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Research & Development Report

Performance and Special Trials on U.S. NAVY Surface Ships

by
Richard J. Stenson – Head, Full Scale Trials Branch
Lowry L. Hundley – Project Manager, Full Scale Trials Branch

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Performance and Special Trials are conducted on the first ship of each new class of ships built for the US Navy, and on ships of existing classes where major modifications have occurred. Performance trials include a series of extensive sea trials designed to obtain definitive data concerning the hydrodynamic capabilities of the ship. Special Trials are a series of unique trials carried out concurrently with Performance Trials to investigate a particular or unusual aspect of a given ship. Performance and Special Trials planning, agenda preparation, trials procedures, instrumentation calibration and installation, trial sites, data collection, and analysis and reporting are presented. Examples of the various types of definitive maneuvers used to evaluate ship performance are given. Finally, advances in instrumentation and data collection techniques which have occurred as a result of portable, small, high speed computers are presented.

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ABSTRACT

Performance and Special Trials are conducted on the first ship of each new class of ships built for the US Navy, and on ships of existing classes where major modifications have occurred. Performance Trials include a series of extensive sea trials designed to obtain definitive data concerning the hydrodynamic capabilities of the ship. Special Trials are a series of unique trials carried out concurrently with Performance Trials to investigate a particular or unusual aspect of a given ship. Performance and Special Trials planning, agenda preparation, trials procedures, instrumentation calibration and installation, trial sites, data collection, and analysis and reporting are presented. Examples of the various types of definitive maneuvers used to evaluate ship performance are given. Finally, advances in instrumentation and data collection techniques which have occurred as a result of portable, small, high speed computers are presented.

ADMINISTRATIVE INFORMATION

The work described herein was performed by the David Taylor Research Center (DTRC), Full Scale Trials Branch (Code 1523). The project was accomplished under DTRC Work Unit 1233-831. The sponsor of the work was the Naval Sea Systems Command (NAVSEA) Code 55W32.

INTRODUCTION

The David Taylor Research Center (DTRC) is located in Carderock, Maryland, a suburb of Washington, D. C. The Center is one of a number of Navy Research and Development Centers reporting to the Space and Naval Warfare Systems Command (SPAWAR). The Center consists of a number of technical departments, including the Ship Hydromechanics Department. The Full Scale Trials Branch is one of three branches in the Ship Powering Division which is part of the Ship Hydromechanics Department.

The Trials Branch is chartered to participate in Builders Trials and Acceptance Trials on ships built for the U. S. Navy and to conduct comprehensive Performance and Special Trials on the first ship of each new class built for the Navy. The Branch also participates in Builders Trials for commercial ships constructed under U. S. Government subsidy. In addition, the Branch conducts special research trials for other government agencies such as the U. S. Coast Guard, the Maritime Administration, and the Military Sealift Command.

Specific aspects of the Performance and Special Trials conducted on the first ship of a new class or modified ships of an existing class will be discussed. Performance Trials include a series of extensive sea trials designed to obtain definitive data concerning the hydrodynamic capabilities of a ship. Special Trials are a series of unique trials carried out concurrently with Performance Trials, or conducted singly to investigate a particular or unusual aspect of a given ship.

All new ship designs and modifications undergo extensive testing from model testing through full scale trials. Model testing and full scale trials both quantify powering, maneuvering, and stability characteristics. Steps involved in the development of a suitable trial agenda, the preparation and installation of the required instrumentation, the conduct of the trials, and the subsequent data reduction are discussed in detail to fully describe these important tests.

MODEL TESTING

When the Naval Sea Systems Command (NAVSEA) formulates a new ship design, DTRC is tasked to conduct a comprehensive series of model tests prior to and during the actual construction of the ship. Model tests offer a cost effective method of predicting full scale ship performance. Actual model test data coupled with experimental correlation factors predict full scale characteristics. Correlation factors are developed through comparison of past full scale and model test results.

Model tests include but are not limited to: resistance, self propulsion, turning, maneuvering, propeller open water tests, propeller cavitation tests, wake surveys, hull flow visualization, bilge keel traces, and seakeeping tests. Therefore, a tremendous amount of data predicting ship performance is available before the new or modified ship's first sea voyage. These data are then utilized to develop a trial agenda suitable for extensive full scale trials.

SHIP ACCEPTANCE BY THE U.S. NAVY

BUILDERS TRIAL

Any new ship must be found fully functional and safe for sea duty prior to determining the detailed full scale performance capabilities. Functional capability certification involves close liaison between the U. S. Navy and the private sector because all new Naval ship construction is currently accomplished in private shipyards. U.S. Government shipyards are currently engaged only in the necessary overhaul, repair, and maintenance of naval ships.

The resident supervisor of shipbuilding (SUPSHIP) represents the Navy and monitors the construction of each ship at each of the major private shipyards. Each SUPSHIP office oversees the contractual agreements between the private yards and the Navy. The SUPSHIP office also provides the necessary liaison between the Navy and the private yard for sea trials conducted prior to delivery of the ship to the Navy.

Each ship must successfully complete a Builders Trial, an Acceptance Trial, and a Final Contract Trial in order to be accepted by the Navy. The ship is operated by and is under the control of the shipyard personnel onboard during the Builders Trial. However, government representatives and government furnished equipment (GFE) are an important part of the Builders Trial.

An example of GFE utilized during these trials is the instrumentation provided by DTRC to determine the ship's capability to develop design full power. The necessary equipment, such as torsionmeters, thrustmeters, shaft r/min counters, and data collection devices are installed and operated under the supervision of DTRC representatives. Full power tests, fuel economy tests, turning tests, backing tests, acceleration and deceleration tests, and testing of all ship components and subsystems are accomplished during the Builders Trial. Deficiencies are identified and corrected and an Acceptance Trial is scheduled.

ACCEPTANCE TRIAL

The Acceptance Trial is conducted approximately one month after the Builders Trial. These trials are conducted by the U. S. Navy Inspection and Survey (INSURV) Board. The Board consists of a team of Navy personnel generally under the direction of a Navy Captain or Admiral. The INSURV Board determines if the shipyard has met all of its contractual requirements and that the ship is safe and meets all design specifications.

Once again, the ship is subjected to a series of tests to demonstrate the ship's acceptability to the Navy. Problem areas are identified and presented to the shipyard. Only after the deficiencies have been corrected is the ship accepted by the Navy for delivery.

FINAL CONTRACT TRIAL

The Final Contract Trial consists of another series of tests to demonstrate that the ship fulfills all design requirements and meets design specifications. It occurs after the ship has been commissioned, fully equipped, and armed. Deficiencies noted during this trial are submitted to the cognizant SUPSHIP office and to the Naval Sea Systems Command (NAVSEA) to determine whether the Navy or the contractor is liable for the necessary repairs. A financial agreement is subsequently reached between the Navy and the contractor regarding deductions or additions to the stipulated contract price.

Data obtained during the Builders, Acceptance, and Final Contract Trials are adequate to determine if the ship is suitable for acceptance by the Navy. However, these data are not adequate to develop suitable operational information required by the fleet. Consequently, more extensive trials referred to as "Performance and Special Trials" must be performed on at least one ship of the class.

PERFORMANCE AND SPECIAL TRIALS

Performance and Special Trials are normally conducted on the lead ship of each new class as well as modified existing ships. These trials are designed to test and quantify the operational characteristics of the hull and the performance of the propulsion and control systems of the ship. The Performance and Special Trials primarily include the following types of trials:

- Standardization
- Trailed and Locked Shaft
- Tactical
- Acceleration and Deceleration
- Maneuvering
- Fuel Economy

In addition, these trials sometimes include:

- Underway Vibration
- Seakeeping
- Miscellaneous Special Tests

Underway Vibration Trials and Seakeeping Trials are conducted by other branches at DTRC. Fuel Economy Trials are conducted by the Naval Ship Systems Engineering Station (NAVSSES) Philadelphia, in conjunction with the Full Scale Trials Branch.

NAVSEA issues a Trial Agenda Letter based on the information generated by the model tests and the particular design features of the ship. This letter is sent to DTRC, the ship, and the shipyard involved. It constitutes the authority to conduct the trials and generally precedes the actual trial date by approximately one year. The letter provides general guidance which indicates the types of trials to be conducted, the desired measurements, and the nominal conditions such as speed, displacement, and trim. It also defines the operating limits for the propulsion machinery for various types of maneuvers. This letter, therefore, forms the basis for the development of the Trial Agenda.

TRIAL AGENDA DEVELOPMENT

The Trial Agenda is a single document which dictates the conduct of the trials. It is developed within the Full Scale Trials Branch by the Trials Director who is assigned the overall responsibility for administrating the trials. The agenda follows the general guidelines contained in the NAVSEA Trial Agenda Letter and provides a detailed run by run schedule of events for each phase of trials.

The agenda specifies the different test teams involved in the overall trials and provides estimates of the time required for each evolution. Furthermore, the agenda specifies: the procedures for conducting each type of maneuver, measurements to be obtained, acceptable trial conditions, the number of personnel required and their respective duties, and any other prerequisites or requirements for conducting each run.

A preliminary agenda is then submitted to the cognizant NAVSEA technical codes and the Prospective Commanding Officer (PCO) of the ship, as well as the PCO's squadron and fleet commanders for comment and review. After all necessary changes have been incorporated into the agenda, it is submitted to NAVSEA for final approval and dissemination to all concerned activities.

TRIAL SITE SELECTION

The selection of a suitable trial site is dependent upon the trial agenda requirements as well as the location of the shipyard building the ship.

Performance and Special Trials on surface ships can be conducted on an acoustic or a radar tracking range. Suitable trial sites are recommended by DTRC and the final selection is made by the Naval Sea Systems Command. The locations and characteristics of available ranges are discussed below.

Acoustic Ranges

A number of sophisticated underwater acoustic tracking ranges are operated by the U. S. Navy. All of these ranges have been utilized by the Trials Branch and are able to accurately track the position of the ship during trials and thus determine its speed and tactical characteristics.

The two East Coast ranges are the Atlantic Underwater Test and Evaluation Center (AUTEC) which is located on Andros Island in the Bahamas and the Atlantic Fleet Weapons Training Facility (AFWTF) established on St. Croix in the U. S. Virgin Islands.

West Coast ranges include the Santa Cruz Acoustic Range Facility (SCARF) on Santa Cruz Island off the coast of Long Beach, California; the Naval Torpedo Station Three Dimensional Range situated in Dabob Bay, Keyport, Washington; and the Nanoose Three Dimensional Range located on Vancouver Island, British Columbia. Ships operating out of Pearl Harbor, Hawaii, utilize the Pacific Missile Range Facility at Barking Sands on the island of Kauai.

The geometry of a typical acoustic range would be similar to AFWTF as shown in Fig. 1. The figure depicts 13 hydrophones anchored on the ocean bottom and connected by underwater cable to the shore installation. The ship is equipped with a specially installed tracking range "pinger" which emits an electronic signal at a variable rate from 1 to 4 s, depending on which pinger is selected. The hydrophones receive these electrical pulses thereby enabling the shore installation to accurately determine the position of the ship through triangulation. The ship's position can then be tracked as a function of time which allows calculation of ship speed relative to the ocean bottom.

Radar Tracking Ranges

DTRC established the Hatteras East Coast Tracking Offshore Range (HECTOR) in August 1982. It is approximately 30 nmi (56 km) off the coast of Oregon Inlet, North Carolina. HECTOR is operated and maintained by the Full Scale Trials Branch and provides easy access for ships operating out of Norfolk, Virginia and Charleston, South Carolina. The center of the range is 90 nmi (167 km) southeast of Norfolk. This range's location is shown in Fig. 2.

In the event that logistics, scheduling, or transit times preclude the use of the acoustic ranges or HECTOR, portable electronic tracking instrumentation is available within the Trials Branch and can usually be installed in close proximity to the ship construction site. Precise coordinates of the necessary fixed reference sites can be determined by a Global Positioning System (GPS), which is a satellite tracking system maintained by the Trials Branch. The following factors must be considered when establishing a temporary range: range geometry, water depth, water currents, marine traffic, and potential sources of electromagnetic interference which could affect the tracking system. The portable tracking equipment has been utilized with great success and will be discussed in detail in a later section. Ranges which have been used for surface ship trials are listed in Table 1.

SHIP CHECK AND PRE-TRIAL CONFERENCE

Following the agenda completion and trial site selection a ship check is made and a pre-trial conference is attended by the ship's officers, representatives for NAVSEA and the Shipyard, as well as DTRC and range personnel. The ship's schedule is established during this meeting and trial objectives and procedures are discussed. Instrumentation requirements for the trials are described and a ship compartment is designated for temporary location of the data acquisition system. Special ship conditions required during the trials, such as displacement and trim, are discussed to provide ample time for ship personnel to determine the best method of achieving the desired conditions.

Ship personnel are often skeptical about the ship's capability to achieve some required conditions, as well as the trials process as a whole. Ship personnel's apprehension usually peaks during the equipment installation phase as they observe stuffing tubes being drilled, cables being routed throughout the ship, rings being clamped around the propeller shafts, and racks of instrumentation arriving onboard. In general, these misgivings soon disappear once the ship realizes that the trial team is experienced and is genuinely concerned about the overall impact on the ship. The objective of the trial team is always to obtain the best data possible with minimum impact on the ship and its schedule.

SHIP PREPARATION

Performance and Special Trials are normally scheduled within 30 days of undocking. This requirement is necessary to minimize the adverse effects of hull and propulsor fouling and thus provide a more "standard" condition for each ship tested. Extensive full scale trial data have conclusively shown that hull fouling can, under certain conditions, substantially affect the powering characteristics of a ship in a few months time.

Features such as bilge keels, stabilizer fins, bow thrusters, or other appendages are noted during the drydock period. A roughness survey is also conducted to quantify the hull and propeller condition. A British Ship Research Association (BSRA) roughness gauge is used for this survey. The texture of selected portions of the hull and appendages are measured and the data are statistically analyzed to obtain a value representative of the average roughness of the hull and appendages. The ship's propeller is inspected for damage and the average propeller roughness is determined.

If a ship is equipped with a controllable pitch (CP) propeller, a calibration curve of onboard propeller pitch setting versus actual propeller pitch is obtained. This calibration is best performed with the ship in drydock to facilitate the necessary measurements on the propeller blades. The ship's schedule often does not permit a drydock calibration and a pierside calibration must then be performed with the assistance of divers.

A specially designed device is attached to the propeller hub to provide a reference surface for measurements to the leading and trailing edges of each propeller blade. At selected pitch settings (zero, design ahead, full ahead, and full astern), actual blade position measurements are obtained concurrently with measurements of the ship's pitch indicator and the oil temperature in the pitch control system. Ideally, these data are obtained for three different oil temperatures to determine the effects of oil temperature on propeller pitch settings.

Following the pitch calibration, the visibility and the accuracy of the ship's draft marks are checked and any other relevant information is recorded in order to fully document the ships's condition at the time of the trials.

TRIAL CONDITIONS

Environmental conditions have significant influence on the data obtained during sea trials. High winds or unfavorable water currents can result in the use of excessive rudder to maintain course in preparation for and during a trial run. Such rudder excursions result in large torque fluctuations and an unsteady ship speed. Additionally, high winds or sea states have a direct, but unquantifiable, impact on propulsion power levels required to maintain given ship speeds. State 3 seas and/or a wind speed of 20 kn is generally considered the maximum environmental conditions allowable for Performance and Special Trials.

Certain tests included in the Performance and Special Trials, e.g., spiral and zig-zag maneuvers, are more susceptible to the effects of wind and sea state. These tests should be conducted when the weather is considerably better than the upper limit environmental conditions stated above. The trial schedule should be amended to utilize the first calm day to perform any environmentally sensitive tests. Unfortunately, limited trial time occasionally results in compromises and tests are sometimes conducted during marginal weather conditions.

TRIAL TYPES AND PROCEDURES

GENERAL

Proper approach conditions must be established and maintained for each run to help ensure reliable Performance Trials data. Unsteady approach conditions as indicated by fluctuations in shaft speed, rudder angle, shaft torque, propeller pitch, or ship speed, can dramatically affect test results and usually produce erratic data. Close liaison between the ship operators and the Trials Director is necessary to maintain the required propulsion conditions for one minute prior to the start or EXECUTE of each run. Alert and informed helmsmen and throttlemen are crucial to the successful implementation of the Test Agenda.

The Officer of the Deck should inform the Trials Director when the ship is on course and at the proper shaft speed and pitch (for CP propellers). The Trials Director and/or the instrumentation operators then independently confirm these conditions by monitoring torque and speed on remote monitors. The requested shaft speed will be attained before the ship's momentum and speed can be stabilized, therefore, shaft torque and the ship's electromagnetic log speed measurements provide the best indications of a steady approach. After all pertinent parameters are steady, a COMEX command is given which results in one minute of steady data collection prior to the initiation of the scheduled trial maneuver or EXECUTE. A FINEX command is given upon the completion of the scheduled maneuver.

This procedure is followed for all runs including runs which begin from the dead-in-the-water (DIW) condition. To avoid redundancy, each trial type discussed below will be described from the EXECUTE point and the approach procedure will not be repeated. As a general rule, the Maneuvering Trials and the Fuel Economy Trials are not conducted on a range because positional information is not needed. However, on occasion, one or more of these trials is conducted on a range.

STANDARDIZATION TRIALS

Standardization Trials are conducted in order to determine the steady-state speed and powering characteristics of the ship. Standardization Trials on conventionally powered surface ships are conducted at two displacements, namely design full load and a displacement at least 10% lighter. Normally, the ship should be as close to zero trim as practicable during both displacements and, if possible, the trim for each of the displacements should be the same. Data at two displacements provide an indication of how changes in displacement affect ship speed and powering. The two sets of data allow interpolation of speed and powering characteristics over a range of displacements which facilitates direct comparison with model data.

Draft readings are obtained immediately prior to the ship getting underway for each trial phase. Readings are obtained at the bow, amidship, and at the stern on both the port and starboard sides. A seawater sample should also be obtained at this time to determine water temperature and specific gravity which are needed for the subsequent displacement calculations. Seawater temperature and specific gravity are also measured at the trials location to determine if any significant differences with the pierside readings are present. Ship displacement and trim are important parts of the Performance and Special Trials and should be closely and carefully monitored throughout the trial period.

Daily ship operations generally allow draft readings to be taken pierside in the morning of each day during the trial period. When the ship remains at sea for several days, draft readings are obtained via a small boat, if possible. This operation is at the discretion of the Commanding Officer and should only be attempted when the sea state is favorable. Attempting to obtain this data in rough seas will result in erratic readings and potentially, personal injury. The ship's displacement history should be monitored through periodic tank soundings to determine any change in displacement attributable to fuel consumption. Arrangements should be made with ship personnel to obtain tank sounding data as needed.

Dynamic environmental conditions must be recorded throughout the trials to facilitate both quantification and qualification of the data. Seawater samples should be taken daily in the vicinity of the operating area to determine the water's specific gravity and temperature. These values are necessary so that Standardization Trial data can be corrected to standard conditions for model correlation. Relative wind speed and direction are monitored during the trial with a specially calibrated wind anemometer which is installed close to the bow and high above the deck in order to measure uninterrupted air flow. Periodic observations of the sea state, air temperature, and general weather conditions are also recorded. The quartermaster normally is supplied with a log book and requested to record this data hourly.

Preparation for conducting a Standardization Trial on an acoustic range begins with the communications link between the test ship and the shore installation which allows the onboard and land clocks to be synchronized, thereby establishing a common time base for all data collected. A base course and a reciprocal course are established based on range geometry for the conduct of the runs. Eight or nine speed settings, referred to as "spots", are generally required to adequately define the standardization curve. A spot is defined as the average of two or three runs in reciprocal directions at the same power level.

Standardization runs are usually conducted starting with the lowest required speed. Ship speed is then increased incrementally until full power is reached. Data collection begins after ship speed, shaft torque, and shaft speed reach steady predetermined values. One minute of steady approach data are collected and then three minutes of steady run data are recorded. Minimum rudder movement, generally ±3 deg, is used to maintain heading during both the approach and the actual run. Throttle settings (and pitch settings in the case of CP propellers) are preset and are not adjusted during the run. Throttle and pitch settings remain fixed as a Williamson Turn is executed following the first pass to position the ship on the reciprocal course in the same general area of the range.

The procedure for conducting the Williamson Turn is to execute and hold a 20 deg rudder movement until the ship's heading has changed 60 deg from the base course. At this time, the rudder is shifted to 20 deg on the opposite side, and held until the ship's heading reaches the reciprocal of the base course. Speed and torque conditions are allowed to stabilize and the ship executes the second pass with shaft speed the same as in the first pass.

Three runs are normally accomplished for each speed "spot". If the current gradient is determined to be 0.2 kn or less and the magnitude of the current is less than 0.5 kn, two run spots are acceptable. The gradient is determined by comparing the speeds of runs in the same direction for steady and equal levels of powering. The current gradient is a function of time, therefore the elapsed time between comparative runs must be kept to a minimum. Typically, a minimum of three runs are made for each "spot" at the initial speed in the standardization series, at the mid-range speed, and at full power.

A simple average of the data is used to determine the speed and power values for a two-pass spot. A mean of means method is used for three pass spots. The values from the second pass are doubled and added to the values from the first and third passes. This sum is then divided by four to determine average values for the spot. The latter method assumes that changes in the effective water current over the ground at the trial course are approximately linear with time during the three consecutive passes. Each method converts the ship's speed over the ground, as determined by the range, to speed through the water. It must be emphasized that steady approach speeds are important. This requires that the length of the approach to higher power runs, particularly the full power spot, be increased to ensure that the ship reaches a steady powering condition prior to the start of each run.

Primary onboard measurements obtained during each run consist of: propeller shaft torque, speed, thrust, first stage shell pressure (steam turbine plant), propeller pitch for CP propellers, relative wind speed and direction, ship's heading, and rudder position. In addition, the ship's electromagnetic (EM) speed log can be calibrated during these trials. This calibration allows the use of the EM log as a speed reference for trial maneuvers conducted in free route. The ship's XY coordinates are determined onshore from the hydrophone outputs on acoustic ranges or onboard ship by the radar transponders and shipboard receiver/transmitter units on radar tracking ranges. The XY positions are recorded at approximately 1 s intervals which allows the ship's position to be determined as a function of time. This positional data provide the means to calculate the ship's speed to accuracies within a tenth of a knot.

It is important to balance the propeller shaft speed for multiple-shaft ships to obtain equal power on each shaft. In the case of ships with four propellers, such as aircraft carriers, the inner shafts will generally reach their maximum torque level prior to the outer shafts. The full power spot may thus be conducted with less shaft speed and higher torque on the inner shafts than on the outer shafts. This arrangement is required in order to balance the power output of each shaft.

Trials on twin shaft ships equipped with CP systems require that both shaft speed and propeller pitch be equal to develop the same power on the two shafts. Equal shaft power can be obtained by balancing shaft speeds and then changing propeller pitch until the two torques are matched. This procedure is necessary when propeller pitch cannot be determined to a high degree of accuracy.

Standardization Trials on ship's equipped with a CP system are normally conducted in both program control (PC) mode and in manual mode. PC mode automatically selects predetermined combinations of propeller pitch and shaft speed in response to the ship speed requested. This mode of operation is designed such that each propeller will operate at or near peak efficiency throughout the ship's speed range. Standardization Trials in the PC mode are typically followed by a series of runs with the propellers over-pitched as well as under-pitched. A family of speed/powering curves is thereby generated to define the full range of capabilities of a given propeller.

The procedures for conducting these trials using portable tracking equipment are generally the same as on the acoustic tracking ranges. One notable exception is that the positional data are collected with onboard equipment, which can be located in the vicinity of the bridge, thus facilitating the conduct of the trials by providing near-real time ship position and speed information. The portable electronic tracking equipment is discussed in detail in a later section.

TRAILED AND LOCKED SHAFT TRIALS

Trailed and Locked Shaft Trials are conducted to determined the speed/powering characteristics of a multiple-shaft ship operating while trailing or locking one or more shafts. These trials are generally part of the Standardization Trials and are accomplished using the procedures described above. Trailed shaft powering data are desirable because ships are often able to secure one or more engines, maintain the necessary speed of advance (SOA), and realize an overall savings in fuel consumption. This is particularly true in the case of ships equipped with gas turbine engines. Here, the driving engine(s) can be operated at a higher speed than that speed required if all engines are operating. This higher turbine speed is closer to the design or optimal efficiency condition, thereby reducing specific fuel consumption.

Trailed or locked shaft data are also useful in the event of a ship casualty. Such data will indicate the maximum speed allowed on the driving shaft or shafts, based on maximum shaft torque restrictions, and will quantify the maximum ship speed attainable in that condition.

TACTICAL TRIALS

Tactical Trials are conducted to determine the turning characteristics of the ship. These trials require tracking of the ship and are conducted on an acoustic range, a radar range such as HECTOR, or with the portable electronic tracking equipment. Tactical Trials are usually conducted at design displacement and at three different approach speeds. Turns are conducted at a minimum of three rudder angles, turning both left and right at each rudder angle and approach condition. Multiple-shaft ships often exhibit similar turning characteristics for both right and left turns, in which case only one turn in the opposite direction is needed at each speed for verification.

The first step in conducting a tactical turn is the communications link and subsequent synchronization of clocks between the shore facility and the ship. After the ship is in the proper position on the range, one minute of steady approach data is recorded before the EXECUTE command is given. Upon this command, the helmsman moves the rudder smartly to the predetermined angle. If the intended rudder angle is slightly exceeded, or not quite reached, no adjustments are made and the rudder is held fixed for the duration of the run. Additionally, no adjustments are made to shaft speed, or to the propeller pitch of CP propellers. A FINEX command is given which effectively ends the run after a heading change of 540 deg (one and one-half turns). The ship's position is tracked throughout the maneuver which provides a plot similar to that shown in Fig. 3.

Tactical Trials on an acoustic range require that predetermined change of heading marks be verbally passed to the shore installation in order to correlate ship heading and position data. This correlation is not necessary at HECTOR or when using the portable tracking system because all of the data are stored on one medium onboard the ship.

Onboard measurements recorded during the tactical turns consist of: rudder angle, ship's heading, angle of heel, shaft speed, propeller pitch for CP propellers, shaft torque, shaft thrust, and relative wind velocity. The positional data obtained by the tracking range enable the two dimensional turning characteristics of the ship to be determined. The calculations used to quantify these characteristics are discussed in the analysis section.

ACCELERATION AND DECELERATION TRIALS

Acceleration and Deceleration Trials are also conducted on a tracking range. The purpose of these trials is to determine the speed and reach versus time profiles (time histories) of the ship for various starting and stopping conditions. All acceleration and deceleration runs are interspersed with tactical circle runs. Drift values determined from the tactical circle maneuvers can then be interpolated over the time of day to mathematically correct the ship's movement to account for the effects of drift due to wind and water current.

Acceleration Trials are generally conducted from zero speed (dead-in-the-water or DIW) to various steady ahead ship speeds using several engine orders including: Ahead 1/3, Ahead 2/3, Ahead Standard, Ahead Full, and Ahead Flank.

In addition, acceleration runs may be conducted from Ahead 1/3 to Ahead Flank and from backing conditions such as Back 1/3 to Ahead Flank.

Deceleration Trials are usually performed from Ahead Flank to DIW using various backing engine orders to bring the ship to a stop, such as: All Stop, Back 1/3, Back 2/3, Back Full, and Back Emergency. Deceleration Trials might also be conducted from approach speeds other than Ahead Flank.

Acceleration and deceleration runs begin with the recording of 1 min of steady approach data. Upon EXECUTE, the proper engine order is requested via the engine order telegraph. The propulsion turbine throttles are opened or closed as required to meet the engine order at the maximum rate allowable without exceeding design operating limits. For CP propeller installations, the propeller pitch and shaft speed are changed as required by the engine order, as rapidly as possible. The ship's position is recorded at approximately 1 s intervals throughout the run until the ship has reached a steady terminal speed. The ship's rudder is used as necessary to maintain heading.

In addition to positional information, onboard measurements taken include: shaft speed, torque and thrust, propulsion turbine first stage shell and astern bowl pressures as well as throttle positions for steam turbine plants, propeller pitch for CP propellers, rudder angle, and ship's heading.

Additional deceleration runs are sometimes conducted using the rudder to aid in stopping the ship. Runs are conducted with the rudder moved to the full left or right position on execute and held for the duration of the run. Runs are also conducted while periodically shifting the rudder from right to left at scheduled time intervals during the run. These maneuvers generally result in less reach and increased deviation from the base course as compared to a similar engine order using conventional procedures (use of rudder solely to maintain heading).

Acceleration and Deceleration Trials can also be conducted using the portable tracking equipment and the general procedures are the same. A more detailed discussion of the data collection techniques for these trials using the portable tracking equipment will be presented in a later section.

MANEUVERING TRIALS

Maneuvering Trials are conducted in free route at sea, away from major shipping lanes. These trials generally include spiral tests, horizontal overshoot tests, and backing tests. The procedures used for each of these tests are discussed below.

Spiral Tests

Spiral tests are designed to determine the inherent dynamic stability of the ship and are normally conducted at approach speeds of Ahead 1/3 and Ahead 2/3. These tests require a large operating area and generally take from 2 to 3 hr to complete at each condition. Spiral tests should be conducted with sea states from 0 to 1 with minimum wind conditions because the ship's response during these maneuvers is particularly sensitive to external forces.

The spiral test begins with the collection of 1 min of steady approach data. No adjustments are made to the shaft speed or propeller pitch settings after data collection begins until the FINEX of the run. At EXECUTE, the rudder is moved to 15 deg right rudder. When the ship's rate of change of heading becomes constant, the rudder is eased to the second setting, 10 deg right, and again held until the rate of change of heading becomes constant. This procedure is repeated at successive rudder angles of 7.5 deg right, 5 deg right, 2 deg right, 0 deg, 2 deg left, 5 deg left, 7.5 deg left, 10 deg left, 15 deg left, 10 deg left, 7.5 deg left, 5 deg left, 2 deg left, 0 deg, 2 deg right, 5 deg right, 7.5 deg right, 10 deg right, and 15 deg right. The data acquisition system continuously records data at a slow rate throughout the maneuver.

The ship's directional stability characteristics are being investigated during the spiral test, therefore, it is important to meet the next scheduled rudder angle coming from the proper direction. For example, when moving from 15 deg right to 10 deg right, if the rudder inadvertently goes to 9 deg right, it must be held there and not corrected to 10 deg right. It is also important to remain at each rudder setting long enough to ensure that the rate of change of heading has become constant. Reaching this condition is especially time consuming at the low rudder angles. Once the steady turning condition is reached, approximately 2 min of data at each setting will suffice.

It is also important that the spiral test be conducted as one continuous maneuver, from 15 deg right to 15 deg left and back to 15 deg right, without breaking off between rudder angle settings. Spiral tests must therefore be conducted in an area free of marine traffic and away from land masses. If a spiral test is aborted at a particular rudder angle, it is possible to resume the test at the preceding rudder angle assuming the shaft speed and/or propeller pitch have not been changed, which would thereby change the approach conditions.

Measurements recorded during the Spiral tests include: rudder angle, ship's heading, roll angle, shaft speed, propeller pitch (CP propellers), EM log speed, relative wind speed and direction, as well as sea state observations.

Horizontal Overshoot Tests

Horizontal overshoot tests are conducted to determine the response of the ship to a checking, or opposite direction, rudder angle. The tests are generally conducted at two approach speeds, Ahead 1/3 and Ahead 2/3, and with both left and right rudder angles of 10 and 20 deg for each speed.

The approach course for the horizontal overshoot tests should align the ship's heading directly with or directly into the wind to avoid a bias in the data due to ambient wind conditions. If the existing wind is from 050 deg true, for example, the appropriate approach heading would be either 050 or 230 deg true. This procedure will insure that the wind's influence on the ship's turning characteristics will be similar, whether the ship is turning left or right.

The EXECUTE mark is given after 1 min of steady approach data has been recorded and the rudder is then moved to its predetermined setting such as 10 deg right. When the ship's heading has changed 10 deg from the base course, the rudder is shifted to the same number of degrees in the opposite direction. The rudder is held at this position while the ship's direction of turn reverses, and the ship's heading passes through the base course and reaches 10 deg on the opposite side of the base course. The rudder is then shifted back to its EXECUTE position and this procedure is repeated through two and one-half cycles.

Measurements obtained during these maneuvers include: rudder angle, ship's heading, approach speed, shaft speed, and roll angle.

Backing Tests

Backing tests are generally conducted at two different approach speeds, Back 2/3 and Back 1/3. The tests are conducted in calm water and if successful, are repeated in moderate sea state. The purpose of the backing tests is to determine whether the ship is able to maintain its heading while backing. The procedure used is to develop a steady, appropriate astern r/min and then to attempt to steer the ship while backing.

Ship speed during a backing test can only be obtained from time referenced position data provided by tracking equipment because the ship's EM log does not provide an output in the astern direction. Additional measurements recorded during the backing tests include: engine order, shaft speed, propeller pitch for CP plants, rudder angle, and heading.

FUEL ECONOMY TRIALS

Fuel Economy Trials are conducted by NAVSSES, Philadelphia, with support from DTRC. NAVSSES calibrates and installs fuel flowmeters and any instrumentation necessary to define the fuel consumption rate required for various operating conditions. DTRC records torque and r/min data concurrent with the fuel economy runs in order that fuel consumption rates can be correlated with shaft horsepower.

Fuel Economy Trials are normally conducted in free route due to the long duration of each run. The length of a given run is a function of the time required for propulsion plant parameters to stabilize and can vary from 15 min to 1 hr. For example, a gas turbine plant will stabilize more quickly than a steam turbine plant. It is advisable to run the Fuel Economy Trials after the ship's EM log has been calibrated. This allows speed data to be obtained from the EM log during the free-route Fuel Economy Trials.

Results of the Fuel Economy Trials are generally reported under separate cover by NAVSSES. However, on some occasions, the fuel economy data are forwarded to DTRC for inclusion in the standardization report.

MEASUREMENT METHODS

GENERAL

Advances in electronic technology during the past decade have significantly improved the capabilities of the Full Scale Trials Branch to collect and analyze data which describes the powering and maneuvering performance of Naval ships. These improvements have contributed to the realization of more accurate measurements, more precisely controlled trials, and greater data outputs. Specific data collection techniques used are discussed below.

CALIBRATION PROCEDURES

Each DTRC supplied transducer used during full scale trials undergoes a minimum of two calibrations during each Standardization or Maneuvering Trials process. The expected maximum or minimum values for each recorded parameter are first determined. Each transducer and signal conditioning unit is then calibrated for this range of values immediately prior to shipment to the installation site. The instruments are again calibrated at the end of the trial upon return to the Center. Every calibration is documented and retained for future reference. A description of the major instruments used in full scale trials is presented below and each is accompanied by a brief description of the normal calibration procedures. The accuracy expected for each of these measurements is shown in Table 2.

SHIP POSITION AND SPEED

Ship position is one of the more important measurements obtained during Performance Trials. Such data are necessary to derive ship speed and to fully define the powering and maneuvering characteristics of the ship. An increasing number of Performance Trials are conducted using portable tracking systems maintained by DTRC or at HECTOR, therefore, these two methods are described in detail.

Portable Tracking Equipment

The Full Scale Trials Branch currently uses the Motorola Falcon system to accurately track the movement of a surface ship during trials. The Falcon operates on the pulse radar principal and requires a receiver/transmitter (R/T) mounted high on the ship and a minimum of two reference stations (transponders) on shore.

The R/T emits an interrogation pulse comprised of a unique code for each of the shore-based transponders at precise time intervals. The elapsed time between the transmitted interrogation and the reply from each transponder is used to determine the ship's range to each reference station. The resulting range measurements and the known distance between the reference stations constitute three known sides of a triangle which allows ship position to be accurately determined through fundamental trigonometric relationships. A typical Falcon installation is shown in Fig. 4.

The standard version of the Falcon operates at line-of-sight ranges up to 20 nmi (37 km) with a probable range measurement accuracy of plus or minus 9 ft (2.7 m). System portability permits trials to be conducted at most geographical locations. Several considerations are required, however, to optimally locate the reference stations and test site to insure that the accuracy potential of the system is achieved. Major considerations are:

1. Geometric relationship between the two reference stations and the ship
2. Range of the positioning system
3. Line-of-sight
4. Antenna patterns
5. Multi-path (range reflections)
6. R/T placement
7. Accessibility of reference station sites
8. Power sources at the reference sites.

Performance Trials are generally conducted with the ship between 2 and 10 nmi (4 and 19 km) offshore. The baseline course length is nominally twice the distance of the ship from shore. The optimum positional accuracy of the system is obtained when the intersection angle of the two range distances is 90 deg. Therefore, trial maneuvers are ideally conducted at an offshore distance such that a 90 deg intersection angle occurs at the midpoint of the maneuvering area. Figure 5 depicts a radar tracking range with the minimum, optimum, and maximum intersection angles.

Placement of the R/T relative to the ship's communication, navigation, and radar antennas is of particular concern. Electromagnetic transmissions from the ship can affect the R/T, therefore, two precautions are normally taken to avoid R/T damage or interference:

1. Locate the R/T as far as possible from high-power antennas
2. Request that non-essential radiation be secured during trials.

The R/T can be damaged even if the Falcon system is off, consequently, its position relative to antennas with similar frequencies should be considered of utmost importance. In particular, the R/T should not be located in close proximity to the AN/SPS-67(V) surface search radar. This radar is replacing the AN/SPS-10 radar and operates on C-Band very close to the 5570 MHz frequency of the tracking system. It is recognized that positioning the R/T can be difficult due to the location and number of permanent antennas. For example, ships such as aircraft carriers have as many as 130 antennas installed topside.

Test ships are generally cooperative and will secure any radiation not necessary for safe operation of the ship. High intensity radiation from the ship's antennas can render the R/T inoperative or result in random position data. Performance Trials provide an excellent opportunity for the ship to conduct drills such as General Quarters (GQ). For this reason, trial interruptions due to radiation during GQ or other drills should be avoided by advance arrangements with appropriate ship personnel. In particular, it is advisable to inform the proper ship personnel of the location of the R/T and to identify any antennas which have interference potential.

In addition to meeting the criteria described above for the positioning system, the test site must have adequate water depth to eliminate shallow water effects which may induce vibration, speed loss, and overloading of the machinery plant at higher speeds. The minimum water depth required is the larger of criterion (a) or (b):

(a) $d > 3.0 * [B * H]^{\frac{1}{2}}$

(b) $d > C * V^2$

where:

d = Depth of water (ft or m)

B = Ship's beam (ft or m)

H = Mean draft (ft or m)

C = Constant (0.3 for English units or 0.09144 for metric units)

V = Maximum ship speed (kn)

<u>Hatteras East Coast Tracking Offshore Range (HECTOR)</u>

HECTOR provides an alternative site for speed/powering trials on surface ships operating on the east coast of the U. S. in lieu of transitting to an acoustic range in the Bahamas or the Caribbean. This site is approximately 4 hr from Norfolk and thus minimizes a ship's transit time to the trial site.

The center of the range is located at 35° 52.5' latitude north and 74°51' longitude west. The range site utilizes two of four offshore towers which are used by the Navy for pilot training. The unmanned towers are 17.5 nmi (32.4 km) apart and at the edge of the continental shelf, consequently a trial site can be established outside the 100 fathom (183 m) curve to avoid shallow water effects.

The Falcon pulse-radar system is utilized at HECTOR. Transponders are permanently mounted on each tower and are powered by a combination of batteries and solar panels. All positional data are recorded onboard and a real time graphics display indicates ship position on the range to permit optimum system geometry to be maintained. Trials are typically conducted within a 2 by 4 nmi (3.7 by 7.4 km) area with an approach heading of 018 deg true for northerly runs and an approach heading of 198 deg true for southerly runs. Multi-path problems are eliminated by installing the R/T between 70 and 180 ft (21 and 55 m) above the water surface and conducting trials within the designated area.

Loran C equipment is generally installed on the test ship by Center personnel prior to the trials at HECTOR. The Loran system is used to vector the ship onto the trial site, because the pulse-radar system is limited to a range of 20 nmi (37 km). Loran data are recorded during the standardization portion of Performance Trials to provide supplemental speed information.

SHIPBOARD TRANSDUCERS

SHAFT TORQUE AND SPEED

Sensing and measuring physical changes at one location and transmitting the results through air to another location by telemetry str the methodd used to provide torque measurements during Performance Trials. Previous systems required physical contact between the rotating shaft and the stationary ship structure via a slipring-brush interface. A telemetry system is free from brush noise and does not require regular maintenance. The 100 Hz frequency response of the torque system facilitates the measurement of both mean and alternating torque.

The Acurex series 1600 horsepower meter consists of a strain-gage bridge sealed in a 18 in. (46 cm) metal tube (sensor bar) which is bolted to two carrier rings clamped around the propulsion shaft. Excitation voltage for the strain-gage bridge is provided by the 6 Vdc output of a regulated bridge rectifier. The rectifier input voltage is supplied by a 160 kHz signal inductively coupled to a rotating antenna. The changing dc output of the strain-gage bridge then proportionally modulates a 5 kHz square wave in the rotary electronics module. These modulated pulses drive a voltage controlled oscillator operating at a frequency of 10.7 MHz. The oscillator output is capacitively coupled from rotor to stator winding and is electrically separated from the power signal. The signal is then demodulated and signal conditioned to produce a dc voltage proportional to shaft torque.

The shaft-mounted portion of the system is shown in Fig. 6. The system is calibrated by subjecting the sensor bar to precise displacement increments which can be related to shaft torque via a knowledge of shaft characteristics and properties such as outside diameter, inside diameter, and modulus of rigidity.

Shaft speed is measured using an infrared light source/sensor and reflective tape strips. The light source is directed toward a band of 60 strips of reflective tape evenly spaced about the shaft, with each strip separated by non-reflective material. As each strip of reflective tape passes under the light source, the light is reflected to the sensor and converted to a voltage pulse. The voltage pulses generated are then converted to a dc voltage suitable for monitoring and recording purposes. Shaft horsepower is then calculated according to the relationship:

$$P = \frac{Q * r/min}{C_2}$$

where:

P = Shaft power (shp or kW)

Q = Shaft torque (ft-lb or N-m)

R/min = Revolutions per minute

C_2 = Constant value (5,252 for English units or 9,549 for metric units)

PROPELLER THRUST

Thrust measurements are obtained on surface ships by replacing the standard thrust bearing leveling plates with leveling plates that contain strain gauge load cells as shown in Fig. 7. This measurement technique provides reasonably accurate thrust data, but the installation is costly and time consuming.

The calibration factor (output voltage versus applied load in pounds or newtons) is determined for each cell with a loading machine at the Center. The voltages recorded during each run are converted to force values by application of the calibration factor and by subtracting the load attributable to the depth of submergence of the propeller. The total correction also takes into account the weight of the rotating parts (shafting and propeller), the angle of inclination of the main shaft, and the trim of the ship.

Leveling plates with strain gauge load cells are often installed to obtain thrust data for model and propeller correlation studies despite their difficult installation procedures. Attempts to develop a more efficient and economical method of obtaining accurate thrust data have been unsuccessful to date.

MACHINERY CHARACTERISTICS

Selected data are recorded to document the operating levels of ship machinery during Performance Trials. Typical measurements include first stage shell pressure of the high pressure turbine, condenser vacuum, astern nozzle bowl pressure, and rudder ram pressures. These measurements may be used as a diagnostic tool to examine or confirm the operating levels of various machinery or to provide supportive data for direct measurements of various parameters such as shaft horsepower. For example, first stage shell pressure can be directly related to shaft power and indirectly to changes in hull condition resulting from marine growth.

Pressure transducers, flow meters, thermocouples, accelerometers, etc., are examples of common transducers utilized during Performance Trials. The dc output from each transducer is conditioned and routed to the recording instrumentation. Past trials have required a thorough knowledge of machinery operating principles, characteristics, and expected performance. As many as 100 different data channels have been monitored and recorded during individual trial periods.

CONTROL SETTINGS AND APPENDAGE POSITIONS

Documentation of the dynamic positions of selected ship machinery controls and certain appendages are essential to the successful completion and subsequent analysis of Performance Trials. These measurements are typically obtained via existing ship's synchro circuits. Measurements obtained in this manner include throttle position, rudder angle, and ship's heading.

The ship's synchro circuits are connected to solid state synchro converter modules which have input impedances of greater than 100,000 ohms. High input impedance devices are used for all interfaces with ship's circuits to avoid impairing the normal operation of ship systems. These synchro modules are configured to produce output voltages which vary in proportion to the mechanical movement being sensed. Calibrations are performed by recording the output of each synchro module as a given control or appendage is moved to and held at a known position.

PROPELLER PITCH

The accurate determination of propeller pitch is perhaps the most difficult measurement to accomplish during Performance Trials. Propeller pitch is normally measured by the ship's mechanical indicator located near the oil distribution box which supplies pressurized oil to the control mechanism. The mechanical indicator provides a means to record the pitch, however, the indicator output is not sensitive to propeller pitch deviations caused by changes in system oil temperature or shaft compression due to thrust. Sensors mounted in propeller hubs during special trials have demonstrated the significant difference which may be present between actual blade position and that reported by the mechanical indicator.

Temporary in-hub sensors are rarely utilized due to the high cost and complexity of the installation. Consequently, propeller pitch calibrations have increased in complexity and now involve supplemental measurements such as system oil temperature and pressure. Propeller pitch mechanical indicator calibrations are generally performed pierside with divers for three different hub oil temperatures. At each pitch setting of interest, divers obtain measurements at the propeller hub while inboard measurements are taken at the pitch mechanical indicator. A correlation is then made between the actual pitch and the mechanical indicator position for each oil temperature. System oil temperature is subsequently measured during the trial and is used in the pitch computation.

Periodically during the trials, propeller pitch is moved to its maximum position, which is fixed by design, to provide a known point such that the pitch calibration can be checked. This verification includes the simultaneous measurement of pitch from the ship's indicator and hub oil pressure. Failure to meticulously perform the pitch calibration and subsequent validations will result in erroneous pitch data. The measurement of propeller pitch continues to be an area of concern. Currently, a permanent in-hub pitch sensor is under development for one class of ship. Hopefully it will prove to be reliable and accurate.

CONDITIONING EQUIPMENT

Each transducer output recorded during a Performance Trial requires signal conditioning or processing to create high resolution data compatible with the electrical characteristics of the data acquisition system. Signal conditioning equipment required to accomplish this processing include: dc amplifiers, synchro to analog converters, frequency to voltage converters, and torsionmeter electronics. Many of these devices are located near the data source to insure a high signal to noise ratio and to reduce the amount of equipment which must be installed in the instrument room.

The specific functions of individual elements of the "conditioning equipment" shown on the instrumentation block diagram, Fig. 8, is either self-explanatory, e.g. dc amplifier, or is discussed in the text which describes the general measurements.

DATA PROCESSING AND CONTROL

DATA ACQUISITION SYSTEM

The Full Scale Trials Branch has discontinued use of an analog scanner and printer system in favor of a digital computer based system in order to take advantage of technological advances previously mentioned and to obtain more detailed performance data. The computer based system, capable of both data acquisition and data analysis, significantly reduces the manpower required to conduct Performance Trials. Experience has shown that Performance Trials can be most efficiently conducted by limiting the amount of manually collected data. Trials which depend on manual data collection are severely limited by the speed at which data can be obtained. Manual recording also hinders the simultaneous sampling of numerous data channels.

Communication difficulties generally arise with a large number of data collection stations. As an example, recording marks can be inadvertently missed as persons in areas such as the engine room experience a great deal of background noise. Accordingly, it is considered imperative that data collection during major trials on large ships be as automated as possible to avoid such problems.

An important step in planning for a Performance Trial on a large ship is the selection of the data acquisition and/or data reduction system location.

Several configurations may be possible for a given ship, but some arrangements have advantages over others. Performance Trials must be directed from the pilot house by the Trial Director to ensure proper execution of each maneuver. Therefore, the pilot house is the preferred location for the data collection system. This arrangement allows the Trial Director and the computer operator to interface more effectively with each other and the pilot house personnel. Discretion should be exercised, however, before the decision is made to locate the instrumentation in the pilot house. Generally, the following criterion must be met before locating in the pilot house.

1. Adequate space must be available such that the added personnel and equipment will not interfere with normal ship operations.
2. Ship personnel should be receptive to having additional instrumentation in the pilot house.
3. The installation must be neat and presentable and should allow easy replacement of any component in the event of equipment failure.
4. Consideration should be given to the possibility of night operations when the pilot house would be rigged for red (no bright lights).

It is likely that the data acquisition system cannot be located in the pilot house. Consequently, a second choice is to locate the equipment within 200 ft (61 m) of the R/T installed on the mast. This arrangement allows the Falcon console to be located with the computer system and minimizes the length of cables routed between the instrument room and the pilot house. In the event a suitable instrumentation room cannot be located within 200 ft (61 m) of the R/T, the Falcon console must be located remote from the computer system and controlled via a bus extender system.

The bus extender system is transparent to the user, highly immune to noise, and requires only two shielded pairs of cable for data transmission. This system allows the computer to control any Institute of Electrical and Electronics Engineer (IEEE) 488 device, such as the Falcon console, at distances up to 4,000 ft (1,220 m). Long separations between the Falcon console and the computer necessitate several long cable runs between the instrument room and the pilot house. Propagation delays are inherent due to the link length, but data transmission rates of 60 kbytes/s are typical.

The area ultimately selected to house the major portion of the data acquisition system should be reasonably quiet, out of the mainstream of the ship's personnel traffic, centrally located to the signals being recorded, and air conditioned. Air conditioning helps avoid equipment failures resulting from extreme temperatures or humidity. Outputs from the transducers previously discussed are routed to the selected compartment, referred to as the instrument room, and are inputed to a measurement and control processor as shown in Fig. 8.

The processor accepts bi-polar 10 V analog signals as well as digital signals and routes the data to the computer. The computer is programmed in basic language and controls the acquisition, computation, and recording of all data channels. The 16-bit computer used by the Full Scale Trials Branch has 4 Mbyte of random access memory and input-output ports for interfacing with a wide variety of peripherals. A flexible disk drive is used for permanent storage. A thermal printer is used after each run for "quick-look" confirmation of the validity of each run.

The instrumentation system described above allows all data to be collected and checked for certain types of errors automatically. The computer program used is menu-driven and allows the operator to select different run modes, scan rates, etc. However, this system causes a dilemma in the event of failure of a major system component such as the computer or the tracking system. It is therefore imperative that substitute components be readily available for critical system elements. If instrumentation problems occur, corrective actions are initiated by the trial engineer who monitors the performance of the instrumentation throughout the trials.

DISPLAY EQUIPMENT

The Trial Director must verify that each run is performed in accordance with accepted trial procedures to ensure comparable test results. In order to assist the Trial Director in recognizing steady conditions and appraising the validity of each run, data from selected parameters are displayed real time via cathode ray tube (CRT) monitors in the pilot house.

One of the pilot house monitors displays machinery data which normally includes torque, shaft speed, horsepower, ship heading, and rudder angle. A second display graphically depicts the ship's movements and allows the Trial Director to know the ship's location on the range at all times. The Trial Director is thereby kept fully apprised of ship conditions without frequent phone communications with the instrument room personnel. Four cable runs are normally required to pass machinery and position data to the pilot house. These cables are noise sensitive and it is recommended that this distance be limited to 200 ft (61 m). An additional cable run is needed for communications.

DATA REDUCTION EQUIPMENT

The necessity of backup instrumentation onboard the test ship, along with the smaller size of today's data processing equipment has resulted in the routine installation of a second data acquisition and control system for each Performance Trial. In addition to serving as a backup system, the secondary equipment is utilized for data reduction concurrent with data acquisition by the primary unit. Thus, while trials are in process, the second system is used to plot time histories, reduce trial data, or perform any processing deemed necessary by the trial team.

Software is continually being developed to further utilize this equipment to more completely document, analyze, and validate each run as well as to identify areas which may warrant further investigation. The equipment is used to accumulate individual run data into a common file thus enabling a run summary table to be output at any time for all common maneuver runs. Additionally, the system is used to calculate and plot drift vectors and to estimate true wind velocity. This information is useful in observing weather trends and provides insight into the scheduling of the different types of trials. An observed trend of decreasing wind conditions may, for example, indicate a favorable opportunity for conducting spiral tests. Undoubtedly, the role of the onboard data reduction system will continue to increase as new software is developed and this tremendous resource is more fully utilized.

POST-TRIAL DATA ANALYSIS

STANDARDIZATION TRIALS

The speed and computational power inherent to the acquisition system described above minimizes the post-trial data reduction effort. This is particularly true of the standardization data shown in Fig. 9. Maximum, minimum, and mean values for all channels are determined during each speed/power run which allows the Trial Director to readily detect inconsistent data. Inconsistent run averages indicate the need for additional runs to clarify any questionable data or to verify unexpected trends. The importance of verifying trial data while at sea cannot be overemphasized. Repeat runs are not possible once the trials have been completed and the instrumentation has been removed.

The basic data presented from Standardization Trials are shaft speed, power, torque, and thrust as functions of ship speed. Data from multiple shaft ships are generally reported as averages or totals of all the shafts.

Standardization data are normally obtained at two different displacements to document the magnitude of the powering changes resulting from differences in displacement. Relevant data such as relative wind speed and direction and ship heading are also presented with the standardization data so that all powering data can be corrected to zero wind condition for comparison with model predictions.

Standardization curves are distributed to the fleet to provide information on the powering characteristics of each new class of ship. The clean hull data provided by these powering trials constitute a valuable reference for future evaluations of the powering efficiency of a given ship. Periodic measurements of the ship speed to shaft speed relationship of a ship, for example, can be compared to standardization data to provide an indication of hull fouling.

TRAILED AND LOCKED SHAFT TRIALS

Data obtained during Trailed and Locked Shaft Trials are presented as a group of curves representing the ship's speed/powering characteristics for various combinations of trailed or locked shafts. The curves of thrust, torque, shaft speed, and horsepower versus ship speed can thus be used to predict the ship's speed/powering capabilities in the event of a casualty which requires the trailing or locking of a shaft.

TACTICAL TRIALS

Tactical circle positional data must be corrected for the drift experienced by the ship due to wind, current, and tides. Tactical circle trials therefore require that the ship complete a change of heading of at least 540 deg for each run. Time dependent positional information which is 360 deg apart in heading are then compared to determine the drift correction coefficients. Corrections are based on the assumption that a true circular path is swept by the ship with a constant rate of change of heading. Accordingly, after the ship's rate of change of heading has become constant, any differences in the ship's position at heading values 360 deg apart are due to wind and water currents.

The magnitude and direction of the drift coefficients can then be obtained by dividing the positional differences (360 deg apart) by the elapsed time between points. These coefficients are defined for X and Y positions and have units of feet, yards, or meters per second. The corrected ship's path is then derived through the addition of the recorded X/Y coordinates and the product of the X/Y drift coefficient and the elapsed time relative to execute for all data points.

A path similar to that shown in Fig. 10 results when the ship's movement during a turn has been drift-corrected. The ship's turning characteristics: advance, transfer, tactical diameter, and steady turning diameter are then determined from the drift-corrected plot. Advance is the distance along the baseline course from EXECUTE (the point at which the rudder began to move) to the 90 deg change of heading position. Transfer is defined as the distance perpendicular to the baseline course from EXECUTE to the 90 deg change of heading position. Tactical diameter is measured from EXECUTE to the 180 deg change of heading position, perpendicular to the baseline. The steady turning diameter is the diameter of the drift corrected circle. In addition to these measurements, the ship's steady speed in the turn is determined from the steady turning circumference and the time required for 360 deg change of heading at a steady turning rate. Sample tactical trial data are shown in Fig. 11.

These data also reveal turning differences that occur with the use of right or left rudder and the possible presence of rudder breakdown. When rudder breakdown occurs, it is generally at higher speeds with large rudder angles and is defined as the point at which an increase in rudder angle results in a decrease in turning rate for a given speed. The rudder essentially loses effectiveness beyond that particular angle of deflection. This effect is shown in Fig. 12 where 40 deg of rudder deflection results in a lesser turning rate than 35 deg.

Other parameters recorded during the Tactical Trial and generally tabulated for reporting purposes are angle and direction of heel. These tactical data are also provided to the fleet and provide valuable operational characteristics for a new ship class.

ACCELERATION AND DECELERATION TRIALS

Acceleration and Deceleration Trials quantify the ship's ability to increase or decrease speed as functions of various initial conditions and subsequent engine orders. In the case of the deceleration maneuver, the time to stop and the distance traveled while stopping are the important parameters needed to define the ship's stopping characteristics. The time and distance traveled before reaching terminal speed from a specific initial condition and engine order defines the accelerating characteristics. The term "reach" is used to define the distance traveled along the ship's extended approach path between EXECUTE and the attainment of terminal speed.

Computer programs which utilize polynomial curve-fitting routines are used to obtain an equation defining relative changes in ship position as a function of time for each acceleration or deceleration maneuver. The resulting reach equation is then differentiated to obtain an expression to define ship speed as a function of time. Reach and speed versus time plots can then be produced to graphically illustrate the ship's movement along the projected approach path during each run. A family of deceleration curves developed by this method is shown in Fig. 13. Acceleration curves look similar except the speed plots curve upward rather than downward.

MANEUVERING TRIALS

Definitive maneuvers such as spirals and horizontal overshoots are performed to characterize the directional stability, handling response, and rudder effectiveness of a given ship.

Spiral Tests

Spiral Test data reduction primarily involves generating plots showing rate of change of heading in degrees per second as a function of rudder angle. The rates of change of heading are calculated by dividing the total change of heading by the elapsed time during a period of steady turning at a constant rudder angle. The actual rudder angle reached is used for plotting purposes rather than the requested, predetermined rudder angle.

An example of a spiral maneuver depicting a directionally stable ship is shown in Fig. 14. As shown in Fig. 14, a directionally stable ship will exhibit the same turning response whether the rudder is moving left to right or right to left. A directionally unstable ship will not turn the same to the left and right as evidenced by the "hysteresis loop" between 5 deg left and 10 deg right shown in Fig. 15.

Horizontal Overshoot Tests

Horizontal overshoot maneuvers are generally characterized by a time history plot of rudder angle and ship's heading. The results of a horizontal overshoot test are shown in Fig. 16. Good horizontal overshoot characteristics are position and heading repeatability between left and right rudder maneuvers and maneuvers with the rudder in the same direction. Small overshoot angles are indicative of the ship's ability to effectively change direction or countermaneuver. Effective countermaneuvering capability is particularly important when operating in restricted waters.

The primary predetermined parameters for horizontal overshoots are approach speed, rudder angle, and execute change of heading (generally 10 or 20 deg).

Backing Tests

The results of this maneuver are presented and analyzed using plots of heading versus time and, if conducted on a range, positional time history plots. However, these tests generally cannot be satisfactorily performed. Most twin propeller ships respond well to large rudder angles while moving backward. However, most single propeller ships or the use of low rudder angles on any ship generally results in the ship being unable to maintain a straight path while backing.

FUEL ECONOMY TRIALS

Results of the Fuel Economy Trials are reported by NAVSSES, Philadelphia. Powering data are normally supplied to NAVSSES by DTRC and the report includes fuel consumption data as a function of shaft power. Fuel consumption rates are sometimes forwarded to DTRC for inclusion in the Standardization Trials report.

MODEL POWERING CORRELATION

Correlation between full scale trial results and model predictions of powering characteristics continues to be an important part of the U. S. Navy's effort to improve its ship design capabilities. Each model to full scale correlation produces data necessary to more precisely determine hull correlation allowance (CA) values which must be applied to model test results to accurately predict the powering performance of a given ship. CA values are constantly being modified as more data are obtained through this correlation process. Such information is necessary to maintain a high level of agreement between model predictions and full scale data. This correlation provides a cost-effective method of obtaining creditable performance predictions for new hull, appendage, and propeller designs.

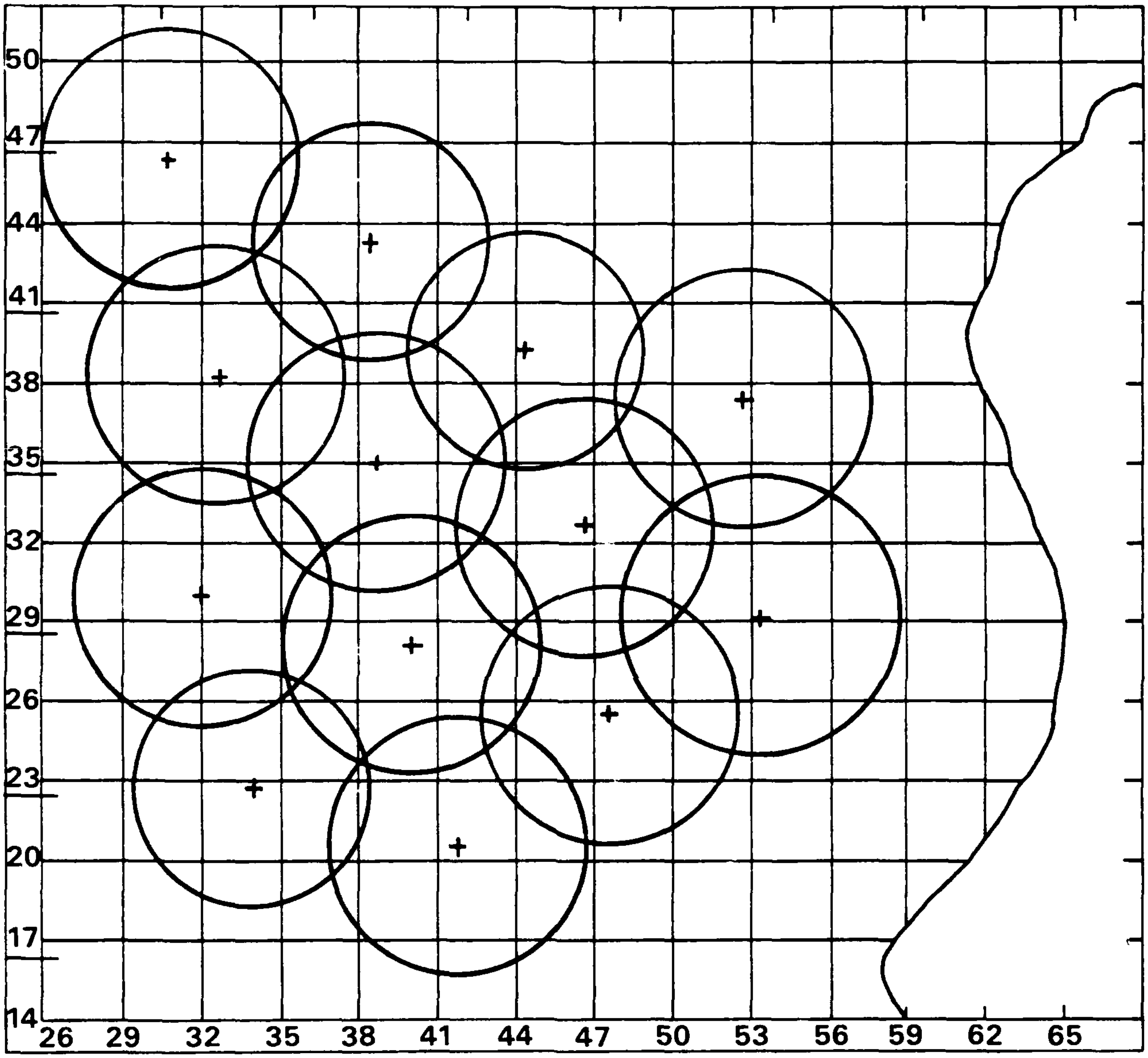
Upon completion of a full scale trial, an additional series of model tests are conducted which duplicate the full scale trial conditions. The model is rigged and appended similarly to the actual conditions existing during the full scale trials (trim, displacement, appendages, and the propellers) Resistance and self-propulsion tests are then conducted again. Corrections are applied for wind, seawater, temperature, and specific gravity, and then a new correlation allowance can be established.

SUMMARY AND CONCLUSIONS

Performance Trials continue to provide the best source of quantitative data on the powering and maneuvering characteristic of U.S. Navy ships. Advances in the performance capabilities of ships have been accompanied by advances in instrumentation capabilities, thus resulting in the more complete characterization of the total ship. Faster sample rates, less onboard manpower, more accurate measurements, faster data turnaround, and a wider choice of selection of trial sites are the trends in full scale trials.

Advances in capability must be accompanied by proper equipment calibration and substitution capability to ensure that each trial is successful. The successful trial is a result of careful planning, close liaison with the ship, and the ability of the trial team to adjust to changing trial conditions which often threaten the realization of trial objectives.

The more controlled aspects of the current full scale ship performance trial procedures reduce the trial time required, while improving trial safety through more precise ship positioning at greater distances from shore. The near-real time processing capability of the instrumentation system also allows instant recognition of any peculiarities, thus providing an opportunity for immediate further investigation as deemed appropriate. Therefore, each properly executed trial produces a wealth of accurate, detailed data to assist the modern naval architect in achieving the goal of producing the fastest and most efficient naval ships in the world.



+ Indicates Hydrophone Locations
and Surrounding Circles Show
Individual Hydrophone Range

Fig. 1. Typical acoustic range layout.

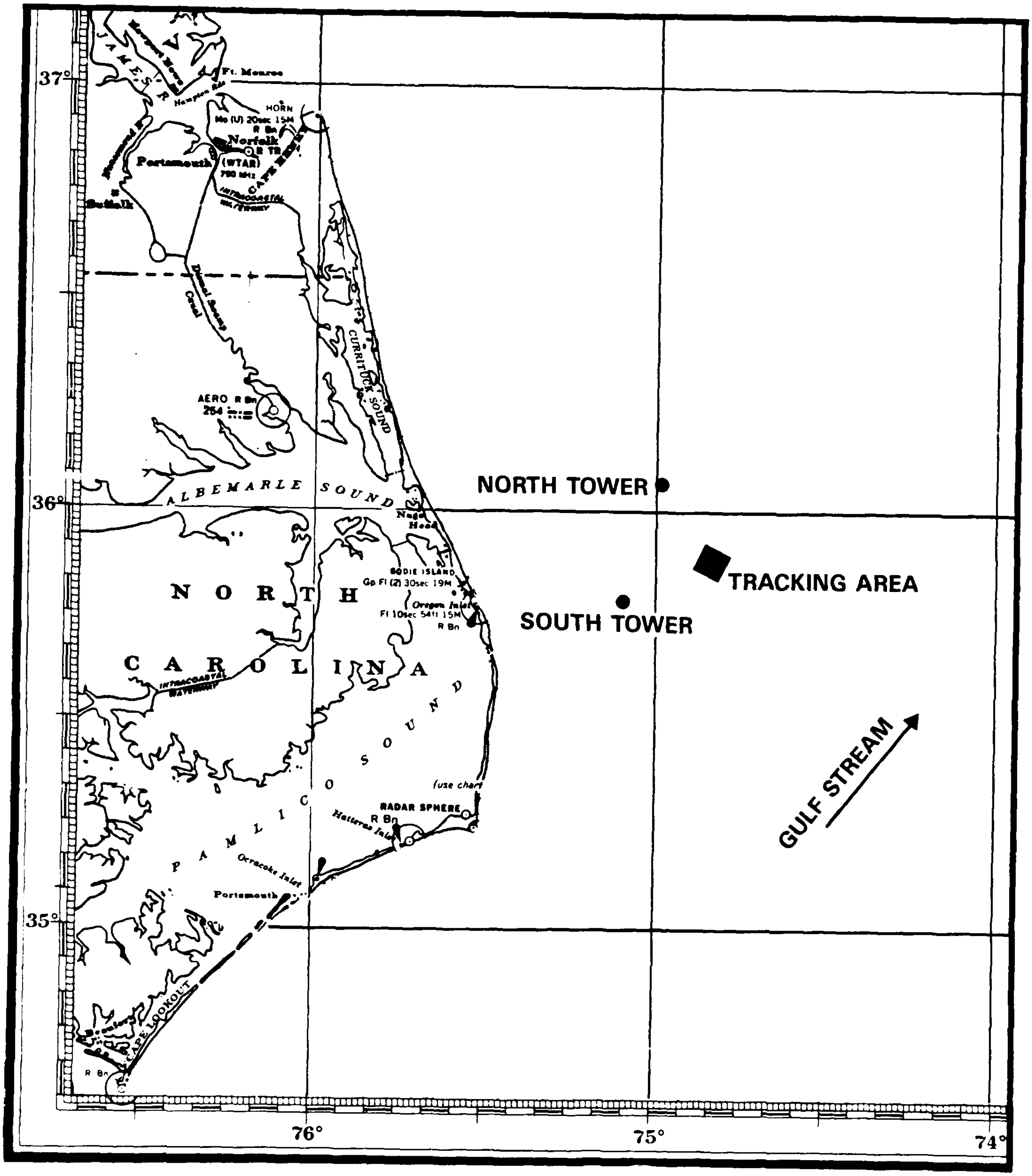


Fig. 2. Location of Hatteras East Coast Tracking Offshore Range.

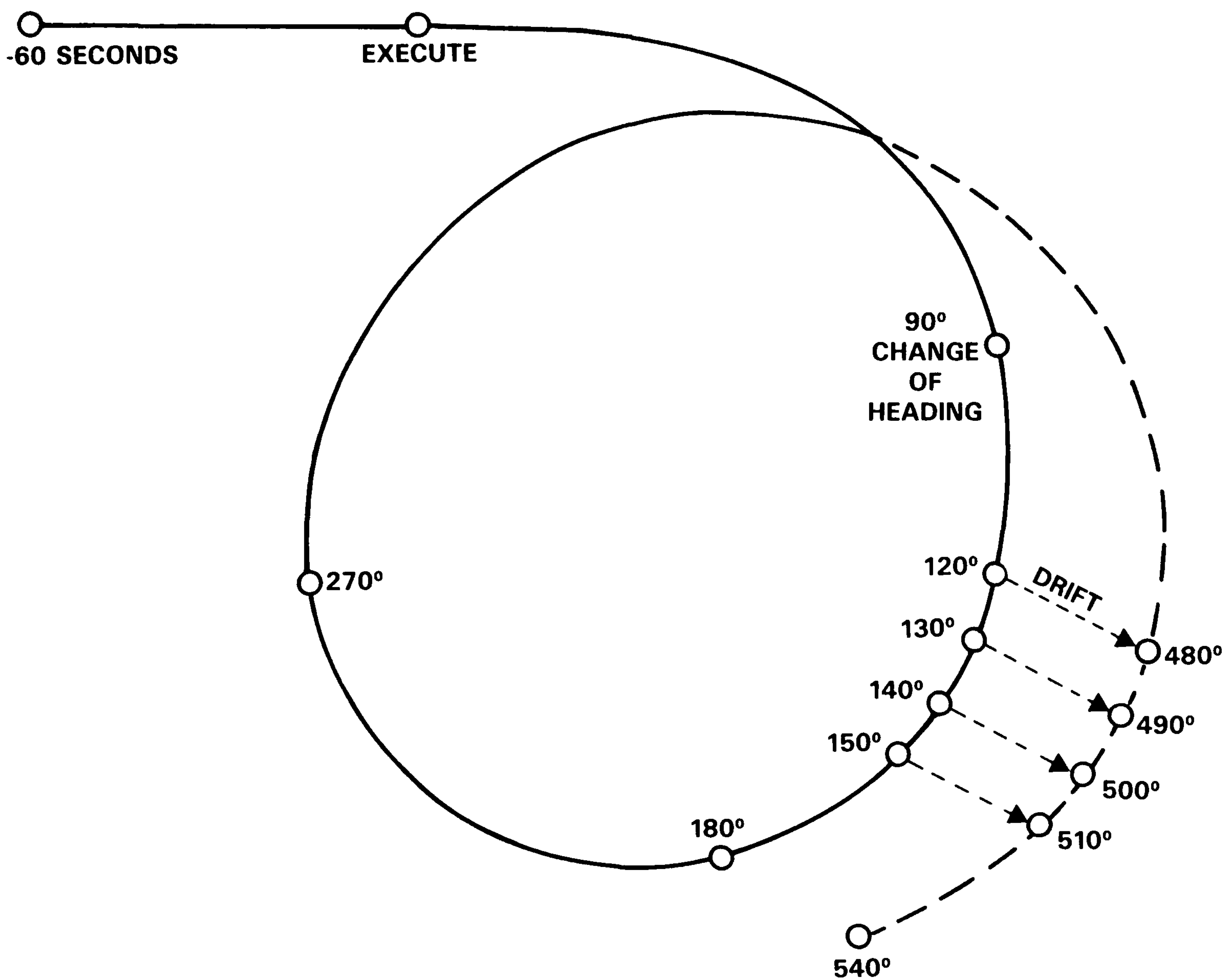


Fig. 3. Tactical turn, uncorrected.

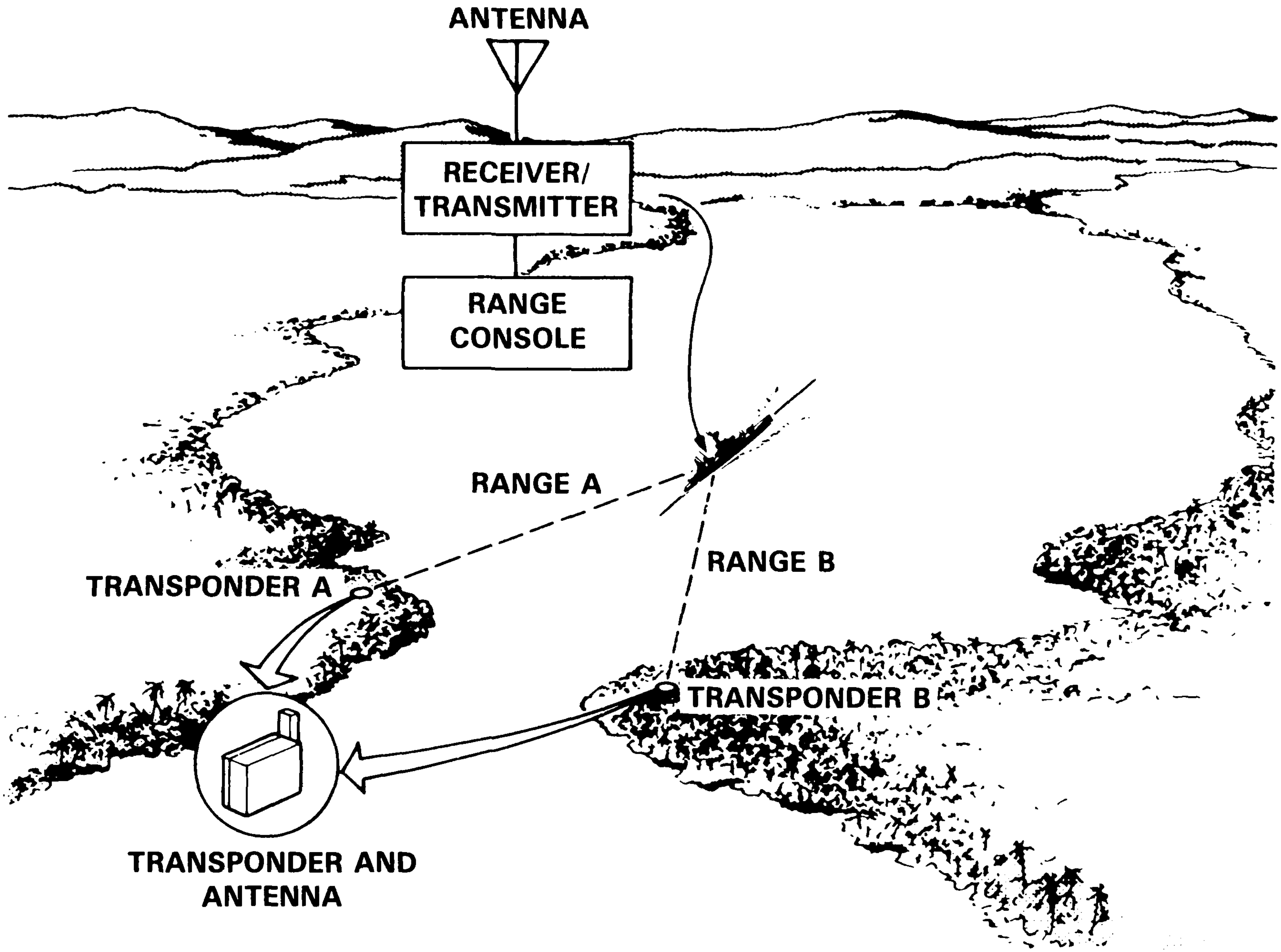


Fig. 4. Typical Motorola tracking system setup.

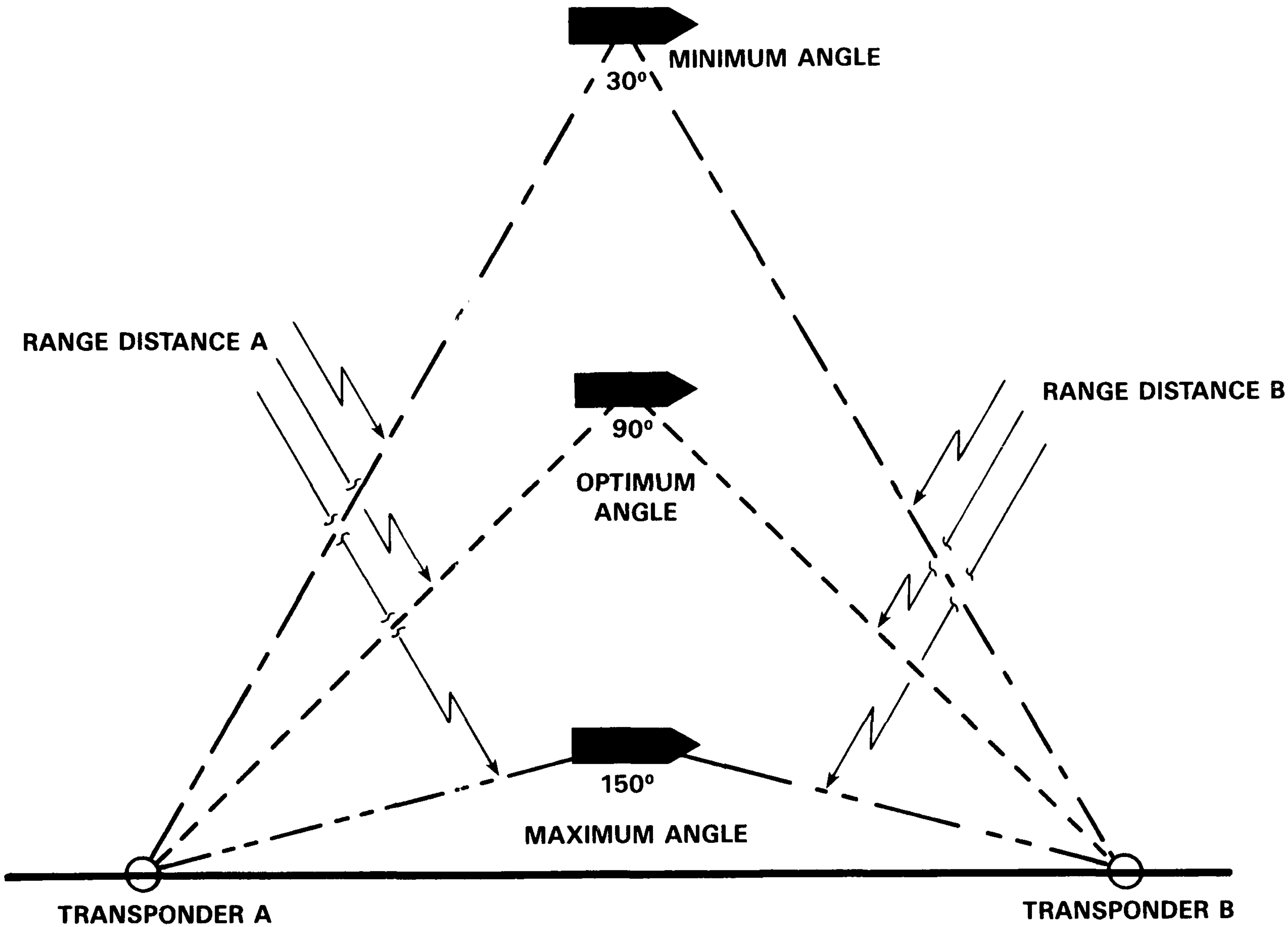


Fig. 5. Tracking system geometry.

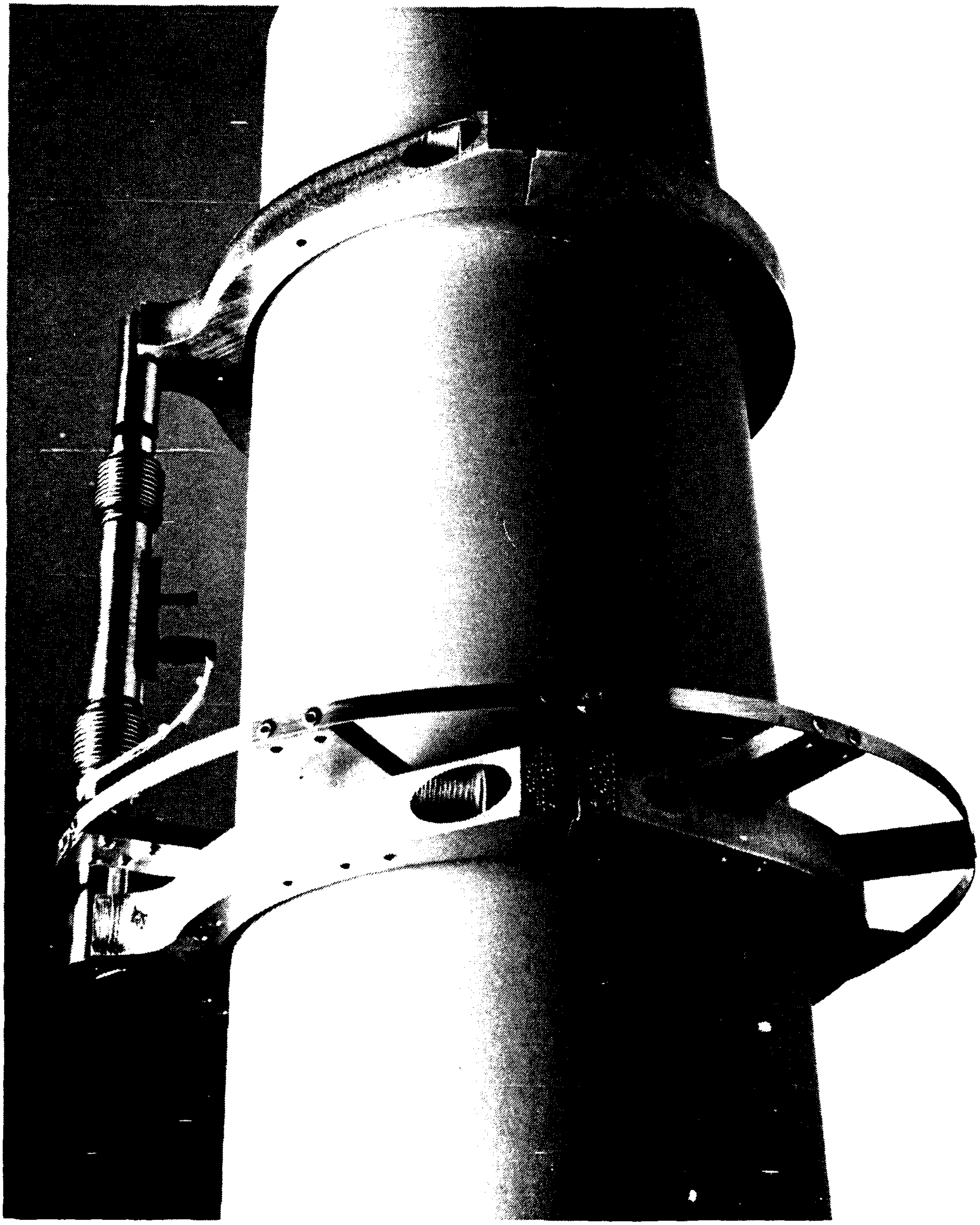


Fig. 6. Acurex torsiometer installation on propeller shaft.

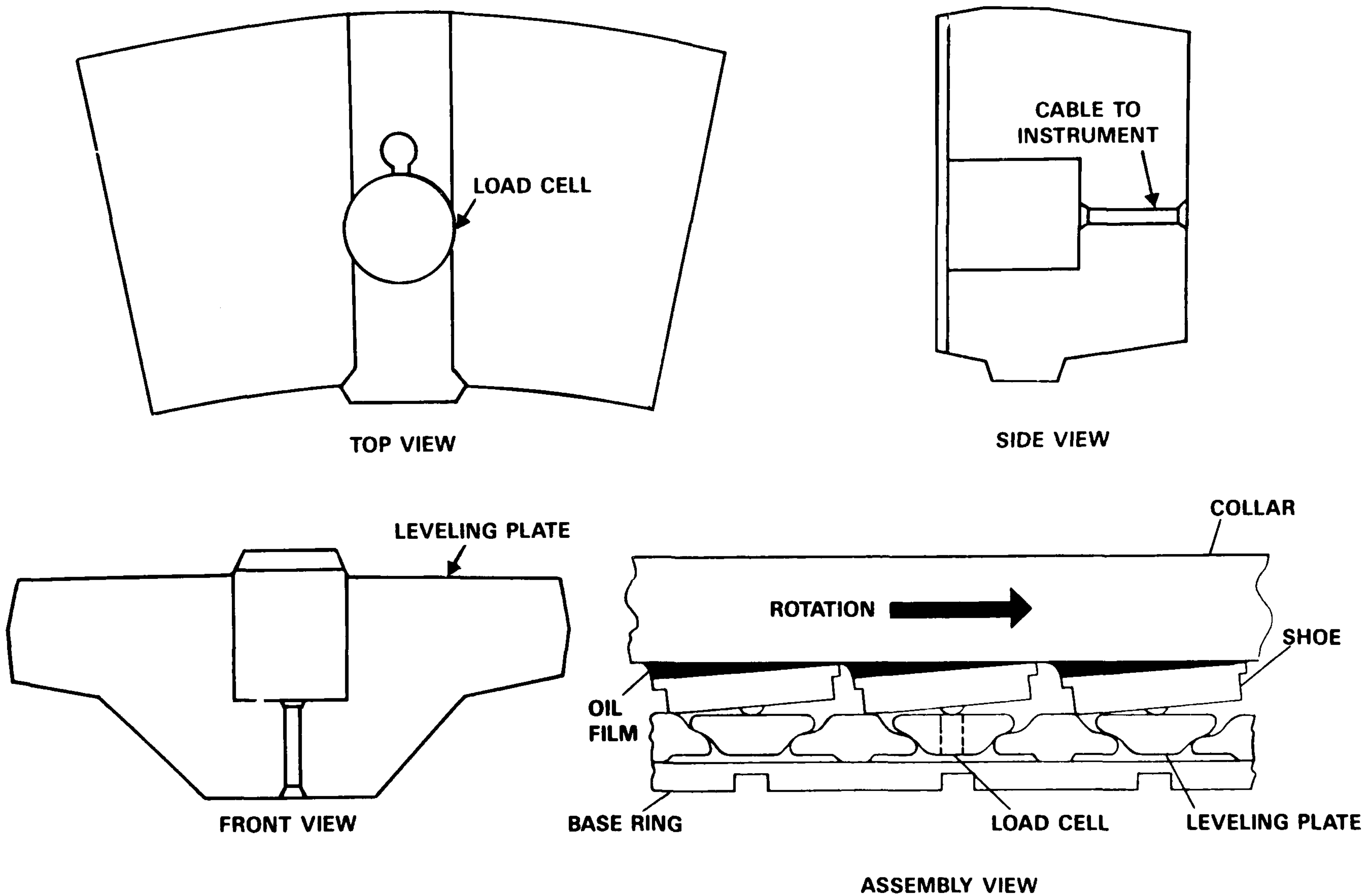


Fig. 7. Instrumented thrust shoe.

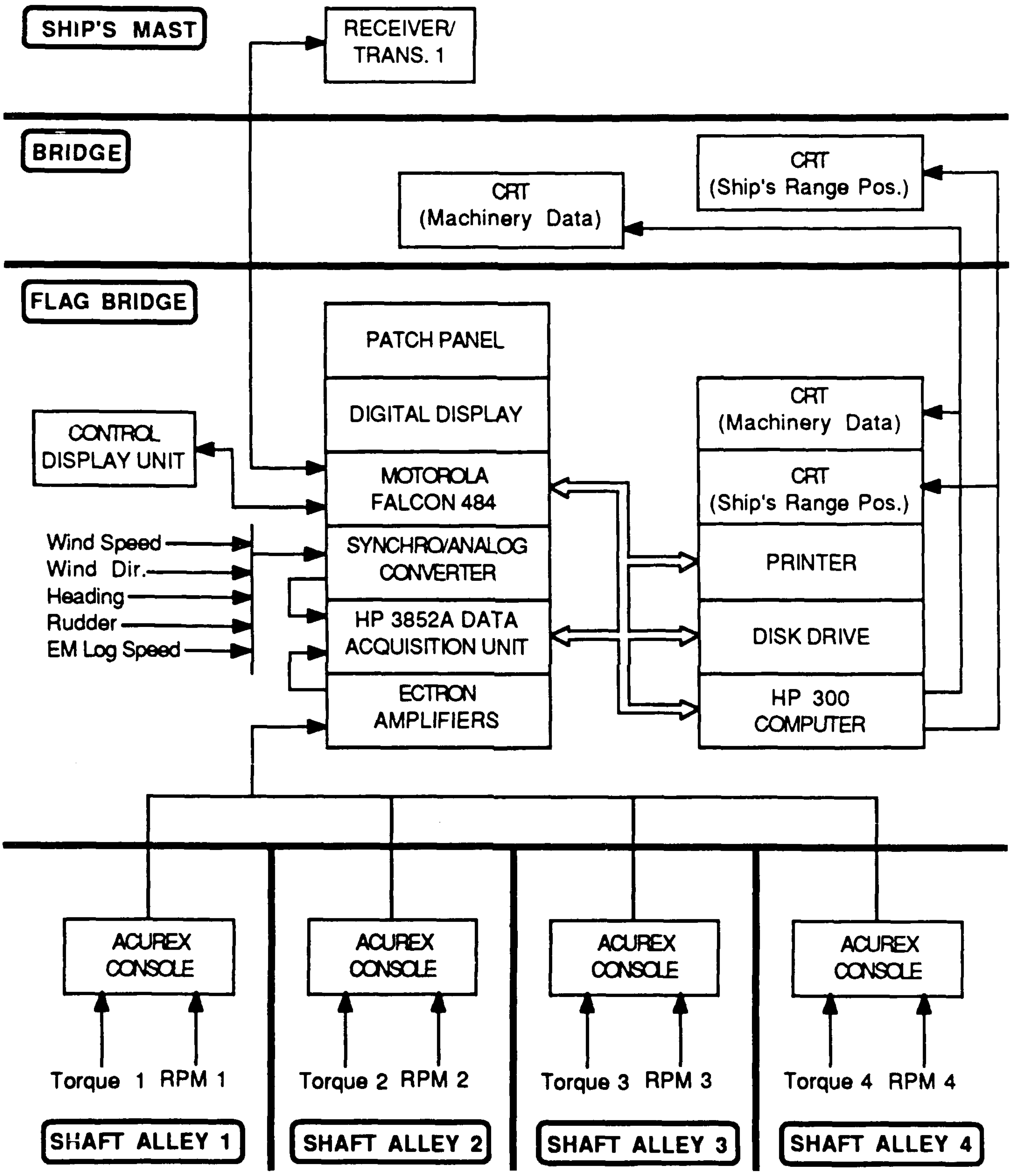


Fig. 8. Instrumentation block diagram.

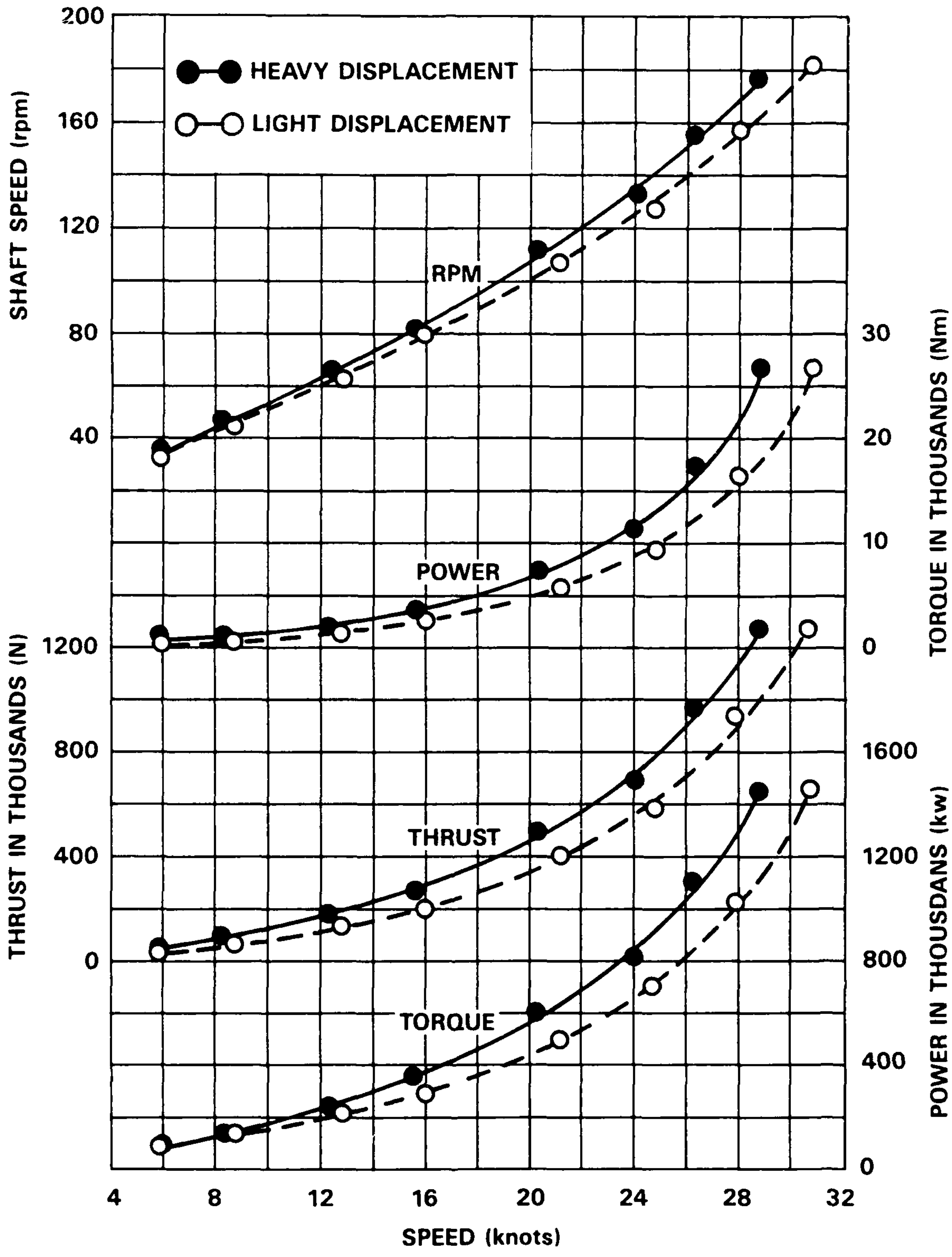


Fig. 9. Standardization Trial data.

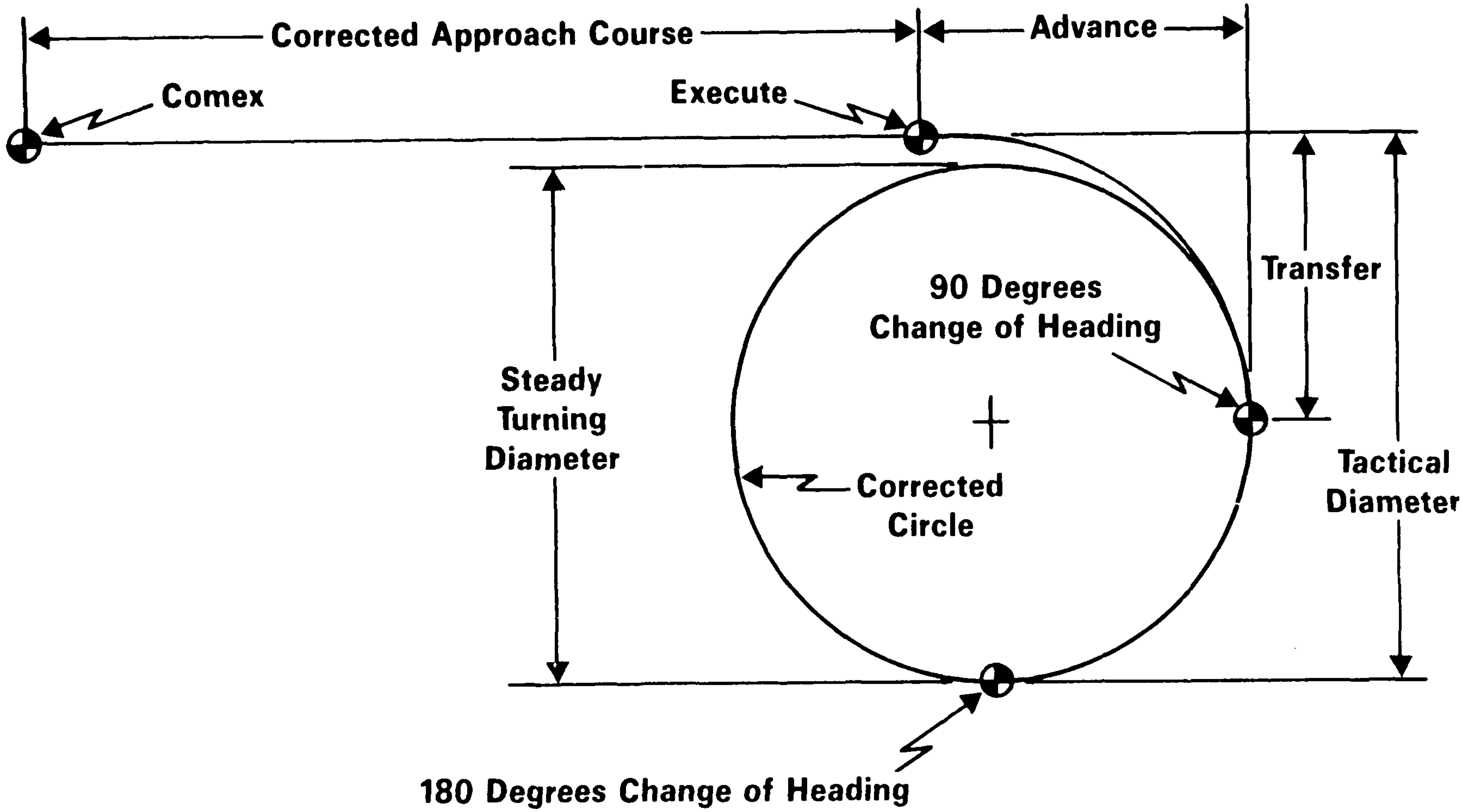


Fig. 10. Tactical turn, drift corrected.

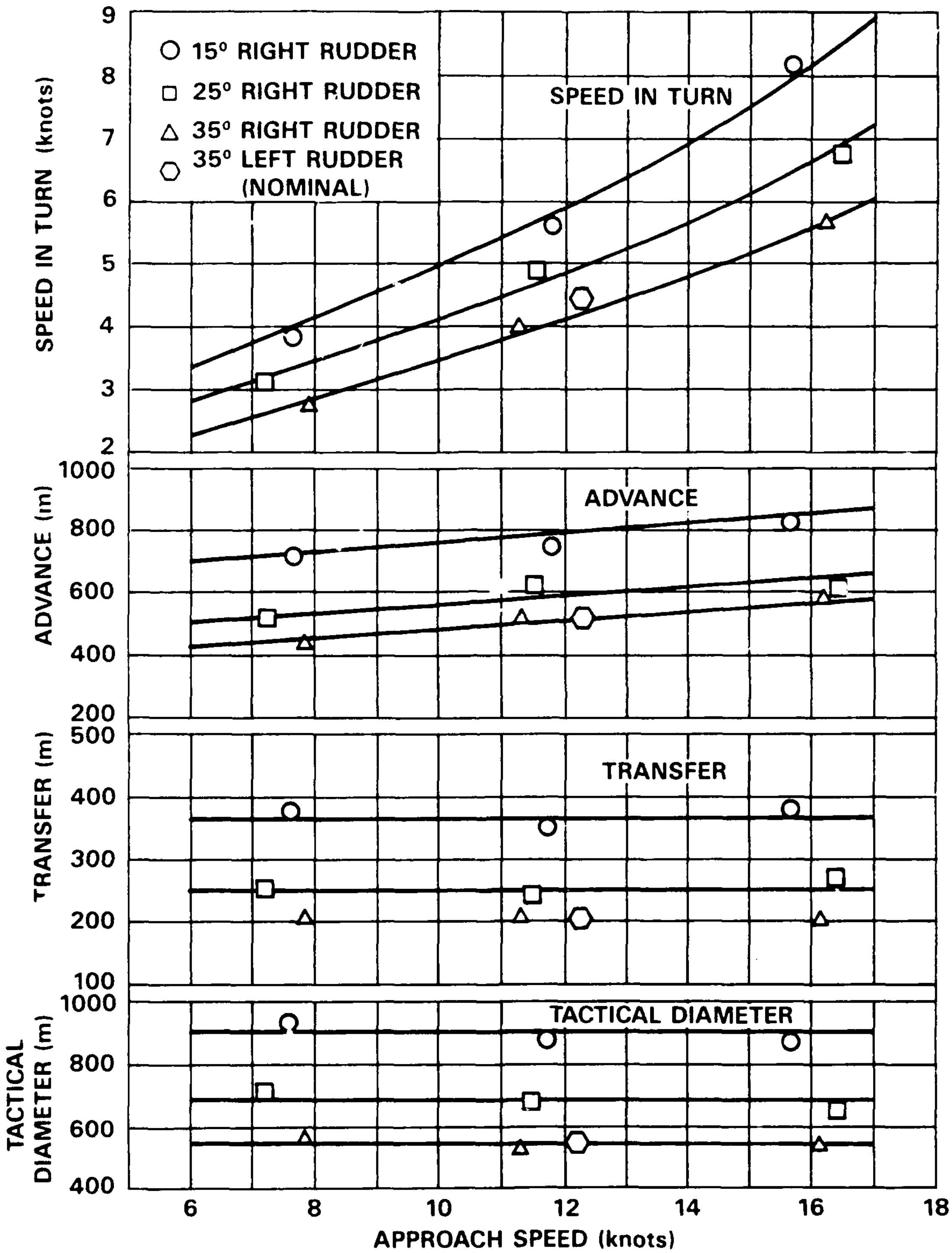


Fig. 11. Tactical trial data.

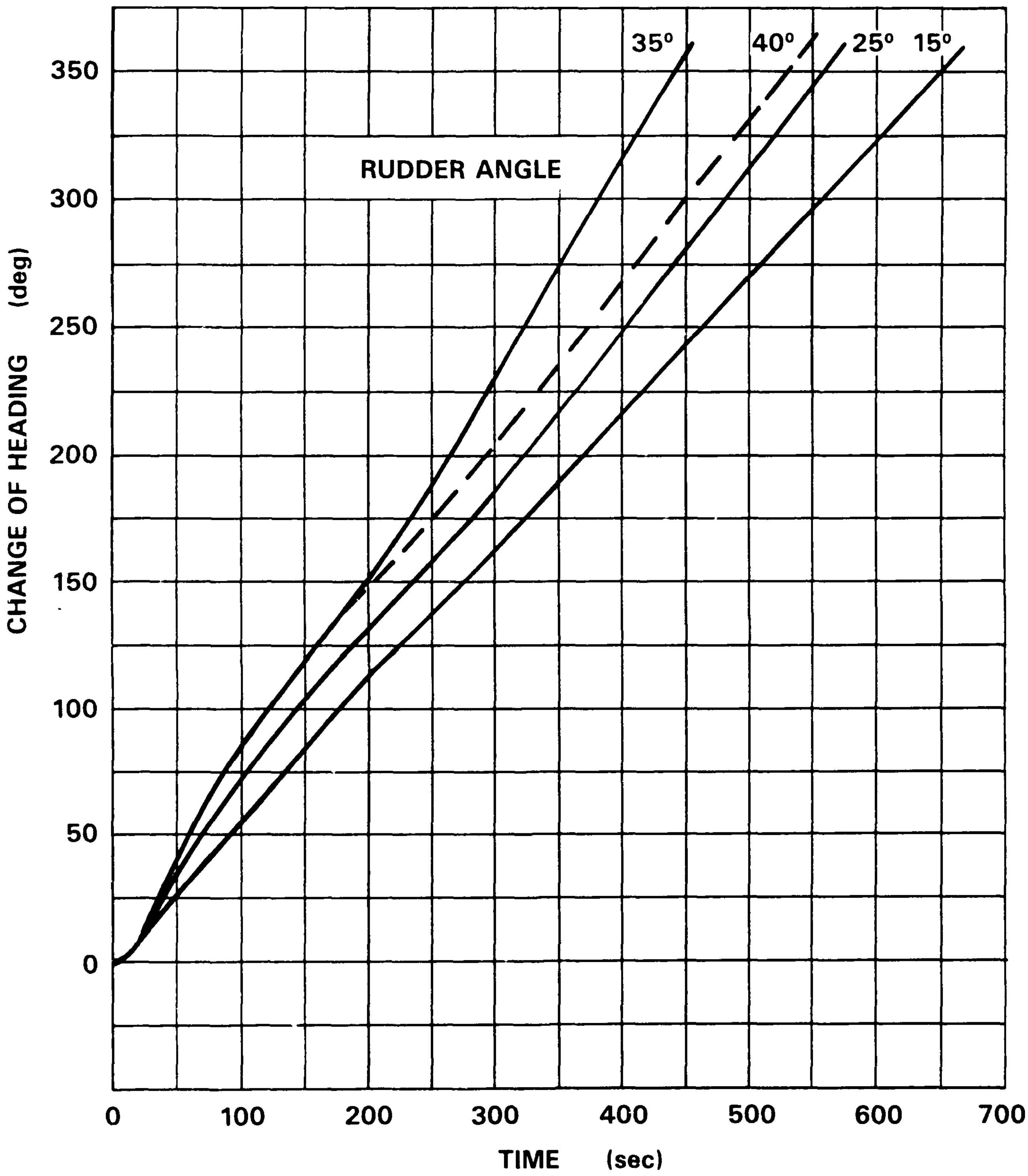


Fig. 12. Change of heading curves.

RUN NO.	APPROACH SPEED (knots)	REACH (m)	TIME IN SECONDS TO DEAD IN THE WATER
301	5.0	36	20.5
302	7.8	69	25.5
303	10.0	104	32.0
304	12.8	160	40.0

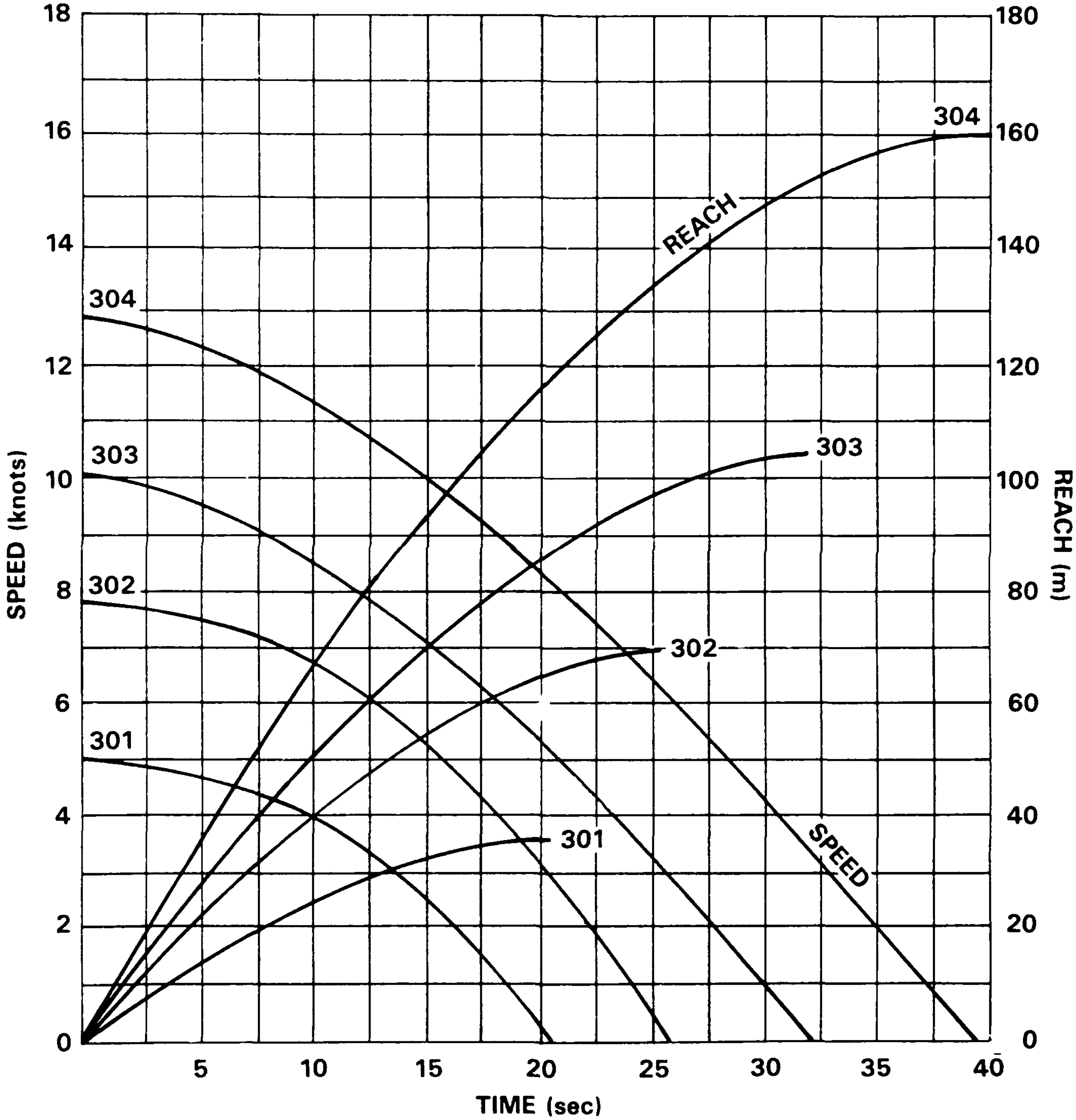


Fig. 13. Typical deceleration maneuvers using full power astern.

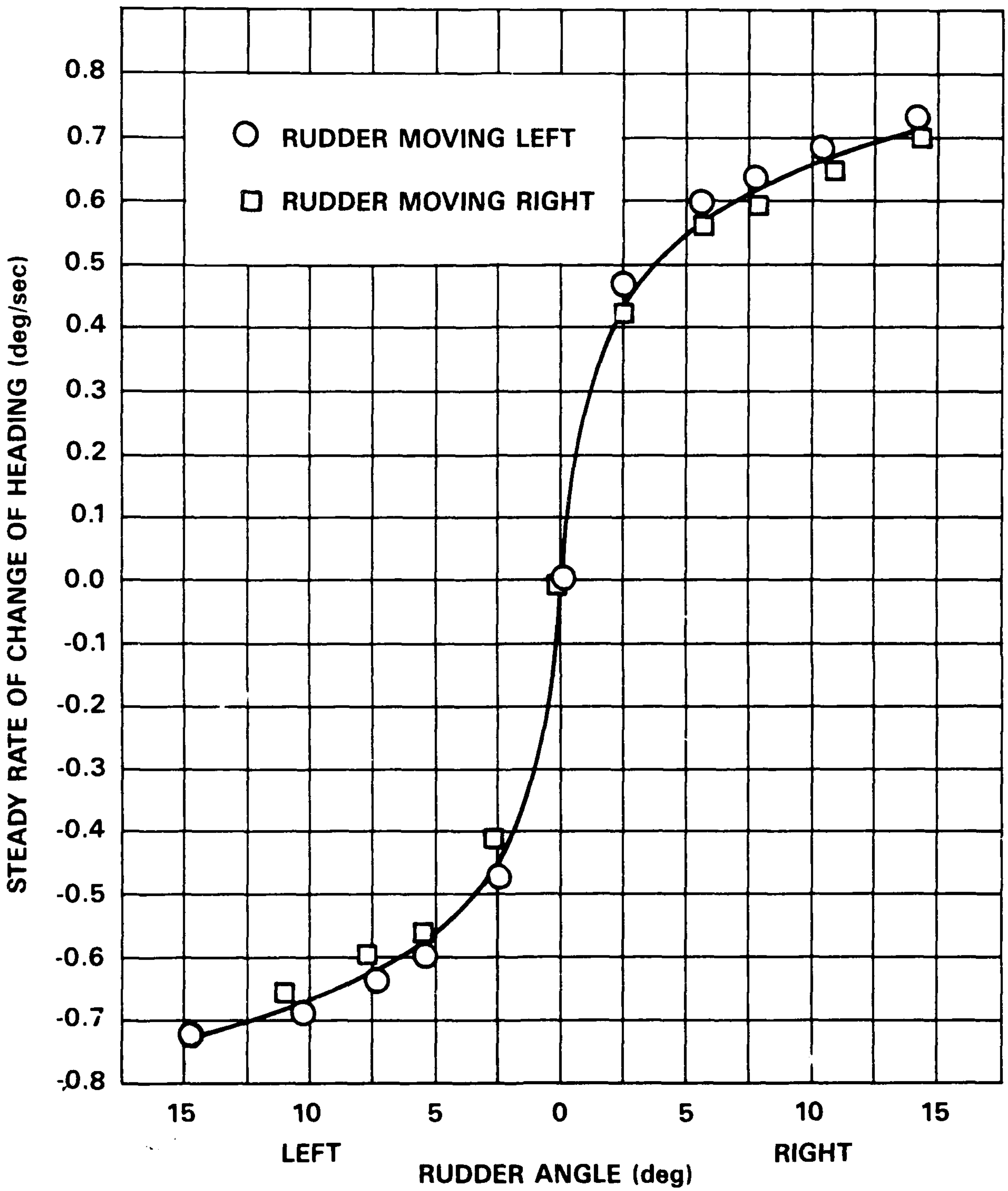


Fig. 14. Spiral maneuver - stable ship.

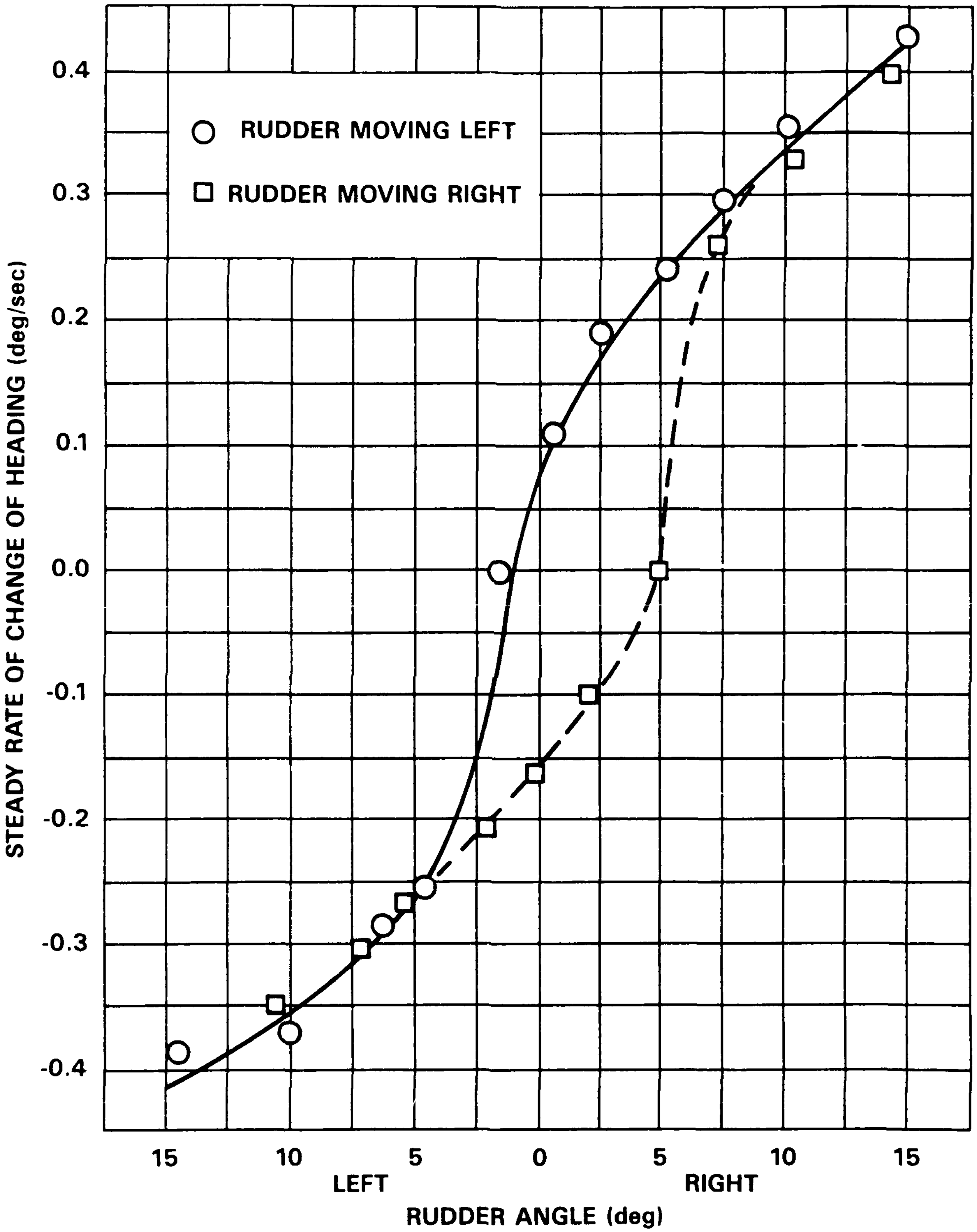


Fig. 15. Spiral maneuver - unstable ship.

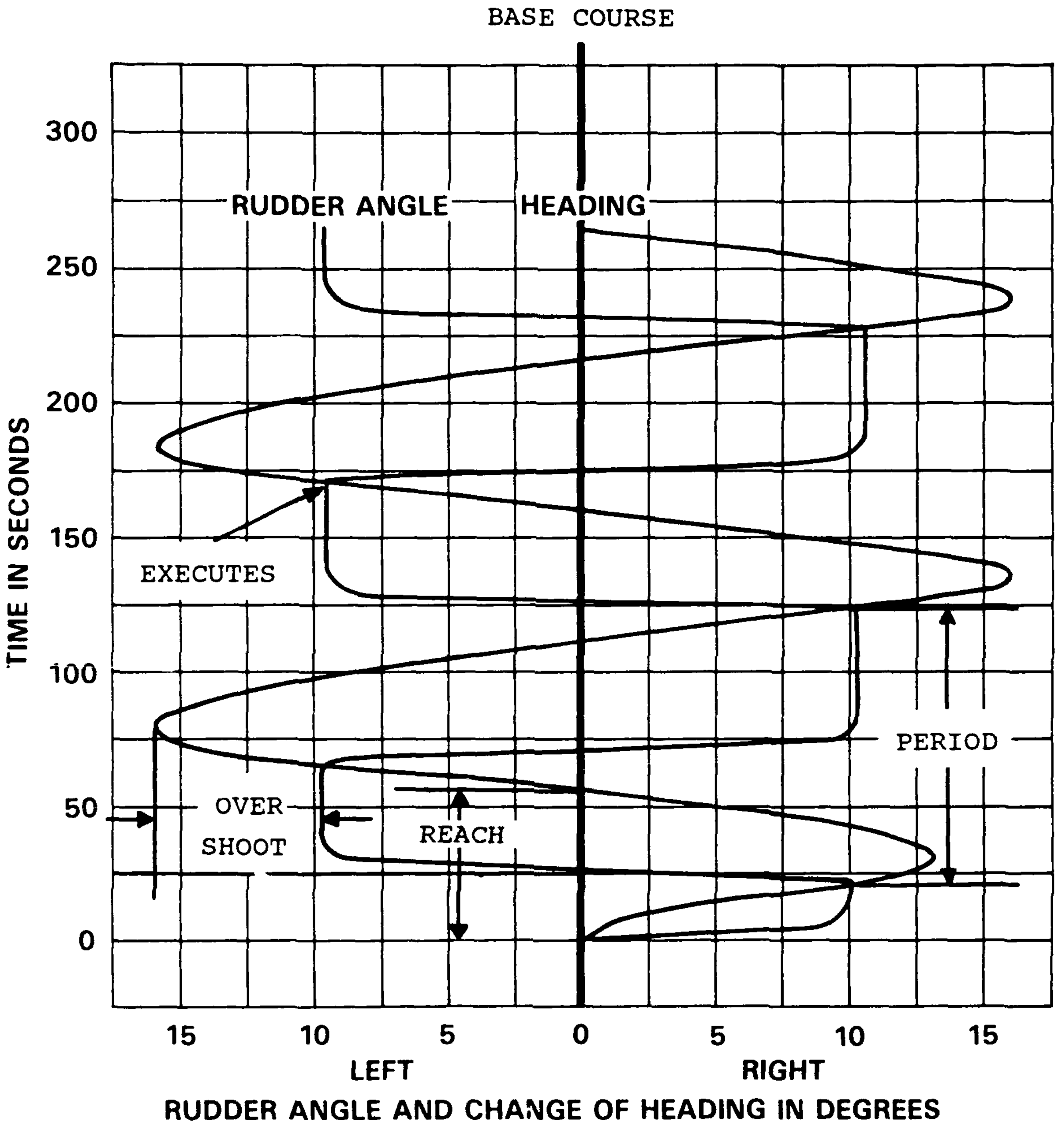


Fig. 16. Horizontal overshoot.

Table 1. Tracking range locations.

EAST COAST RANGES

Range	Type of Range
Hatteras East Coast Tracking Offshore Range (HECTOR) Oregon Inlet, North Carolina	Radar
Atlantic Fleet Weapons Training Facility (AFWTF) St. Croix, U. S. Virgin Islands	Acoustic
Atlantic Undersea Test and Evaluation Center (AUTEC) Andros Island, Bahamas	Acoustic
WEST COAST RANGES	
Naval Torpedo Station Three Dimensional Underwater Tracking Range Dabob Bay, Washington	Acoustic
Naval Torpedo Station Three Dimensional Underwater Tracking Range Nanoose, British Columbia	Acoustic
Santa Cruz Island Acoustic Range Facility (SCARF) Santa Barbara, California	Acoustic
HAWAII	
Pacific Missile Range Facility Three Dimensional Tracking Range Barking Sands, Kauai, Hawaii	Acoustic

PREVIOUSLY USED PORTABLE RADAR TRACKING SYSTEM LOCATIONS

La Jolla, California	Key West, Florida
Lualualei, Oahu, Hawaii	Point Reyes, California
Yokosuka, Japan	Kaneohe Bay, Hawaii

Table 2. Typical measurement accuracies.

Measurement	Source	Calibration Source	Resolution	Accuracy
Steady Ship Speed	Pulse-Radar System	Surveyed Baseline	0.01 kn	±0.05 kn
Instantaneous Ship Speed	Pulse-Radar System	Surveyed Baseline	0.2 kn	±0.5 kn
Steady Ship Speed	Acoustic Range	Surveyed Hydrophone Sites	±0.02 kn	±0.1 kn
Shaft Torque	Deflection Sensor	Deflection Calibration Stand	0.02% FS	±1.5% FS
Shaft Speed	Infrared Light Sensor	Electronic Oscillator	0.1 r/min	±0.5 r/min
Pressure	Pressure Transducer	Hydraulic Calibration Stand	0.05% FS	±0.1% FS
Thrust	Load Cells	Hydraulic Calibration Stand	0.05% FS	±3% FS
Wind Speed	Anemometer (DC Generator)	Wind Tunnel	0.1 kn	±0.5 kn
Wind Direction	Anemometer (Synchro Transmitter)	Visual Alignment	0.1 deg	±1.0 deg (±5 deg alignment)
Rudder Angle	Synchro Transmitter	Rudder Quadrant	0.1 deg	±0.25 deg
Ship Heading	Gyrocompass	Gyrocompass	0.1 deg	±0.25 deg
Steady EM Log Speed	Synchro Transmittter	Standardization Trials	0.05 kn	±0.25 kn*
Throttle Position	Synchro Transmitter	Ship Throttle	0.1% FS	±1% FS

*When calibrated.
Resolution = least detectable change in measurement.
FS = Full Scale.