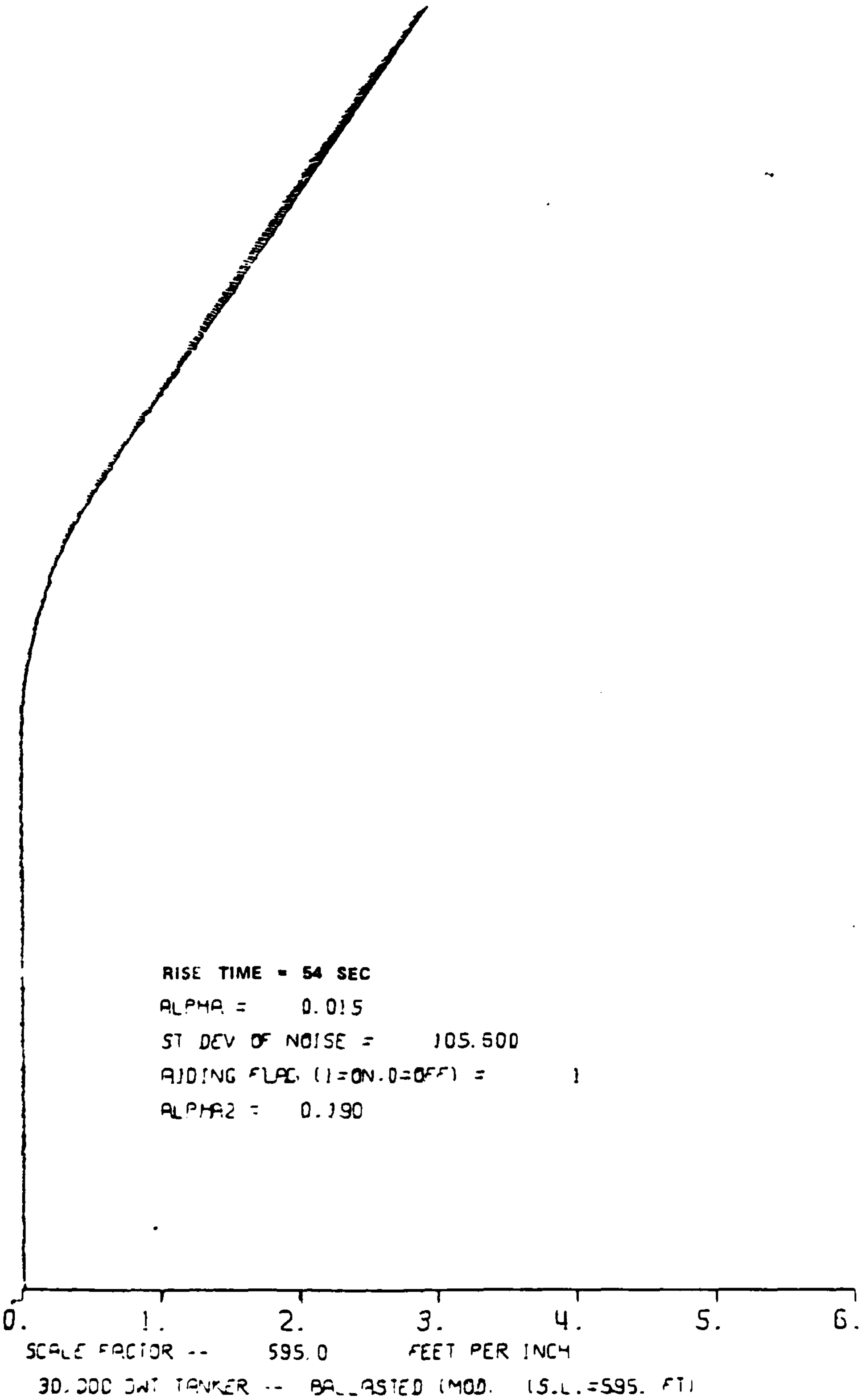

RISE TIME = 54 SEC
ALPHA = 0.015
ST DEV OF NOISE = 105.500
AIDING FLAG (1=ON,0=OFF) = 1
ALPHA2 = 0.190
0.
1.
2.
3.
4.
5.
6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD. (S.L.=595. FT)

Figure B.42

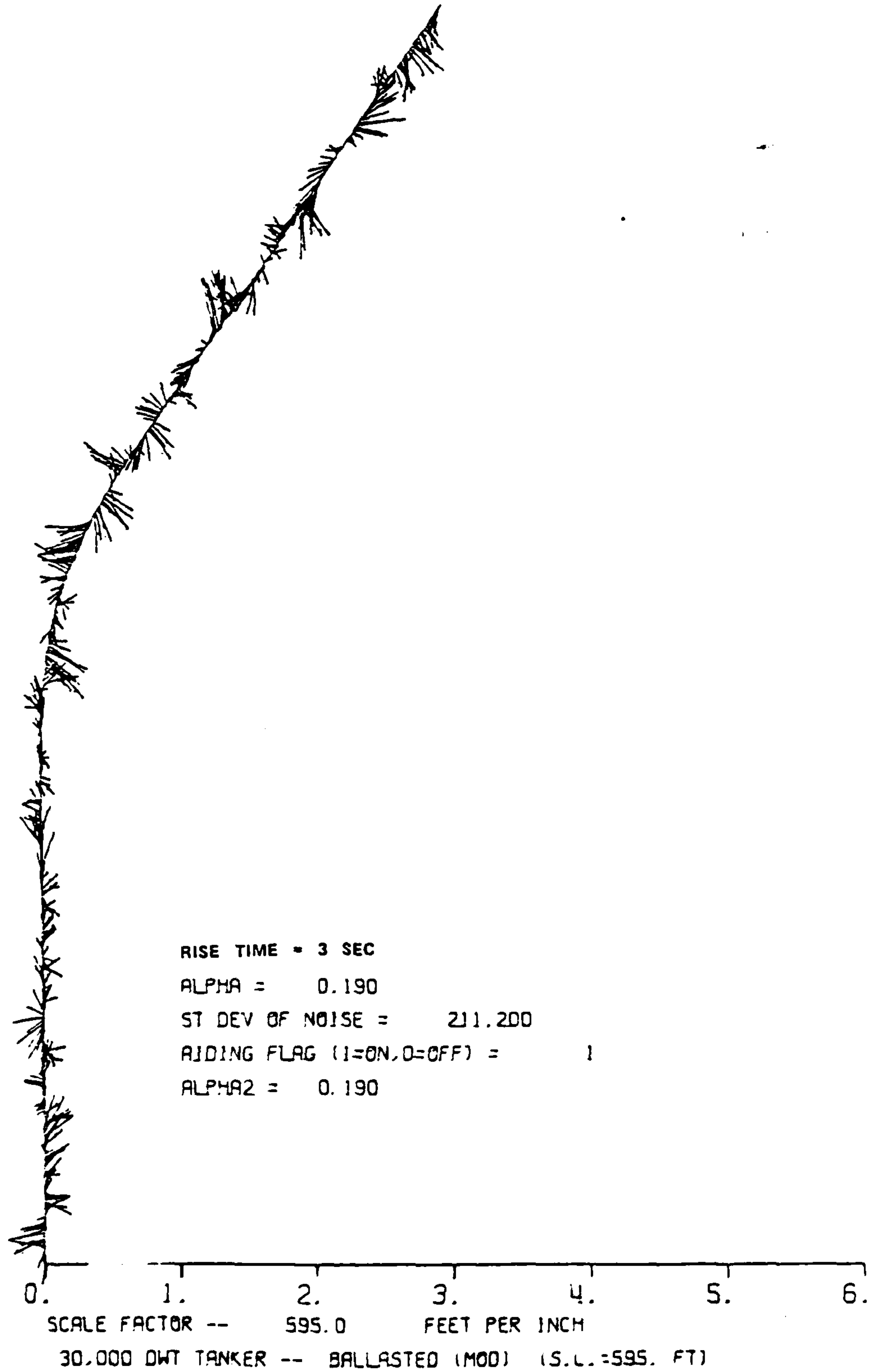

RISE TIME = 3 SEC
ALPHA = 0.190
ST DEV OF NOISE = 211.200
AIDING FLAG (1=ON,0=OFF) = 1
ALPHA2 = 0.190
0.
1.
2.
3.
4.
5.
6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.43

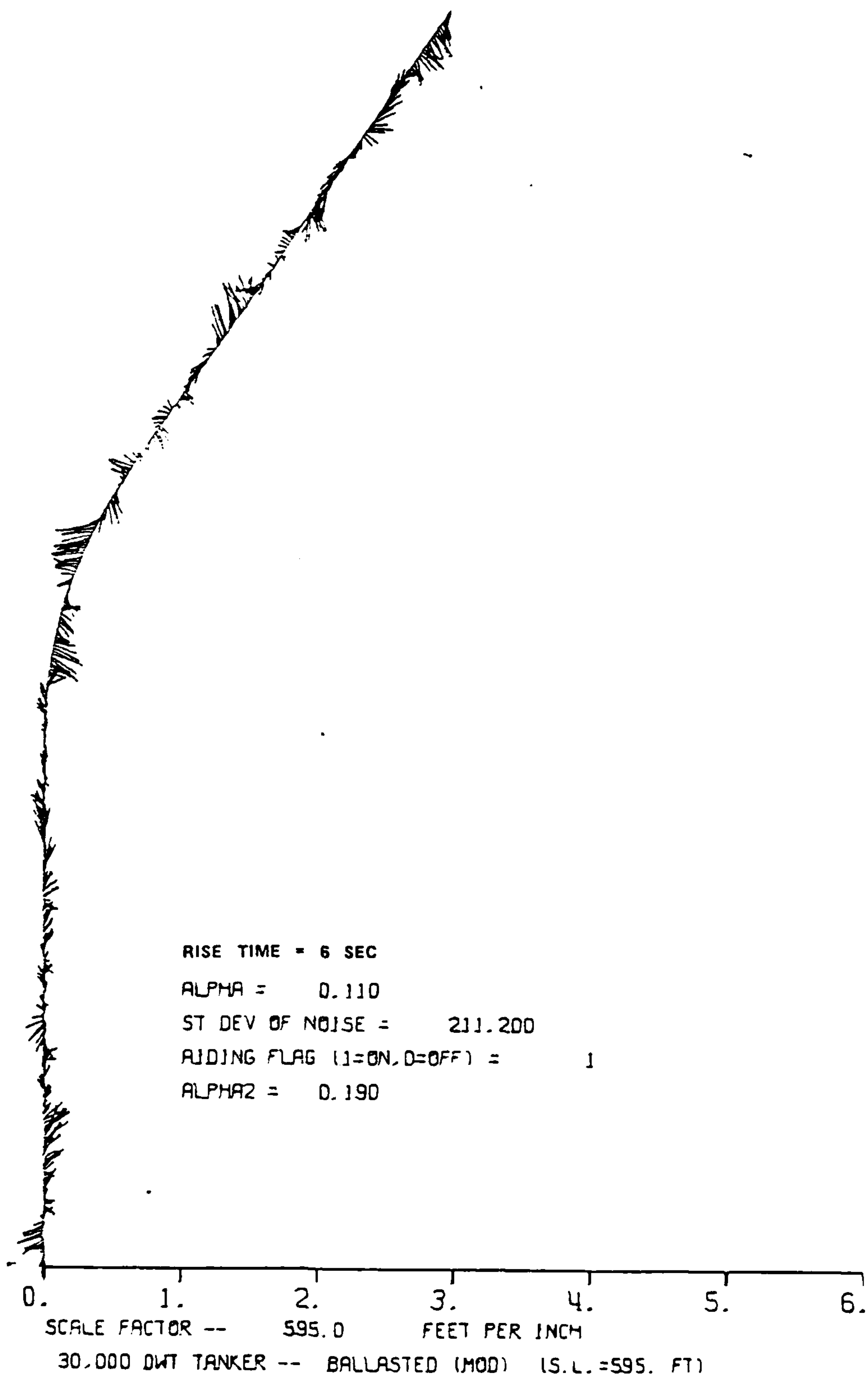

RISE TIME = 6 SEC
ALPHA = 0.110
ST DEV OF NOISE = 211.200
AIDING FLAG (1=ON,0=OFF) = 1
ALPHA2 = 0.190
0.
1.
2.
3.
4.
5.
6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.44

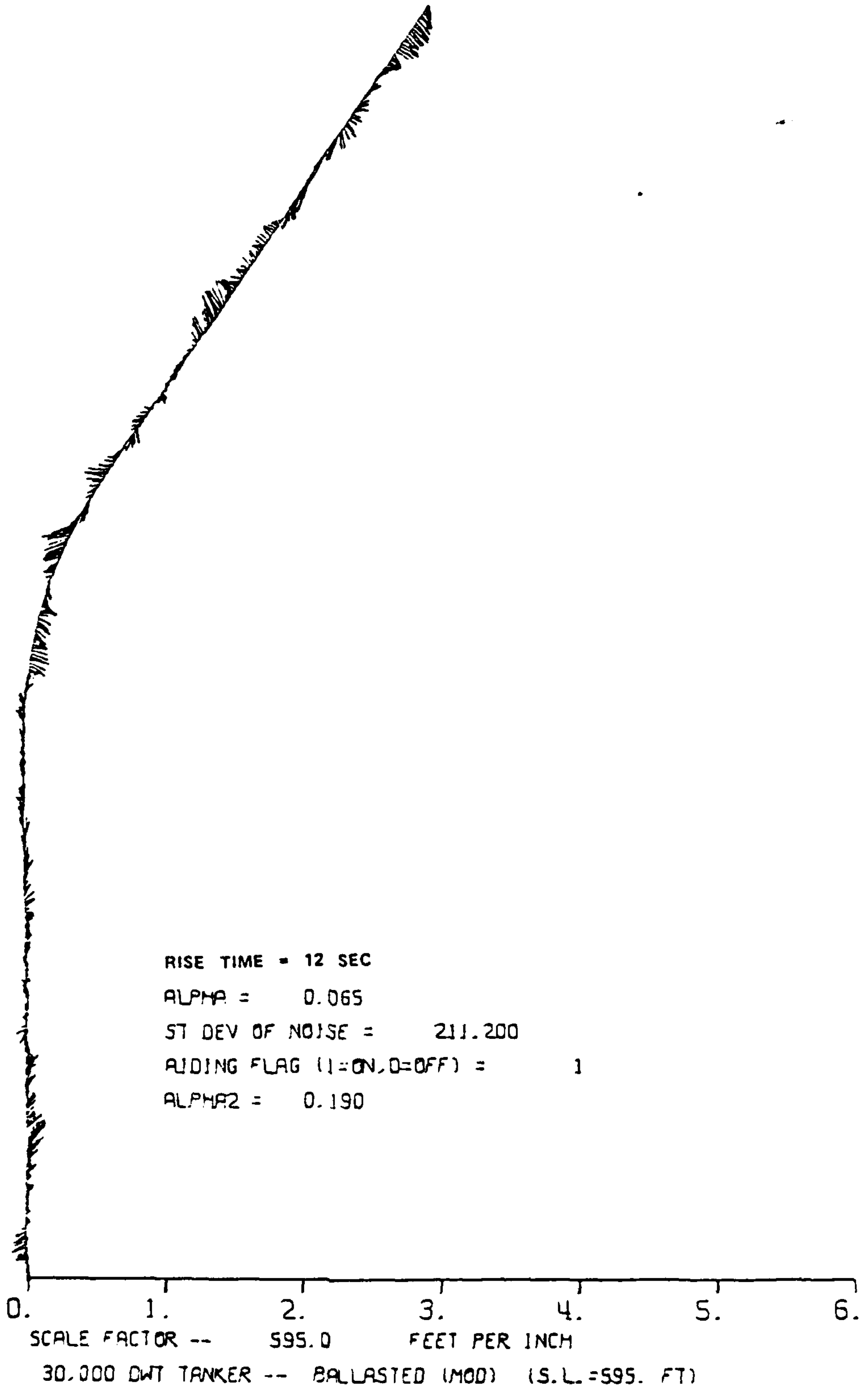

RISE TIME = 12 SEC
ALPHA = 0.065
ST DEV OF NOISE = 211.200
AIDING FLAG (1=ON,0=OFF) = 1
ALPHA2 = 0.190
0. 1. 2. 3. 4. 5. 6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.45

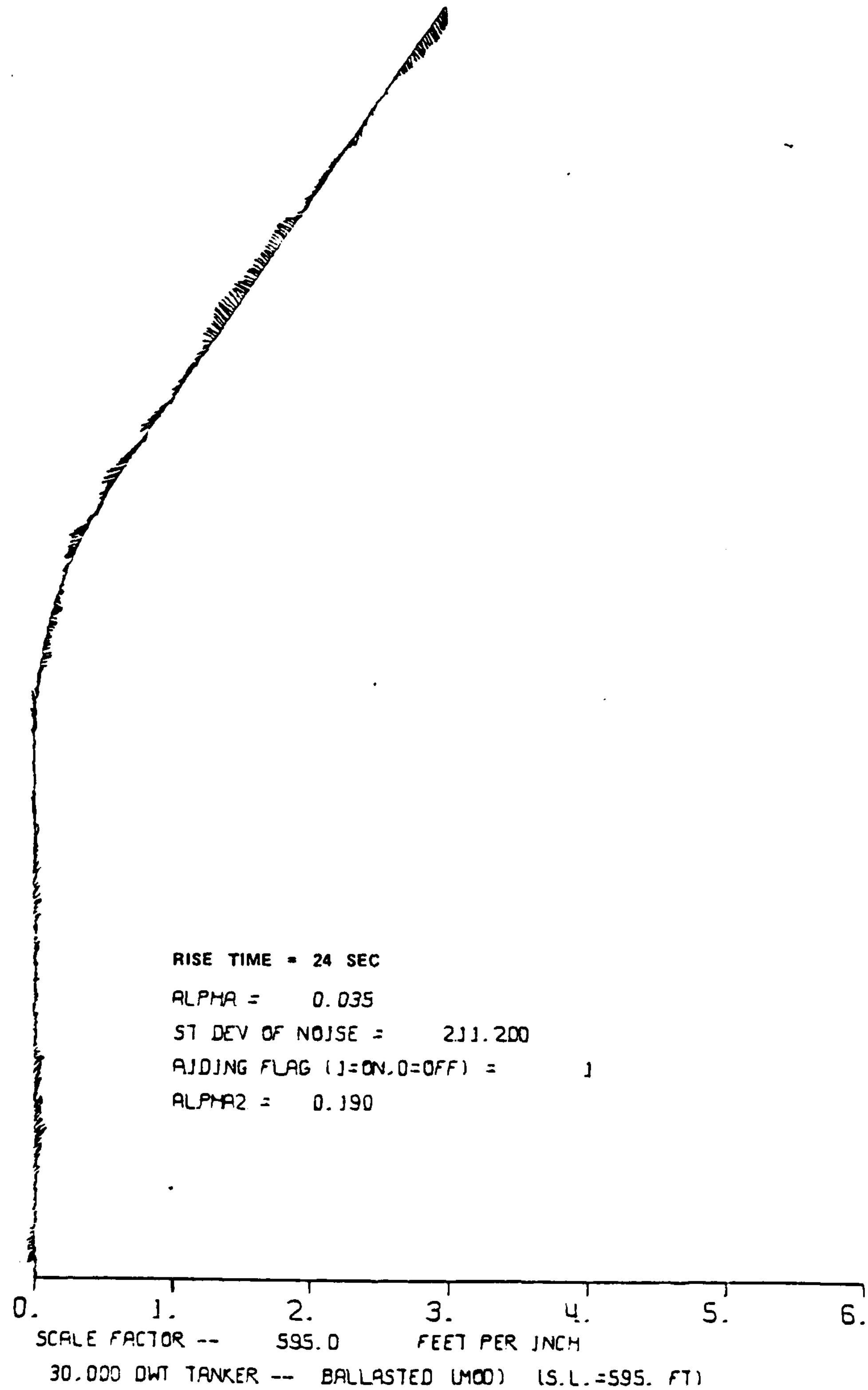

RISE TIME = 24 SEC
ALPHA = 0.035
ST DEV OF NOISE = 211.200
AIDING FLAG (1=ON,0=OFF) = 1
ALPHA2 = 0.190
0.
1.
2.
3.
4.
5.
6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.46

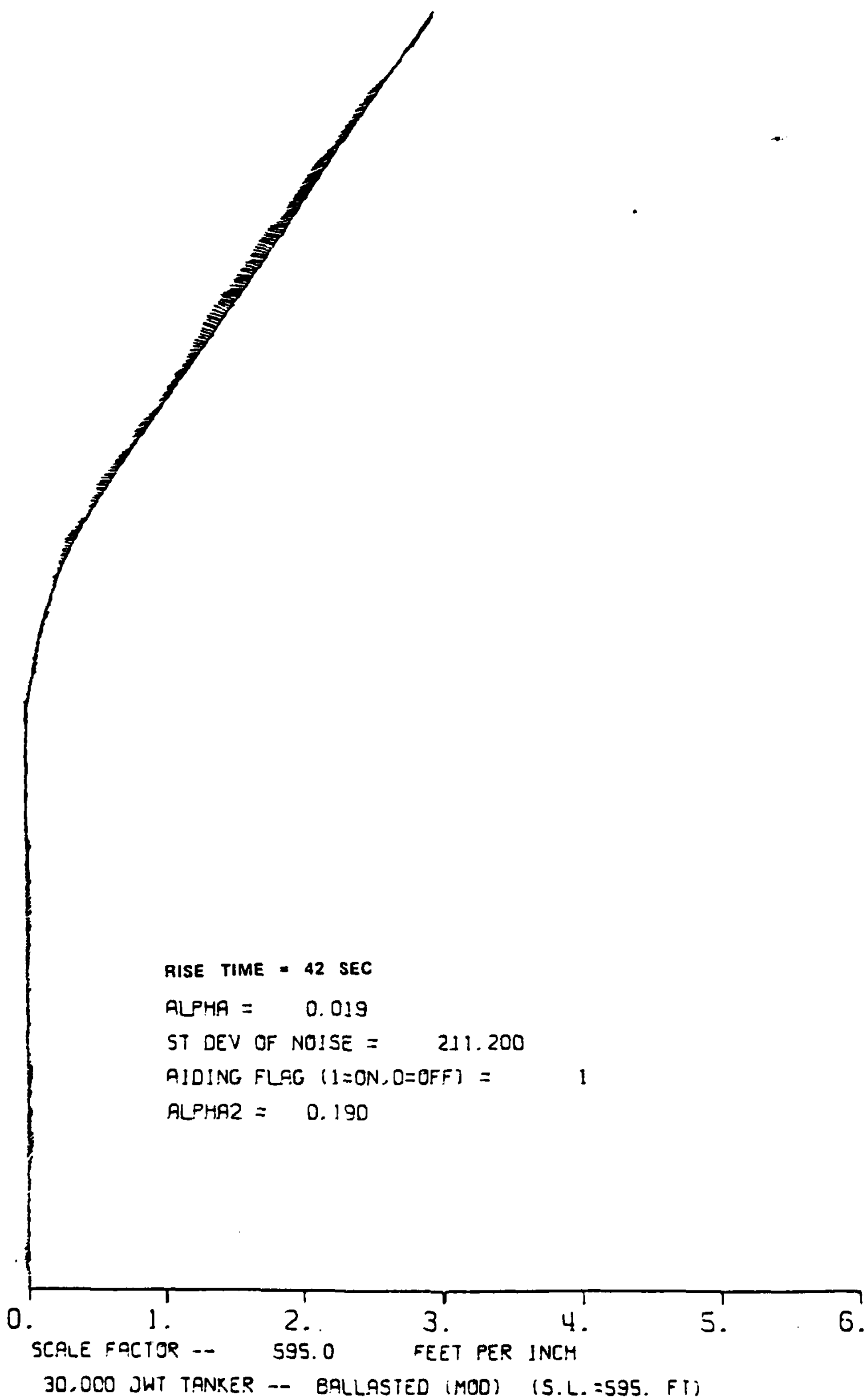

RISE TIME = 42 SEC
ALPHA = 0.019
ST DEV OF NOISE = 211.200
AIDING FLAG (1=ON,0=OFF) = 1
ALPHA2 = 0.190
0.
1.
2.
3.
4.
5.
6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.47

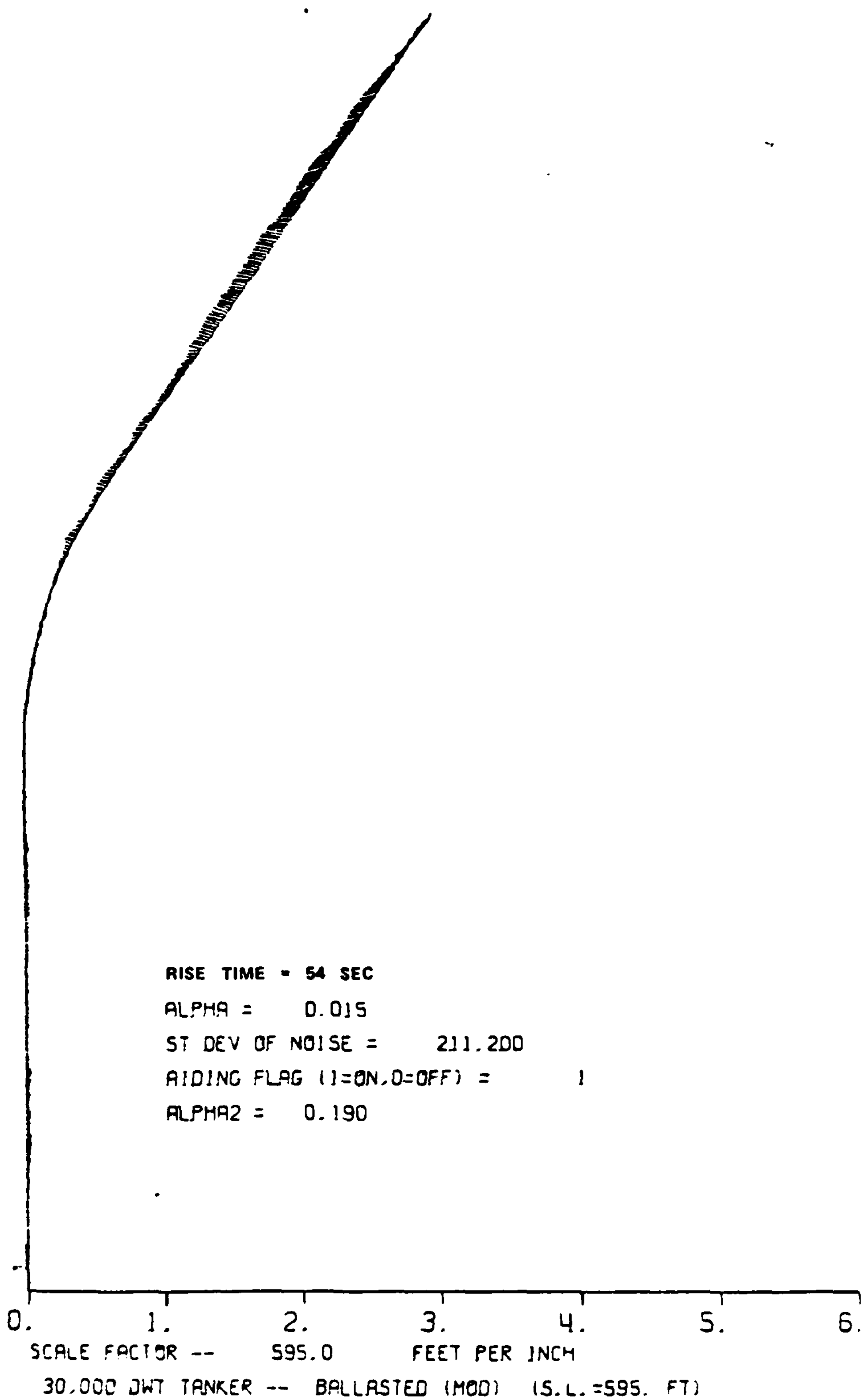

RISE TIME = 54 SEC
ALPHA = 0.015
ST DEV OF NOISE = 211.200
AIDING FLAG (1=ON,0=OFF) = 1
ALPHA2 = 0.190
0.
1.
2.
3.
4.
5.
6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER -- BALLASTED (MOD) (S.L.=595. FT)

Figure B.48

APPENDIX C
INSTRUCTIONS TO SUBJECTS

Introduction. We have asked you to participate in this experiment to evaluate the effectiveness of several types of navigation displays for piloting a ship. You will use these displays separately to determine their usefulness in navigating the ship for 5 miles through a 500-foot wide channel. The different displays will be described in detail when you are ready to use them.

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 6 knots, with a 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 way point (reference chart). The channel is 500 feet wide and 36 feet deep.

Your starting position will be 2.3 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.

C.1 INSTRUCTIONS FOR DIGITAL DISPLAY, D-1

The display that you will use now is a digital display of ownship's position in the channel. The information that you will be provided in the first leg is described below.

- CROSSTRACK DISTANCE is shown in feet to the right or left of the channel centerline, and its direction is indicated by arrows.
- DISTANCE TO WAYPOINT is shown in nm. The waypoint is a point in the center of the bend. You will have to determine beforehand at what distance from the way point you will initiate your turn.

Once you are ready to initiate the turn, rotate the LEG SELECTOR switch to the next leg ("LEG 2") and the CROSSTRACK DISTANCE readout will indicate your distance in feet from the centerline of the new leg. Through the turn, you should try to maintain a turn rate which will bring you out at 306 degrees gyro exactly on the new centerline. You will be on a heading of 341 degrees in the first leg, at 8 knots, half ahead, approximately 2 nm from the turn. Just take the ship in normally. Are there any questions? (See Figures C-1 and C-2.)

C.2 INSTRUCTIONS FOR DIGITAL DISPLAY, D-2

The display that you will use now is a digital display of ownship's position in the channel with recommendations for making the turn. The information that you will be provided in the first leg is described below.

a. CROSSTRACK DISTANCE is shown in feet to the right or left of the channel centerline, and its direction is indicated by arrows.

b. CROSSTRACK SPEED is shown in feet per minute in the direction that ownship is moving.

c. ACTUAL TURN RATE is shown in degrees per minute to right or left.

d. DISTANCE TO WAYPOINT is shown in nm. The waypoint is a point in the center of the bend. You will have to determine beforehand at what distance from the waypoint you will initiate your turn.

Once you are ready to initiate the turn, rotate the LEG SELECTOR switch to the next leg ("LEG 2") and the CROSSTRACK DISTANCE readout will indicate your distance in feet from the centerline of the new leg. Also upon selection of the next leg you will be shown a RECOMMENDED TURN RATE which you should try to continuously match with ownship's turn rate. This will bring you on the centerline of the new leg. Once your course is within 5 degrees of the new leg, RECOMMENDED TURN RATE will disappear. You will be on a heading of 341 degrees in the first leg, at 8 knots, half ahead, approximately 2 nm from the turn. Just take the ship in normally. Are there any questions? (See Figures C-3 and C-4).

C.3 INSTRUCTIONS FOR GRAPHIC DISPLAY VARIABLE, G-1

The display that you will use now 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 3/4 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. Ownship's image is the actual shape and size of ownship scaled to the display. You will be on a heading of 341 degrees in the first leg, at 8 knots, half ahead, approximately 2 nm from the turn. Just take the ship in normally. Are there any questions?

C.4 INSTRUCTIONS FOR GRAPHIC DISPLAY, G-2

The display that you will use now 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 moves across the

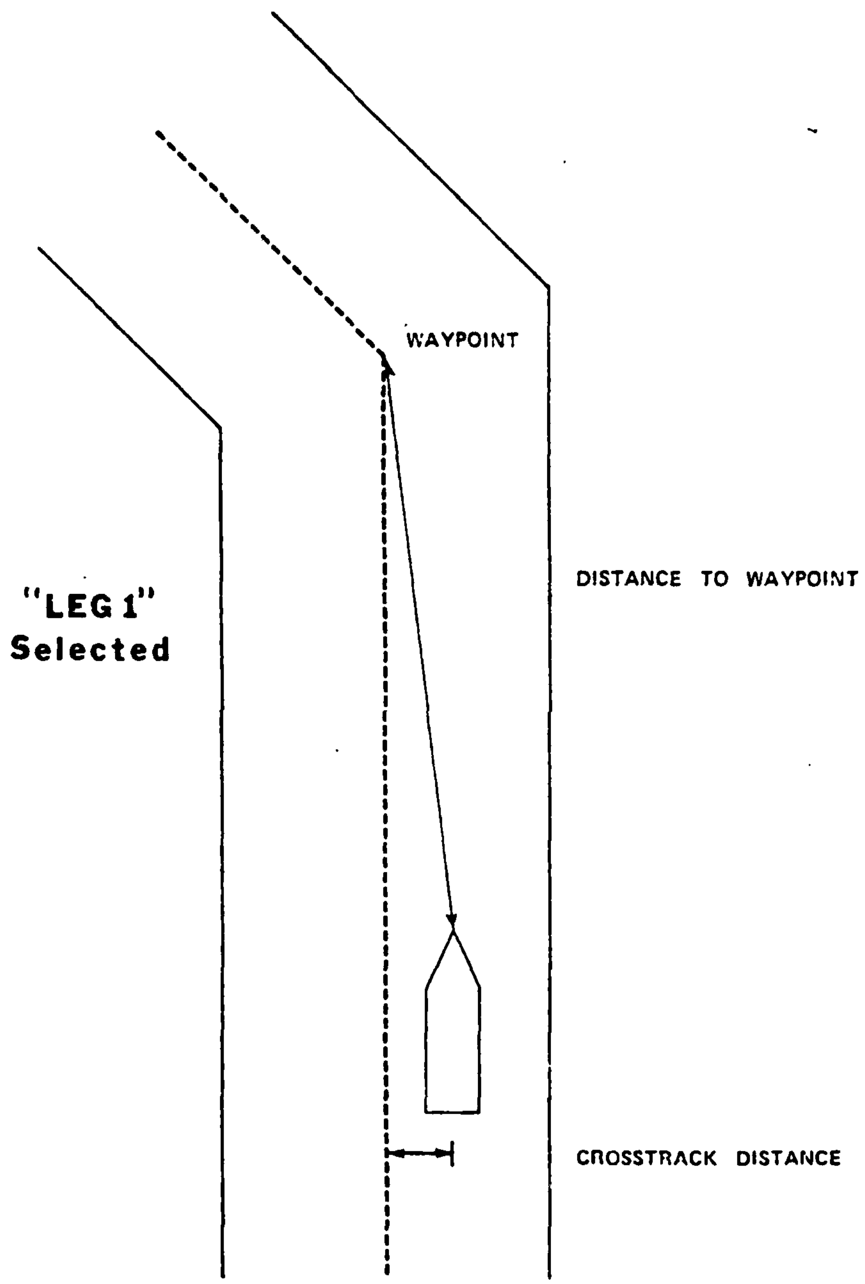


FIGURE C-1. DIAGRAM FOR D-1 INSTRUCTIONS

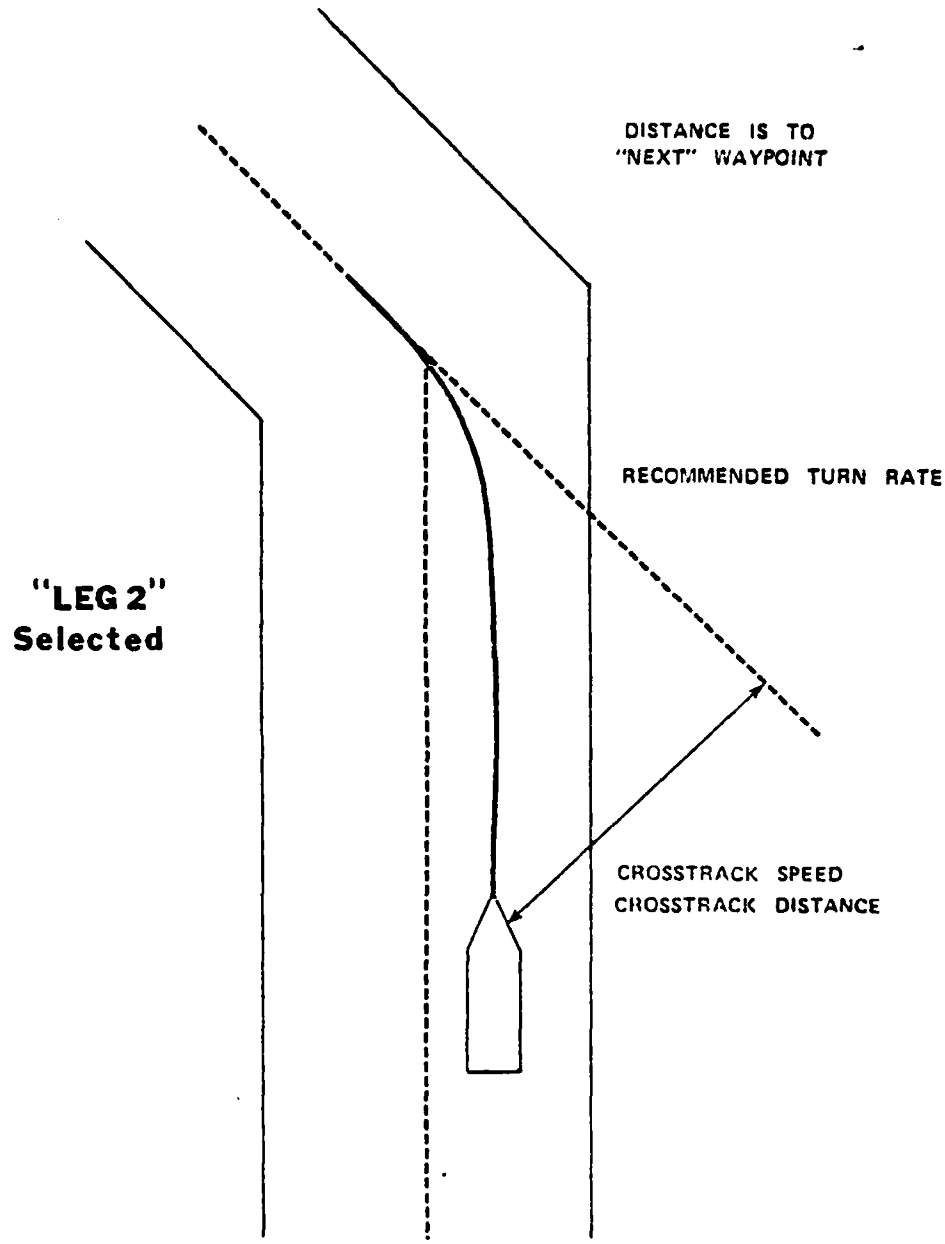


FIGURE C-2. DIAGRAM FOR D-1 INSTRUCTIONS

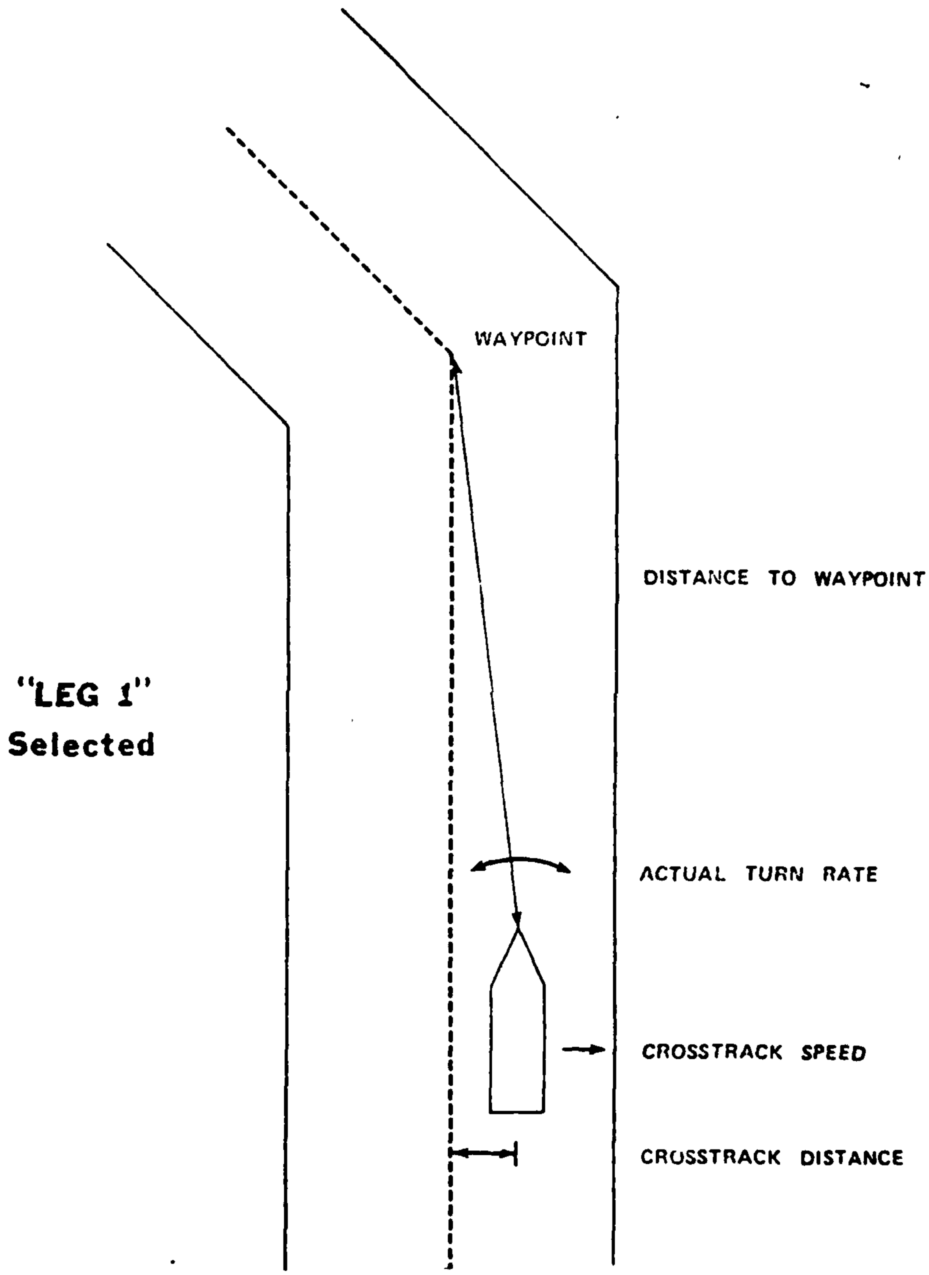


FIGURE C-3. DIAGRAM FOR D-2 INSTRUCTIONS

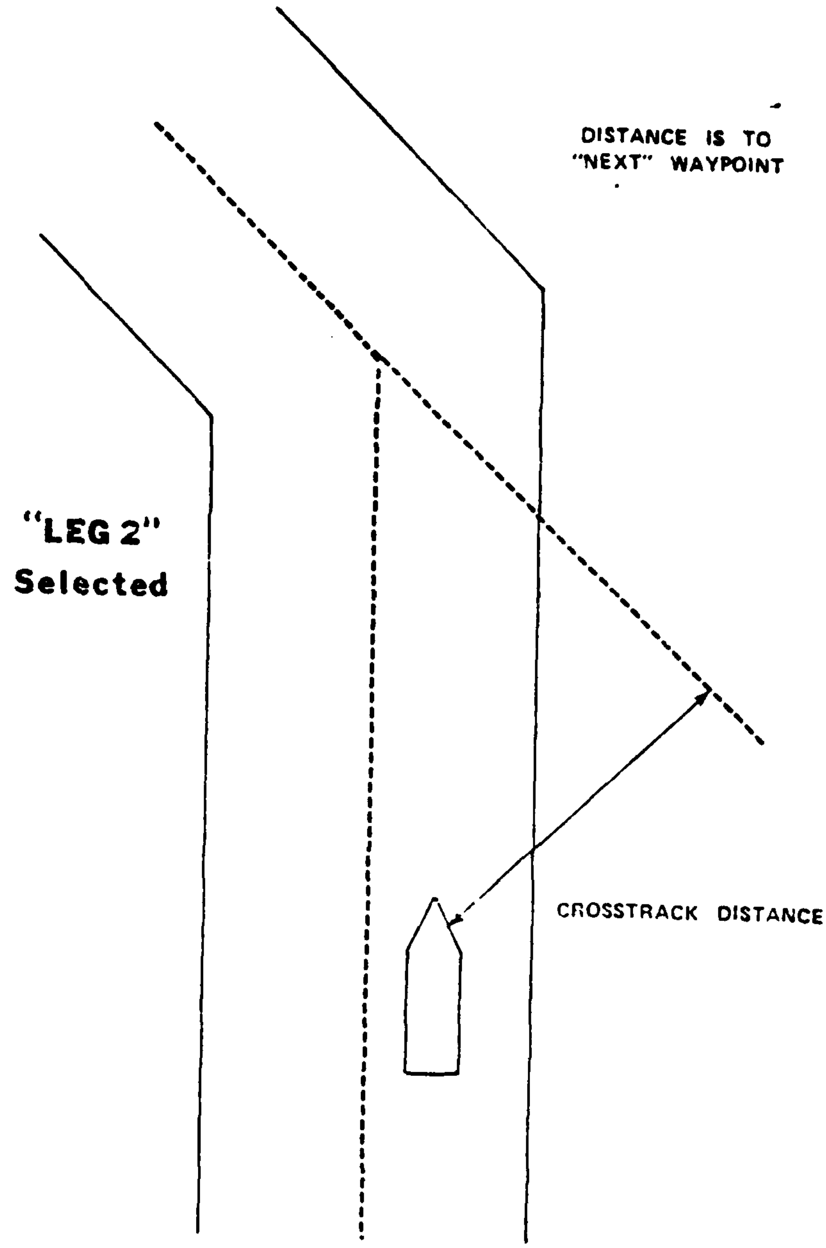


FIGURE C-4. DIAGRAM FOR D-2 INSTRUCTIONS

screen for 3/4 of the distance before it is reset. 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 course vector which represents the course-made-good of ownship. It is drawn for the distance ownship will travel in a selected amount of time. This time may be shortened or lengthened up to 3 minutes by rotating the PREDICTION TIME CONTROL. Ownship's image is the actual shape and size of ownship scaled to the display. You will be on a heading of 341 degrees in the first leg, at 8 knots, half ahead, approximately 2 nm from the turn. Just take the ship in normally. Are there any questions?

C.5 INSTRUCTIONS FOR PERSPECTIVE DISPLAY, P-1

The display that you will use now is a perspective display which represents what you would see out the window if channel boundaries were visible. The channel boundaries will be shown as dashed lines. However, these dashes are symbolic and do not represent distance. As a result, the dashed lines will not move along ownship as you proceed down the channel. You will be on a heading of 341 degrees in the first leg, at 8 knots, half ahead, approximately 2 nm from the turn. Just take the ship in normally. Are there any questions?

C.6 INSTRUCTIONS FOR STEERING DISPLAY, S-1

The display that you will use now is a predictor steering 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 3/4 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 predictor steering vector which represents ownship's projected track. This vector is computed from ownship hydrodynamic equations and the effects of wind, current and propeller forces. The vector may be curved or straight depending upon ownship's motion and the amount of rudder which is applied. A dotted ship's image is also projected at the end of the vector. This image shows the computed aspect and drift angle of ownship by the time it has arrived at that location. For example, ownship on a straight track, with no drift angle, rudder amidships, and no wind or current would display a relatively straight vector ahead. When rudder is applied, the vector will curve right or left to indicate ship's projected track through the turn. Ownship's image at the end of the vector will change to indicate resultant drift angle. During the turn, normal slowing will occur and the vector will shorten. If rpm is increased or decreased, the vector length will change to show predicted change in ship speed. The predictor steering display should enable you to select the appropriate rudder for all maneuvers. However, you are cautioned that the predictor is computed only from forces acting on the ship at that instant. Forces such as wind and current ahead of ownship are not included in the prediction. Their effects are computed and displayed only when the ship begins to feel them. This may require additional pilotage on your part.

The vector is drawn for the distance ownship will travel in a selected amount of time. This time may be shortened or lengthened up to 3 minutes by rotating the

PREDICTION TIME CONTROL. Ownship's image is the actual shape and size of ownship scaled to the display. You will be on a heading of 341 degrees in the first leg, at 8 knots, half ahead, approximately 2 nm from the turn. Just take the ship in normally. Are there any questions?

C.7 INSTRUCTIONS FOR STEERING DISPLAY, S-2

The display that you will use now is a simplified predictor steering 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 moves across the screen for 3/4 of the distance before it is reset. 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 simplified predictor steering vector which represents ownship's projected track. This vector is computed from ownship's speed and present rate of turn. As long as no turn rate is experienced, regardless of rudder position, the vector will remain straight in the direction of ownship's course. Once a rate of turn is developed for whatever reason, the resulting curved track will be indicated. As turn rate and speed increases or decreases through a maneuver, the track curve will tighten or straighten respectively. You are cautioned, however, that the vector indicates ownship's track at a constant rate of turn. Since, through a maneuver ownship's rate of turn is continuously changing, it is important to remember that ownship will actually track inside the curve if the swing is increasing and outside the curve if the swing is decreasing.

The vector is drawn for the distance ownship will travel in a selected amount of time. This time may be shortened or lengthened up to 3 minutes by rotating the PREDICTION TIME control. Ownship's image is the actual shape and size of ownship scaled to the display. You will be on a heading of 341 degrees in the first leg, at 8 knots, half ahead, approximately 2 nm from the turn. Just take the ship in normally. Are there any questions?

APPENDIX D
INTERVIEW QUESTIONNAIRES

CATEGORY 1

Subject:__________________

Run:_____________________

POSTRUN QUESTIONNAIRE (ALL RUNS)

1. In general, the transit was:

   _____ entirely too fast
   _____ faster than it should have been
   _____ slower than it should have been
   _____ entirely too slow

2. Initially I maneuvered to the centerline:

   _____ too fast
   _____ too slow
   _____ too early
   _____ too late

3. Except for the initial offset through the straight legs of the waterway, ownship was:

   _____ never on the centerline
   _____ seldom on the centerline
   _____ usually on the centerline
   _____ always on the centerline

4. My turn rudder at the bend should have been:

   _____ earlier
   _____ later
   _____ larger
   _____ smaller

5. My check rudder after the bend should have been:

   _____ earlier
   _____ later
   _____ larger
   _____ smaller

6. My overall pilotage of the run was:

   _____ poor
   _____ fair
   _____ good
   _____ excellent

7. In this run, I:

_____ understood very little about the display
_____ understood some of the display
_____ understood most of the display
_____ completely understood all of the display

8. In this run, the displayed information was:

_____ never accurate
_____ sometimes accurate
_____ usually accurate
_____ always accurate

9. To adequately learn this display:

_____ most of the run was required
_____ several maneuvers of the ship were required
_____ a few minutes of observation were required
_____ the instructions alone were sufficient

10. The rate of speed at which the information on the display was updated was:

_____ too slow
_____ slow but acceptable
_____ fast but acceptable
_____ too fast

CATEGORY 2
(SECOND DIGITAL DISPLAY RUNS)

11. In this run with the DIGITAL display compared to the last run with the DIGITAL display I: (check one)

a. _____ initially steadied up on the centerline better
_____ initially steadied up on the centerline worse

b. _____ transited the straight legs better
_____ transited the straight legs worse

c. _____ rounded the bend better
_____ rounded the bend worse

d. _____ steadied up in the second leg better
_____ steadied up in the second leg worse

e. _____ started the turn earlier
_____ started the turn later

f. _____ used a different strategy for the turn
_____ used the same strategy for the turn

g. _____ used more overall rudder
_____ used less overall rudder

h. _____ used more engine orders
_____ used fewer engine orders

i. _____ found the display more useful
_____ found the display less useful

j. _____ found the display more accurate
_____ found the display less accurate

k. _____ found the display easier to understand
_____ found the display more difficult to understand

l. _____ was better able to determine ownship speed
_____ was less able to determine ownship speed

m. _____ was better able to determine ownship position
_____ was less able to determine ownship position

n. _____ was better able to determine ownship swing
_____ was less able to determine ownship swing

o. _____ used the gyro repeater more
_____ used the gyro repeater less

p. _____ referred to the chart more
_____ referred to the chart less

CATEGORY 3
(SECOND GRAPHIC DISPLAY RUNS)

11. In this run with the GRAPHIC display compared to the last run with the GRAPHIC display, I probably: (check one)

a. _____ initially steadied up on the centerline better
   _____ initially steadied up on the centerline worse

b. _____ transited the straight legs better
   _____ transited the straight legs worse

c. _____ rounded the bend better
   _____ rounded the bend worse

d. _____ steadied up in the second leg better
   _____ steadied up in the second leg worse

e. _____ started the turn earlier
   _____ started the turn later

f. _____ used a different strategy for the turn
   _____ used the same strategy for the turn

g. _____ used more overall rudder
   _____ used less overall rudder

h. _____ used more engine orders
   _____ used fewer engine orders

i. _____ found the display more useful
   _____ found the display less useful

j. _____ found the vector to be more accurate
   _____ found the vector to be less accurate

k. _____ found the display easier to understand
   _____ found the display more difficult to understand

l. _____ was better able to determine ownship speed
   _____ was less able to determine ownship speed

m. _____ was better able to determine ownship position
   _____ was less able to determine ownship position

n. _____ was better able to determine ownship swing
   _____ was less able to determine ownship swing

o. _____ used the gyro repeater more
   _____ used the gyro repeater less

p. _____ referred to the chart more
   _____ referred to the chart less

CATEGORY 4
(SECOND STEERING DISPLAY RUNS)

11. In this run with the STEERING display compared to the last run with the STEERING display, I probably: (check one)

a. _____ initially steadied up on the centerline better
   _____ initially steadied up on the centerline worse

b. _____ transited the straight legs better
   _____ transited the straight legs worse

c. _____ rounded the bend better
   _____ rounded the bend worse

d. _____ steadied up in the second leg better
   _____ steadied up in the second leg worse

e. _____ started the turn earlier
   _____ started the turn later

f. _____ used a different strategy for the turn
   _____ used the same strategy for the turn

g. _____ used more overall rudder
   _____ used less overall rudder

h. _____ used more engine orders
   _____ used fewer engine orders

i. _____ found the display more useful
   _____ found the display less useful

j. _____ found the vector to be more accurate
   _____ found the vector to be less accurate

k. _____ found the display easier to understand
   _____ found the display more difficult to understand

l. _____ was better able to determine ownship speed
   _____ was less able to determine ownship speed

m. _____ was better able to determine ownship position
   _____ was less able to determine ownship position

n. _____ was better able to determine ownship swing
   _____ was less able to determine ownship swing

o. _____ used the gyro repeater more
   _____ used the gyro repeater less

p. _____ referred to the chart more
   _____ referred to the chart less

q. _____ thought the vector behaved as I expected
_____ thought the vector did not behave as I expected

r. _____ thought ownship more closely followed the vector
_____ thought ownship less closely followed the vector

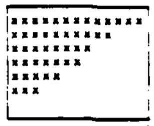
12. Of the predictor steering vectors in general, I found them to be: (check any that apply)

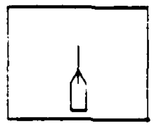
_____ too short
_____ too slow
_____ occasionally outside the channel
_____ not believable
_____ too sporadic (jumping around)
_____ potentially confusing
_____ mostly beneficial in the bend
_____ mostly beneficial in the straights
_____ of greater benefit to the helmsman

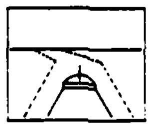
CATEGORY 5

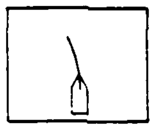
Subject:____________________
Run:______________________

POSTSIMULATION QUESTIONNAIRE

Using D =  DIGITAL display

G =  GRAPHIC display

P =  PERSPECTIVE display

S =  STEERING display

1. Rank the displays by putting a D, G, P, and S in the appropriate spot.

	1	2	3	4
a.	Most effective for pilotage			Least effective for pilotage
b.	Easiest to learn			Most difficult to learn
c.	Used during my best run			Used during my worst run
d.	Easiest to judge ship position			Most difficult to judge ship position
e.	Easiest to judge ship speed			Most difficult to judge ship speed

	1	2	3	4
f.	Easiest to judge swing			Most difficult to judge swing
g.	Easiest to select turn point			Most difficult to select turn point
h.	Easiest to select required turn rudder			Most difficult to select required turn rudder
i.	Most accurate			Least accurate
j.	Fastest update rate			Slowest update rate
k.	Simple in appearance			Complex in appearance
l.	I would use in the real world			I would not use in the real world
m.	Most expensive			Least expensive

2. In general, the overall simulation was: (check any which apply)

_____ too long
_____ disorganized
_____ difficult for me to perform
_____ tiring
_____ unrealistic
_____ insufficiently equipped
_____ sometimes confusing
_____ too much work for one watch officer
_____ boring
_____ too simplistic to represent the real world
_____ too repetitive
_____ a contributor to my headache or eyestrain
_____ less challenging than I expected

APPENDIX E

MANEUVERING ANALYSIS RATIONALE

Appendix E contains the rationale and methodology for determining the measures shown on the "Comparison in Maneuvering Performance" tables discussed in Section 5.

MANEUVERING ANALYSIS

CRITERIA FOR DETERMINING:

1. <u>Return to centerline</u>

a. Alongtrack distance (ATD) from start of run to ownship crosses centerline (or in the event ownship does not cross centerline)

b. ATD from start of run to ownship makes its first closest approach to 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 start of run to first course command 340 degrees or larger (or in the event no course command 340 degrees or larger is given)

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

2. <u>Overshoot following return to centerline</u>

a. Largest crosstrack distance (CTD) immediately following when ownship crosses centerline (or in the event ownship does not cross the centerline)

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

3. <u>Steady up on the centerline</u>

a. ATD from start of 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 start of run to first time three similar crosstrack distances occur consecutively (±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>Initial turn rudder</u>

a. The amount of rudder initially applied to execute the turn and the ATD from the waypoint (center of the bend) at which it was applied

5. Maximum turn rudder

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

6. Frequency of turn rudder actuations

a. Total number of rudder actuations prior to check rudder

7. Technique of turn rudder application

a. Designation "A" when only one rudder is selected and maintained up until check rudder (or midships)

b. Designation "B" when a small rudder is selected initially, then increased to a larger rudder prior to check rudder (or midships)

c. Designation "C" when a large rudder is selected initially, then decreased to a smaller rudder prior to check rudder (or midships)

d. Designation "D" when a small rudder is selected initially, then increased to a larger rudder, then returned to a smaller rudder prior to check rudder (or midships)

e. Designation "E" when a large rudder is decreased to a small rudder, midships, or reverse rudder, then returned to a large rudder at any time prior to check rudder (or midships)

8. Initial check rudder

a. The amount of rudder initially applied to check the swing and the ATD from the waypoint (center of the bend) at which it was applied

9. Maximum check rudder

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

10. Frequency of turn rudder actuations

a. Total number of rudder actuations prior to steady up

11. Steady up in second leg

a. ATD from 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 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

APPENDIX F

STATISTICAL COMPARISON OF TRACKKEEPING PERFORMANCE

Appendix F 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.

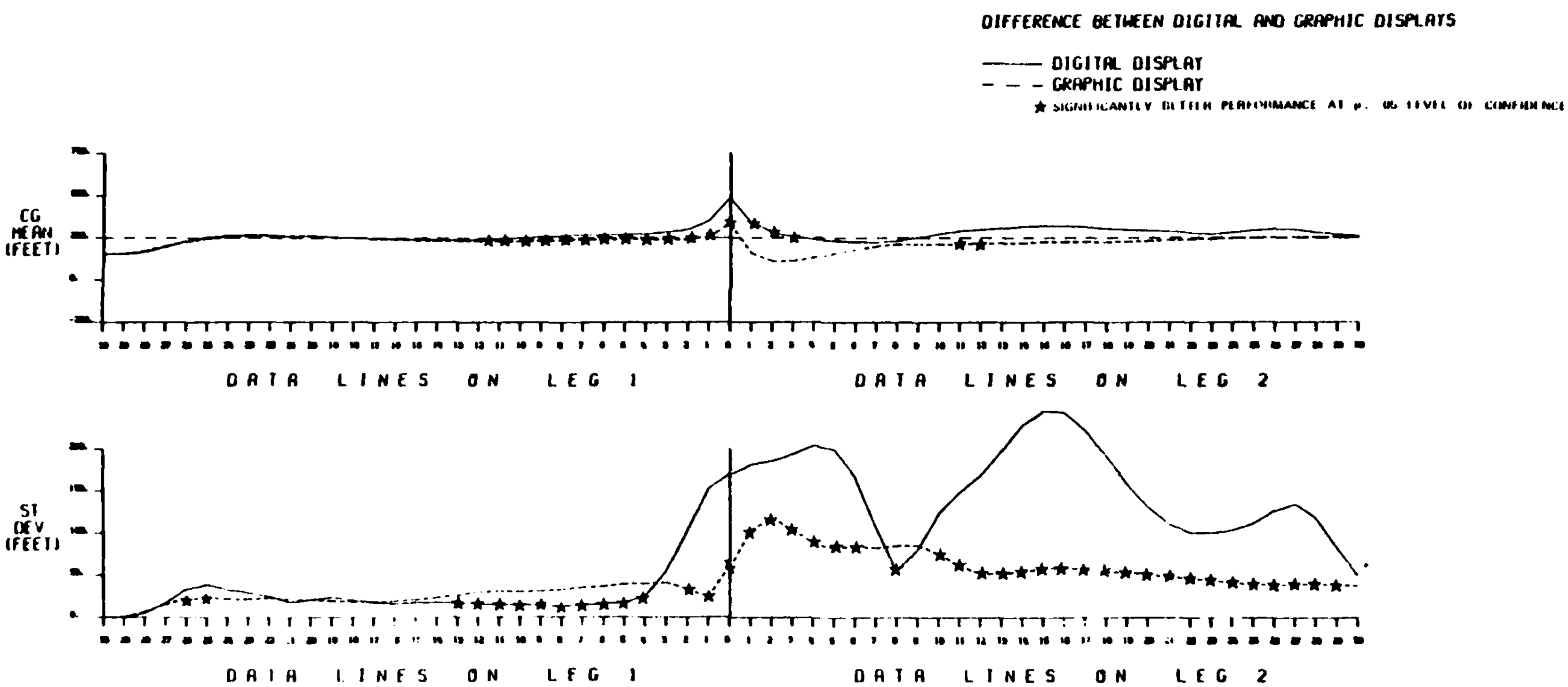


FIGURE F-1. STATISTICAL COMPARISON OF DIGITAL AND GRAPHIC CONCEPTS

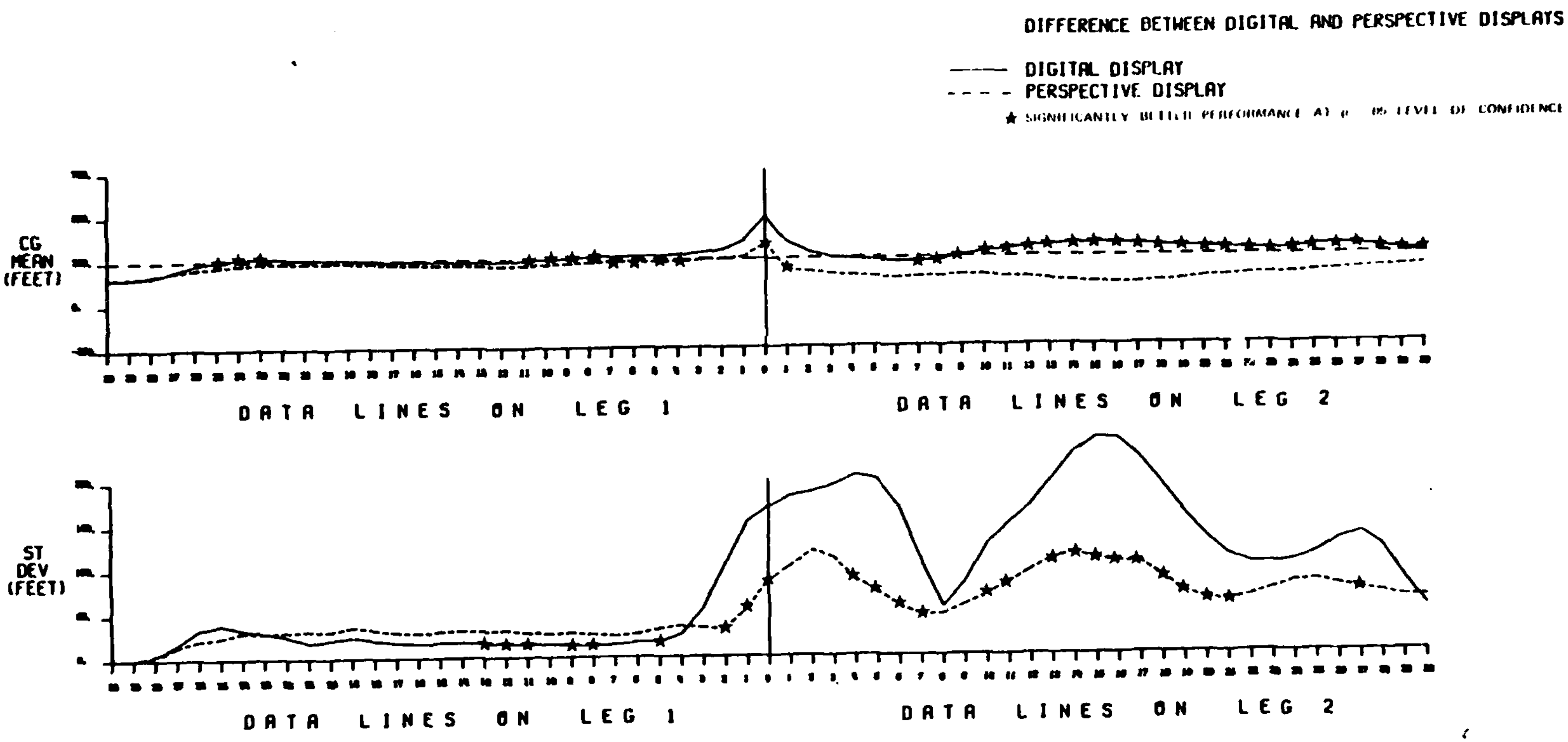


FIGURE F-2. STATISTICAL COMPARISON OF DIGITAL AND PERSPECTIVE CONCEPTS

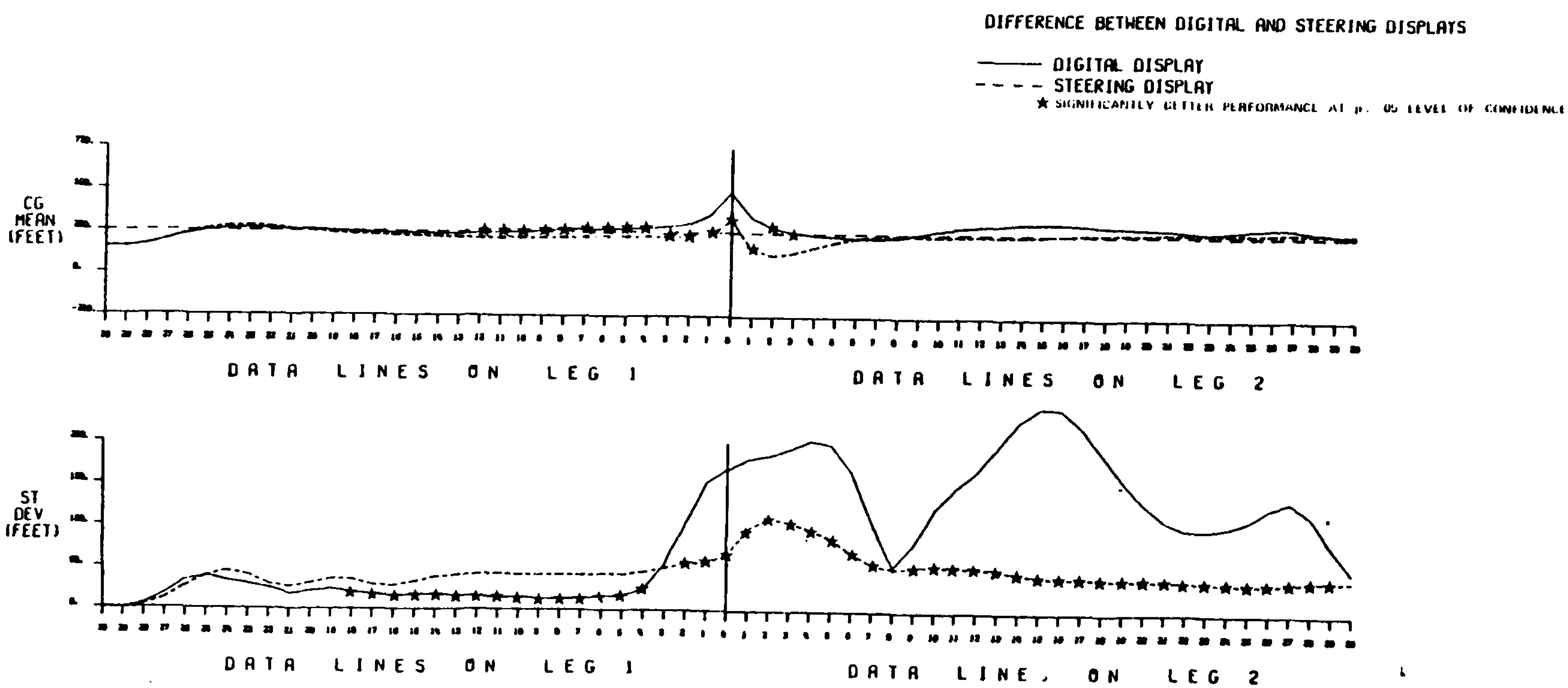


FIGURE F-3. STATISTICAL COMPARISON OF DIGITAL AND STEERING CONCEPTS

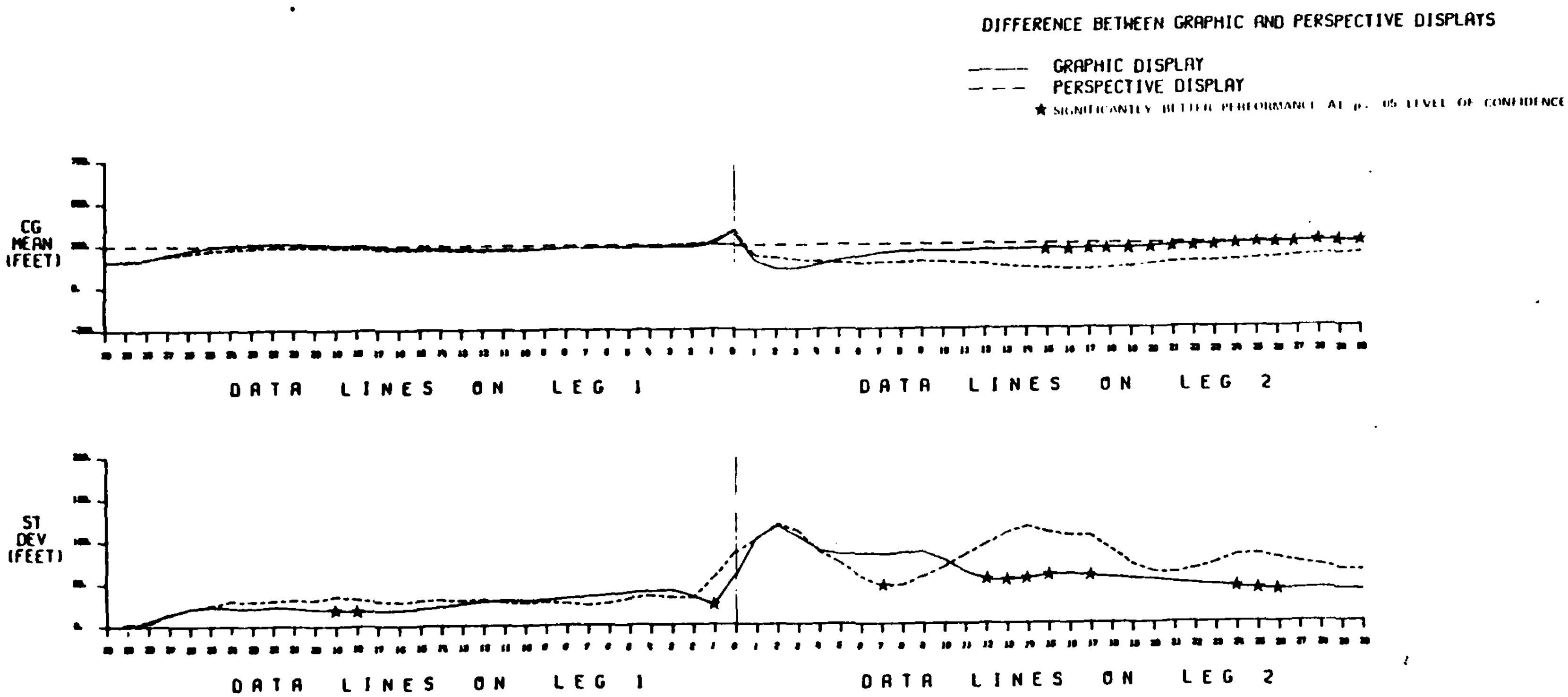


FIGURE F-4. STATISTICAL COMPARISON OF GRAPHIC AND PERSPECTIVE CONCEPTS

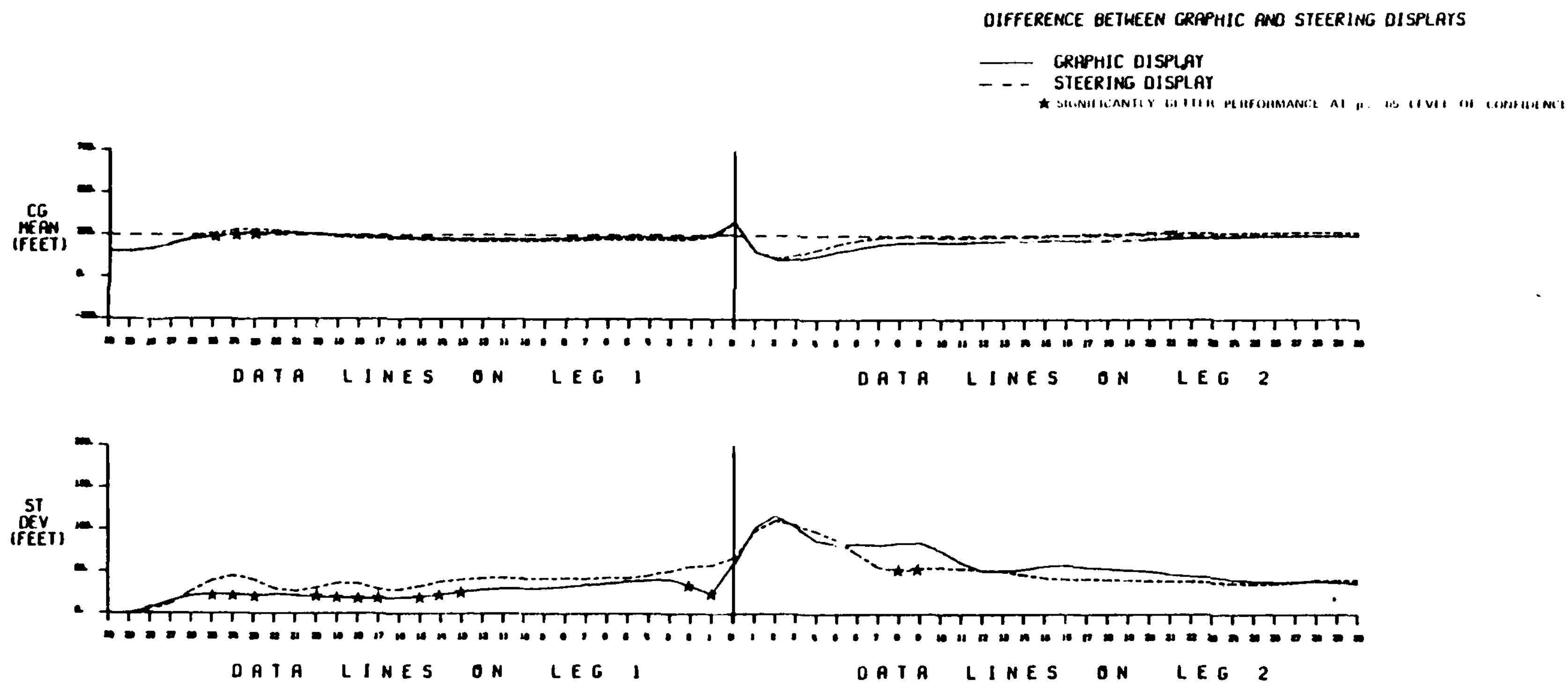


FIGURE F-5. STATISTICAL COMPARISON OF GRAPHIC AND STEERING CONCEPTS

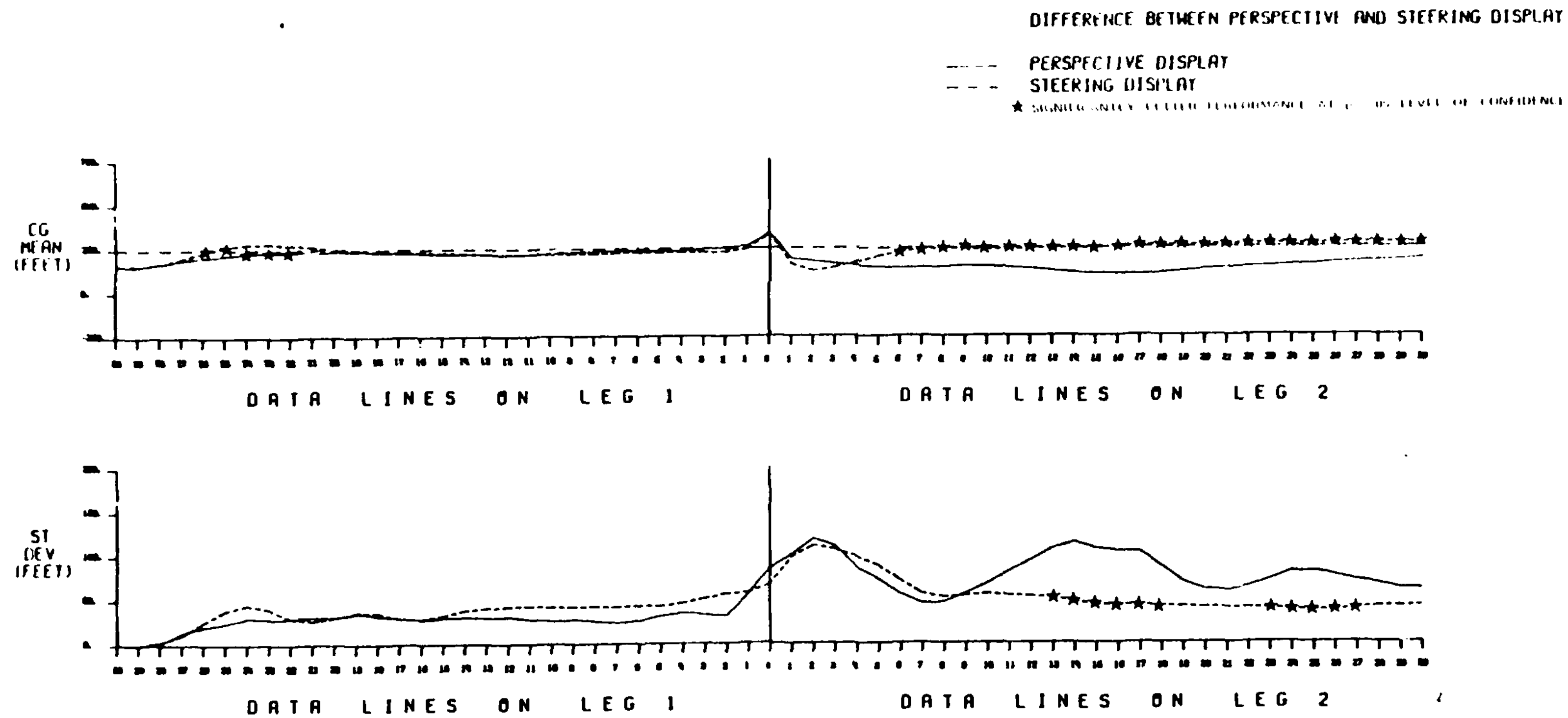


FIGURE F-6. STATISTICAL COMPARISON OF PERSPECTIVE AND STEERING CONCEPTS

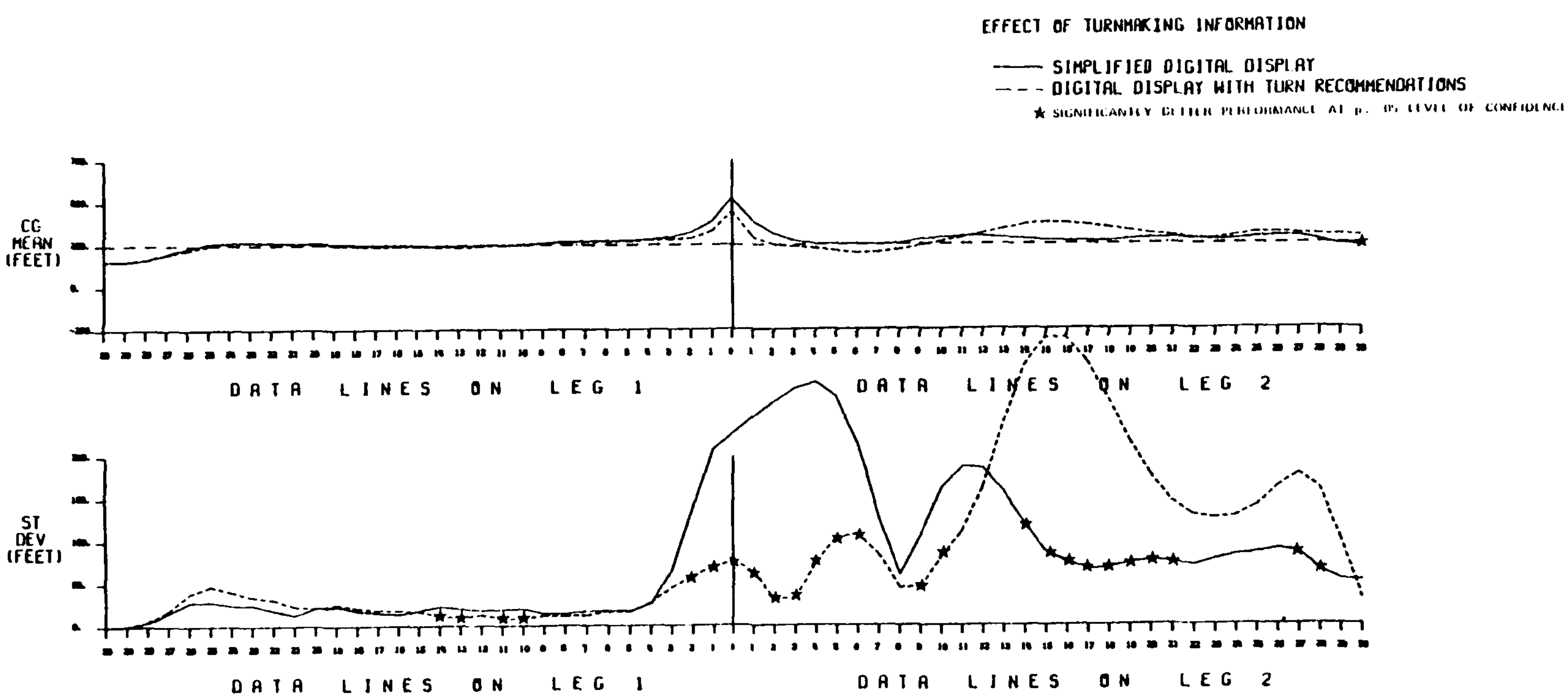


FIGURE F-7. STATISTICAL COMPARISON OF DIGITAL DISPLAYS

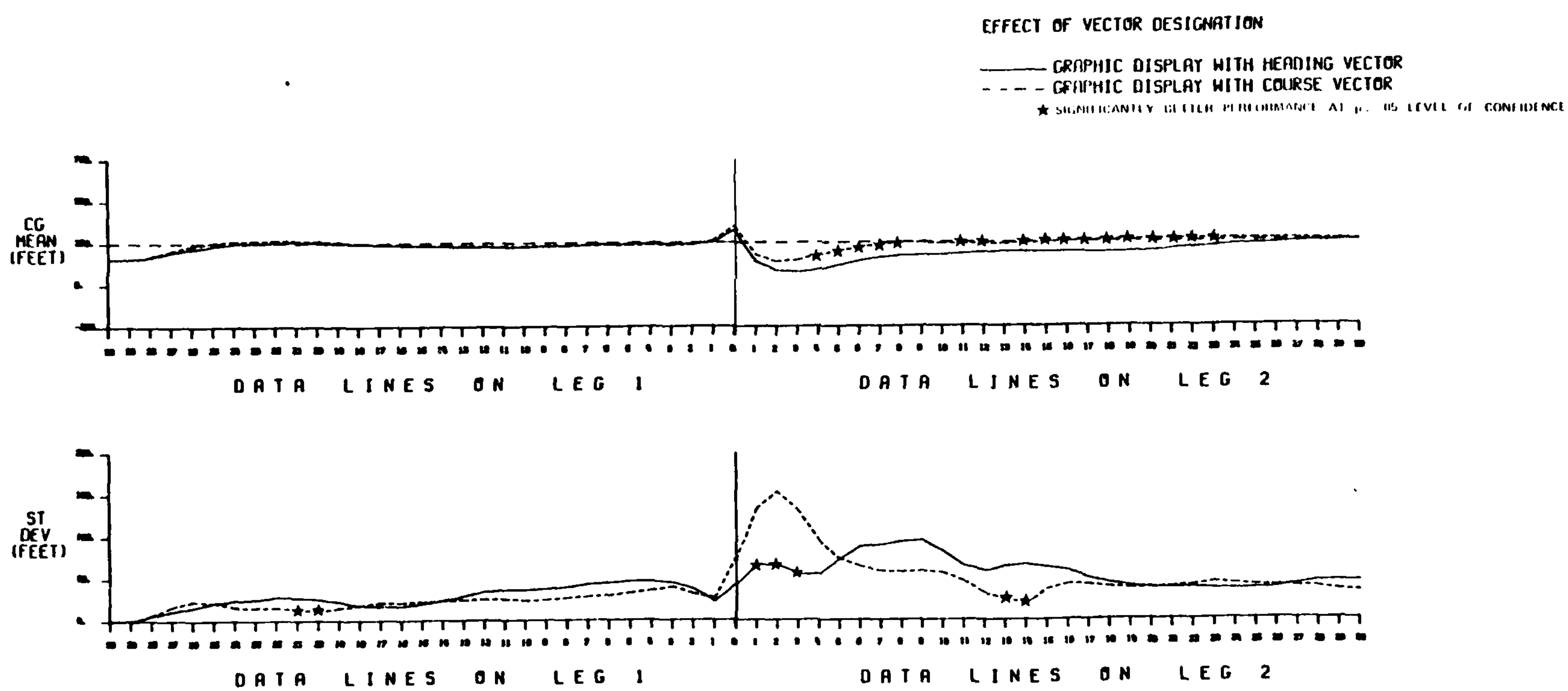


FIGURE F-8. STATISTICAL COMPARISON OF GRAPHIC DISPLAYS

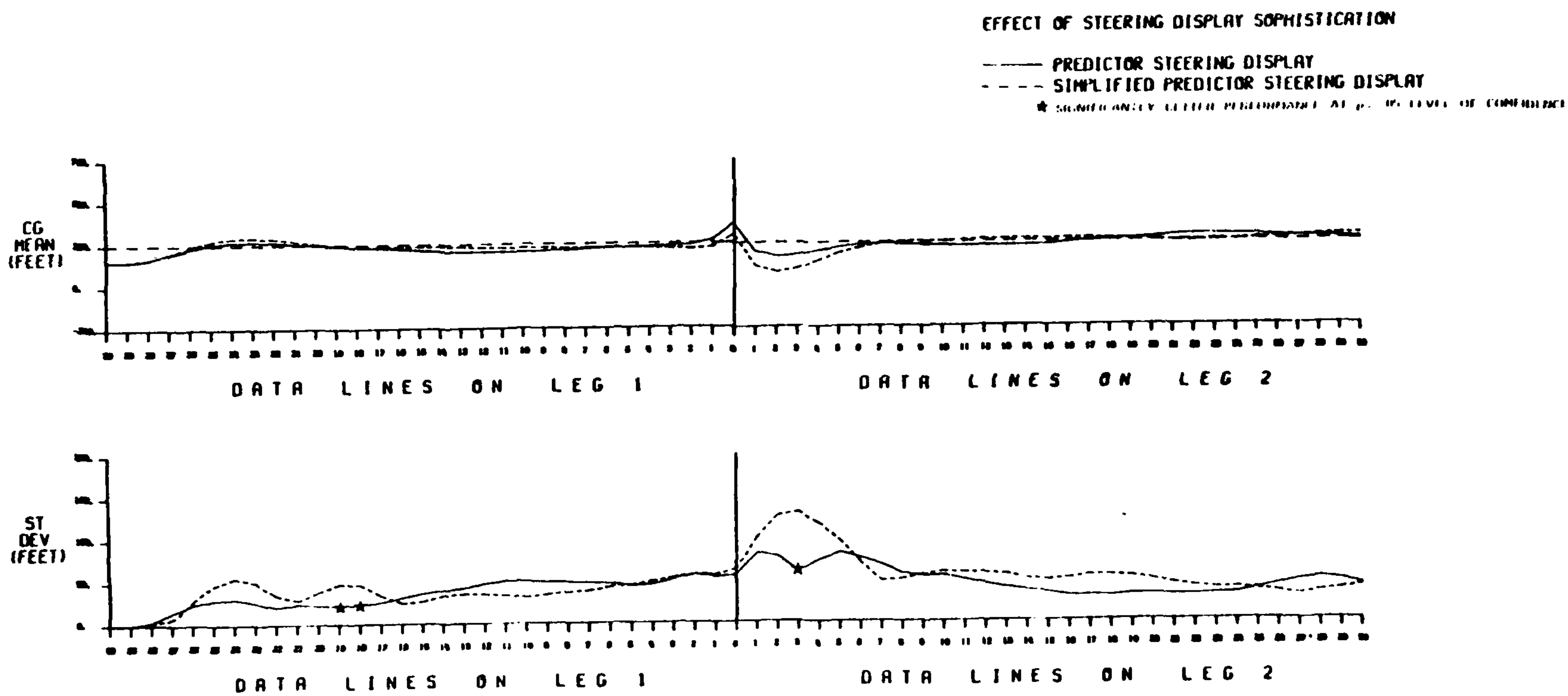


FIGURE F-9. STATISTICAL COMPARISON OF STEERING DISPLAYS

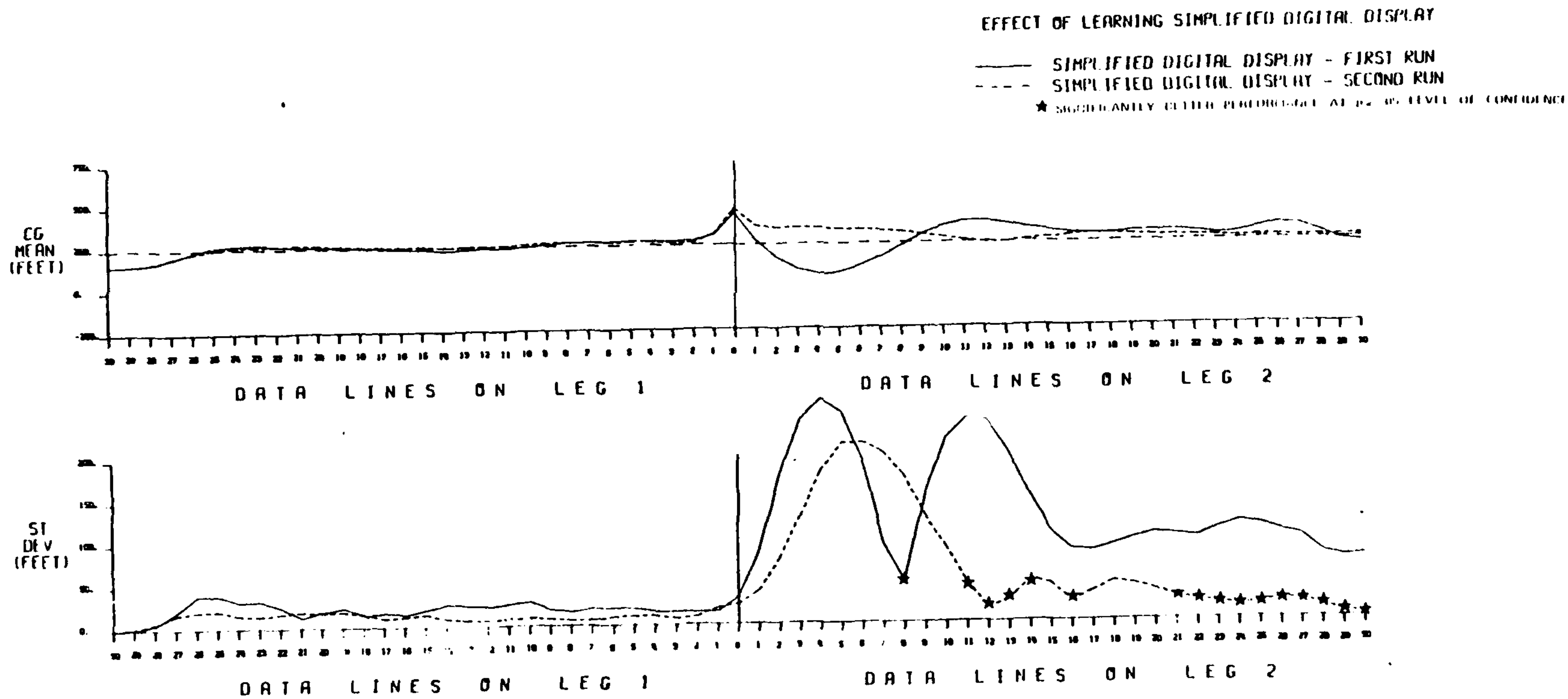


FIGURE F-10. STATISTICAL COMPARISON OF SIMPLIFIED STEERING DISPLAY

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