Ferry Wake Study

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16. Abstract

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FERRY WAKE STUDY

by

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ABSTRACT

Wave heights were measured for three classes of vessels operated by the Washington State Ferries system on Puget Sound, Washington. Variation of wave height with distance from the sailing line was determined for each vessel class over a range of speeds. Instrumentation and testing procedures used are described. Various wave measuring technologies are discussed, and it is concluded that the spar-buoy wave-staffs used were most appropriate for the measurements sought.

SUMMARY

The specific objective of the study reported here was to measure waves generated by three classes of vessels operated by the Washington State Ferries system. Waves were to be measured at various distances from the sailing line over a range of discrete speeds for each of the three ferry classes. The classes to be tested were: Issaquah, Super, and Evergreen State. The specific question to be addressed was: are there indeed differences in the waves generated by the various ferry classes

Descriptions of the test procedures followed, instrumentation employed, data reduction procedures, and results obtained constitute the body of this report, and are contained in Chapters IV-VI. All results presented apply for vessels moving at constant speed along a straight course; no curved course or maneuvering tests were conducted.

A secondary objective was to perform a literature search and summarize available information on ship-wave data and methods of wave measurement which might be suitable for ship-wave determination. Chapter II presents a brief review of ship-wave concepts. Chapter III presents a brief review of methods used for ocean wave measurements, with attention being drawn to those procedures which seem best adapted to ship wave measurement.

The list of references cited in Chapters II and III is relatively short, and the two chapters make no pretense to being complete discussions of the topics. The references cited are considered to be representative. Computerized literature search listings were obtained from three sources, utilizing key words: wave measurement, wake measurement, water wave, ship wave (wake), vessel wave (wake), and others. The three sources, and the total number of citations in each, are listed below.

Defense Technical Information Center, Defense Logistics Agency, U.S. Department of Defense: 780.

National Aeronautics and Space Administration, Scientific and Technical Information Branch: 429.

Dialog Information Services, Inc. (search from the National Technical Information Service data base): 46.

The listings from the three searches have been retained by the investigators on this project.

I. CONCLUSIONS AND RECOMMENDATIONS

The procedures used for direct measurement of waves generated by the ferries tested were satisfactory and produced data of sufficient quality to answer the specific question to be addressed: are there indeed differences in the waves generated by the Issaquah, Super, and Evergreen State classes. The instrumentation utilized performed reliably on the whole in the natural (Puget Sound) environment.

It was determined that for vessel speeds above approximately 14 knots, the Issaquah class ferries do indeed produce larger waves than do the Super Class ferries. If relative wave heights produced are a concern, results presented in Chapter VI of this report can be used as an operations guide for establishing vessel speeds on specific Puget Sound routes.

The Super Class ferries are alone among the three classes tested in that they produce no significant increase in height of (primarily) divergent waves with increased vessel speed.

The Issaquah Class ferries also produce smaller waves at high speeds than do the older Evergreen State Class ferries running at the same speeds. There does not seem to have been so much past concern with heights of waves generated by Evergreen State Class ferries, but perhaps this is because of the relatively low maximum speeds which they can attain.

Relatively low-key efforts at using stereophotogrammetry did not produce results that could be incorporated in this report, but could be considered for possible future applications. Aerial photogaphy was used, however, as a valuable data acquisition procedure.

II. SHIP WAVES

This chapter presents a brief discussion of some characteristics of ship waves. While it is not intended as a serious literature review, a number of references are indicated. The discussion emphasizes ship-generated waves in deep water. This choice is considered appropriate with respect to the main objective of the present study, namely, the measurement of waves generated by various classes of automobile ferries operating in Puget Sound. A limited discussion of ship waves in shallow water also is included. The interaction of ship-generated waves with the shoreline is not discussed, although this may be a major concern when vessels operating in deep water sail close enough to shore that waves they generate could possibly have an impact on beaches or coastal facilities along inhabited areas of the shoreline.

The term 'deep water' used above is in reality a relative term, and is related to the ratio of the length of surface, gravity waves to the undisturbed water depth. Pertinent notation is shown in Fig. 2-1, where a series of monochromatic waves of length L and height H are each moving with a phase velocity (celerity) C in still water of uniform depth d. The common linear (small amplitude) wave theory gives the equation

$$C = \frac{L}{T} = \sqrt{\frac{gL}{2\pi} \tanh \frac{2\pi d}{L}} \qquad (2\text{-}1)$$

where T = wave period.

For deep water waves, where the waves do not "feel" the bottom, $d \geq 0.5L$, $\tanh(2\pi d/L)$ approaches unity, and

$$C^2 = \frac{gL}{2\pi}. \tag{2-2}$$

Alternate forms of Eq. (2-2) are

$$L = \frac{gT^2}{2\pi} \quad \text{and} \quad C = \frac{gT}{2\pi} \tag{2-3}$$

indicating that for deep water waves the wave properties depend upon the period and are independent of water depth.

Ship wave systems in deep water tend to approximate the wave patterns theorized by Kelvin for the case of a point pressure disturbance moving at constant velocity over the surface of an initially still, deep, inviscid fluid. The pattern consists of a system of transverse waves following behind the point, plus a series of divergent waves radiating from the point. The most pronounced diverging waves for an actual ship are usually the bow waves, although stern waves are also produced. As a consequence of the fact that in deep water only half of the energy of a wave is propagated with the wave phase velocity, the system of transverse and diverging waves grows in the aft direction and the entire pattern is contained within two straight lines making angles α of 19°28' with the sailing line. The Kelvin wave pattern has been discussed extensively in the literature, e.g., Lighthill (17). Wave patterns produced when the point disturbance ("ship") is moving along a circular path have been discussed by Stoker (27). Details of actual ship wave patterns have been discussed by many authors; representative treatments have been given by Taylor (28), Comstock (7), and Sorensen (24).

The wave pattern created by a ship moving in deep water is shown in Fig. 2-2. According to the Kelvin theory, transverse and divergent waves meet at a common tangent that forms an angle β = 54°44' with the sailing line, and the line of cusps so formed is at the angle $\alpha = 19°28'$ with the sailing line. Kelvin's theory produces infinite wave heights at the intersections of the transverse and divergent waves along the cusp line at $\alpha = 19°28'$; the physical interpretation of the theory is that at these locations the wave heights are greatest and the crests the sharpest, so that at these points, if anywhere, breaking waves will be found.

As documented for a long time, e.g., Hovgaard (13), while in general the wave patterns approximate the Kelvin theory actual wave angles are influenced by vessel speed and hull form. The bow wave system and the stern wave system resemble Kelvin wave groups, but an actual wave group is due to pressure forces spread over the ship hull.

For a ship moving at a constant velocity, the important feature is that the wave pattern of Fig. 2 as a whole moves with the ship, so the transverse waves move in the same direction as the ship with its speed V_s, and have the speed given by Eq. (2-2), i.e.,

$$V_s^2 = C^2 = \frac{gL_t}{2\pi} \qquad (2\text{-}4)$$

The divergent waves, which are the usual waves of concern, will have a different speed in the direction normal to their crest as they move into the undisturbed water. The component of celerity parallel to the sailing line must equal the ship's speed if the fixed wave pattern relative to the ship is to be maintained. The corresponding wave length L_d of the diverging wave is then

$$L_d = \frac{2\pi V_s^2}{g}\cos^2\theta \qquad (2\text{-}5)$$

The forward curvature of the diverging wave crests requires that the wave speed period, and also L_d, must increase with increased distance from the sailing line. In passing, it may be noted that the apparent period T (time between successive wave crests) recorded by a fixed wave gage at a distance x from the sailing line is greater than the effective period associated with the propagating diverging wave and with its properties (including water particle velocities and displacements).

Field measurements by Sorensen (23) indicate that, for a vessel traveling at constant speed along a straight sailing line, maximum wave heights experienced as the envelope of diverging waves passes a fixed point off the sailing line decrease as the offset distance 'x' increases. Also, for a given vessel, heights of ship waves increase with vessel speed; this latter presumes that the submerged hull configuration does not change. These trends have been verified by other experiments in both model and field tests, including recent observations by Nece and Skjelbreia (19) of waves generated by a 40-foot Coast Guard cutter.

Effects of finite water depth on ship waves will now be considered briefly.

As noted above, the waves do not feel the bottom until $d \leq 0.5L$, the limit on deep water conditions. Noting again that the transverse waves are longer than the diverging waves, the limiting depth Froude number, as shown by Sorensen (24) is

$$F_d = \frac{V_s}{\sqrt{gd}} = \frac{C_t}{\sqrt{gd}} = \frac{\sqrt{gL_t/2\pi}}{\sqrt{gd}} = 0.56 \qquad (2\text{-}6)$$

Thus, at depth Froude numbers above about 0.6, the ship-generated wave system will begin to respond to water depth.

Wave-making characteristics of a ship hull are quite sensitive to effects of shallow water. If the ship is treated as being at rest in a flowing stream of finite, restricted depth (but still unrestricted width) the water passing close to and beneath the hull, leading to an increased sinkage, or 'squat'. Squat, in very shallow water, may set an upper limit to the speed at which ships may travel without touching bottom. Further, application of the Bernoulli equation shows that, in addition to squat, increased heights of the ship generated waves must accompany the increased velocities near the hull.

As d/L decreases, tanh $(2\pi d/L)$ approaches $2\pi d/L$ and for shallow water (defined typically as $d < 0.5L$ or $d < 0.4L$) the wave velocity is given approximately by the equation

$$C = \sqrt{gd}\ . \qquad (2\text{-}7)$$

The wave pattern for the traveling pressure disturbance (point) in the Kelvin analysis then must go through a distinct change when $V_s = \sqrt{gd}$, i.e., when $F_d = 1.0$. For disturbance speeds less than 0.6 $\sqrt{gd}$, the wave pattern of Fig. 2-2 is appropriate, with $\alpha = 19°28'$. As V_s increases above this value, the angle α increases and approaches 90° as V_s approaches $\sqrt{gd}$. When $V_s = \sqrt{gd}$ the point is moving forward at the same speed as the wave disturbance it produces, so the entire wave-making is concentrated in a single crest through the point and at right angles to its direction of motion; the transverse and diverging waves have merged into the single wave. All of the wave energy is transmitted with this wave of translation, and the speed is called critical. As a wave traveling in water of depth d cannot have a velocity greater than $\sqrt{gd}$, when $F_d > 1$ no transverse waves can exist and the resulting wave pattern consists of a series of diverging waves which radiate from the moving pressure point and for which the leading wave under these supercritical conditions forms an angle α from the sailing line

$$\sin \alpha = \frac{\sqrt{gd}}{V_s} = \frac{1}{F_d} \tag{2-8}$$

The analogy to small disturbance waves in supercritical open channel flow is obvious. The result of Havelock's analysis for the variation of α with F_d, as reproduced by Sorensen (23), is shown in Fig. 2-3.

Model tests by Johnson (15) were conducted on a series of hull forms towed in deep and shallow water and over a range $0.6 < F_d < 2.0$. Experimental observations generally agreed with the theoretical α vs. F_d variation shown in Fig. 2-3. For a given hull operated in water of constant depth, maximum wave heights increased rapidly as F_d was increased from about 0.6 to about 1.0; most displacement hulls operate in this subcritical range. Hay (11) also showed via model tests that for a hull operating in water at a constant depth, maximum ship wave heights increased relatively slowly with speed in deep water (depth Froude numbers up to 0.6), and then increase much more rapidly with subcritical vessel speeds when F_d exceeds 0.6 to 0.7.

One of three representative data plots (curve only) presented by Johnson (15) has been replotted in Fig. 2-4, where the data for a model ship with "good" lines have been converted using Froude law scaling at 1:30 scale ratio.

Equivalent prototype dimensions for the vessel are: length ℓ = 99.6 ft, beam = 28.2 ft, draft D = 4.0 ft, displacement = 125 tons; the water depth is 15.6 ft. At F_d = 0.8, the vessel speed is 17.9 fps = 10.6 knots. The indicated wave heights plotted on the figure are those occurring at x/ℓ = 0.9, or at x = 90 ft. The data set from which Fig. 2-4 was derived also verifies that maximum wave heights decrease slowly with increasing distance x from the sailing line.

To put Figs. 2-3 and 2-4 in perspective with respect to the present study, required vessel speeds for F_d of 0.5 for discrete water depths are listed in table 2-1. The brief tabulation shows that limited depth effects are of little concern for most ferry operations on Puget Sound.

Table 2-1

Vessel speeds to achieve F_d = 0.5

Water Depth		Vessel Speed	
Fathoms	Feet	Knots	Ft/sec
10	60	13.0	22.0
20	120	18.4	31.1

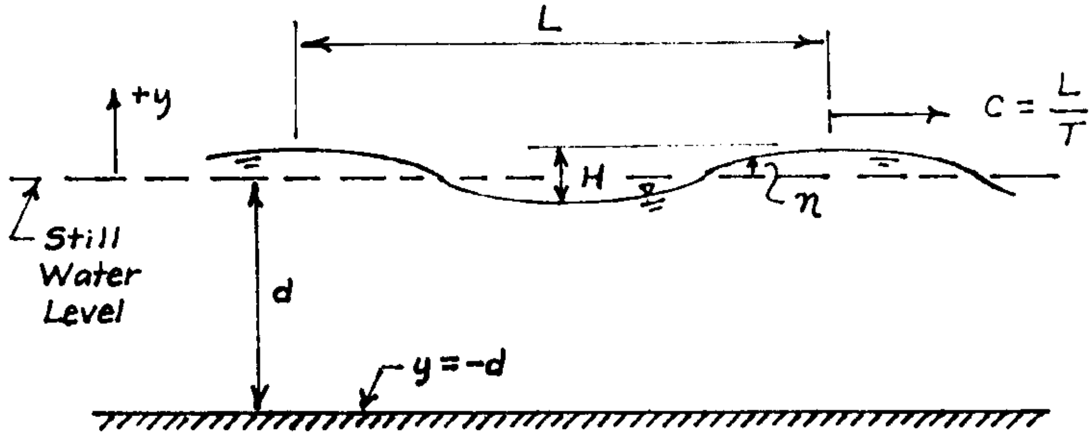


Figure 2-1. Definition Sketch for progressive surface wave.

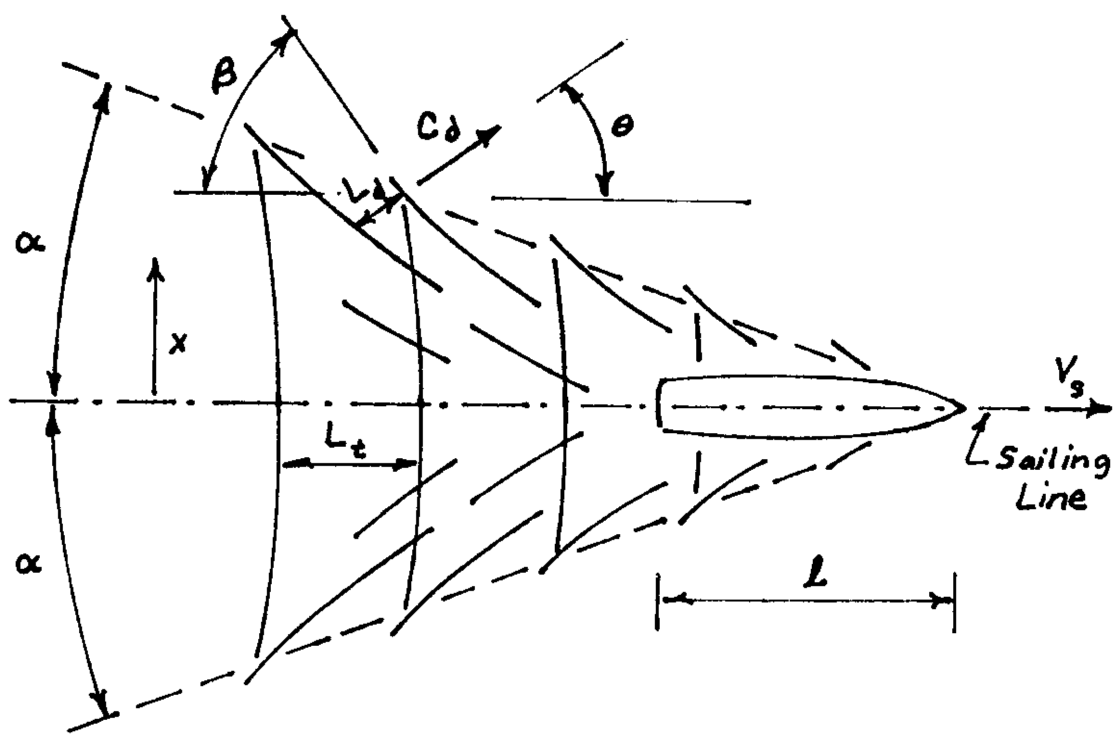


Figure 2-2. Ship wave pattern in deep water.

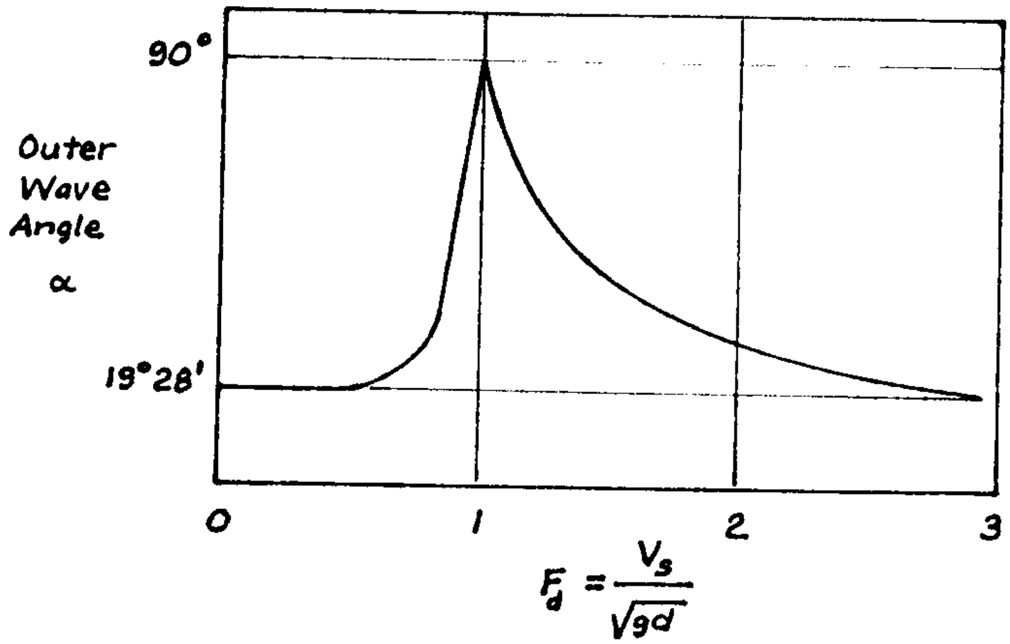


Figure 2-3. Outer wave angle as a function of Froude number.

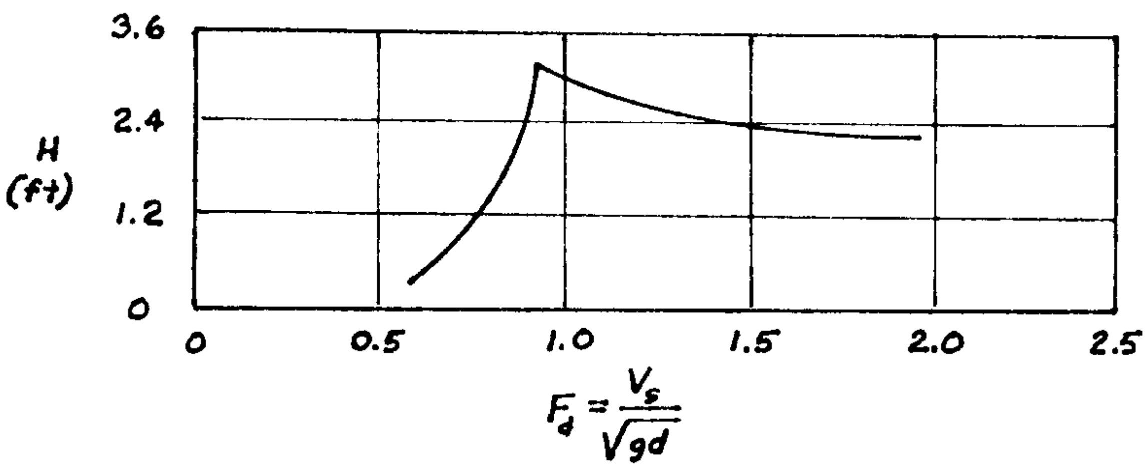


Figure 2-4. Typical behavior, wave height vs. Froude number, at a fixed distance from sailing line (calculated from results in Ref. (15)

III. WAVE MEASUREMENT TECHNOLOGIES

A. Introduction

This chapter discusses, in rather general terms, a variety of wave measurement technologies, with emphasis on methodologies for measuring ocean wave phenomena. Data sampling, reduction, and analysis techniques have become more diverse and sophisticated with continuing advances in the response and capabilities of wave instruments. The organization of this chapter draws heavily on a fairly recent survey by Ribe (22), the objective of which was to determine the (then) status of ocean wave sensors and organize the available literature in a logical manner; a good bibliography was included, and readers of this report are referred to it for more detail than is included here. Mention of commercially available products in this report is not an endorsement, and those listed are examples; there is no effort to make a complete list of commercial products.

In the discussion to follow emphasis is placed on nondirectional wave sensors. Nondirectional sensors sum the contributions of waves arriving at the sensors from all directions. For many purposes, including the present wave study, this information may be adequate.

It is appropriate to, first, mention the traditional (and almost immediately available) visual estimate by observers of both wave height and direction. As indicated by Wiegel (30), among others, visual estimates of waves in a natural sea state are related to the significant wave height (average height of the highest one-third of the waves). Visual estimates can be refined or improved by using telescopes to observe water level variation at buoys or pile-mounted gages with marked scales. In the absence of such visible scales, the accuracy of the estimates will vary with the experience of the observers; this is particularly true for shipboard observations. An additional problem of visual estimates of ship waves is the short period of record.

B. Nondirectional Wave Sensors

1. Wave Staffs

A wave staff is a fixed vertical member piercing the water surface and producing an output which is a function of the water level on the staff. The measurement procedures are relatively simple and economical.

a. Resistance staffs. The most common type of wave staff is the electrical-resistance type. For short staff lengths, the resistance element could be a small-diameter vertical wire, or a pair of closely spaced parallel wires; these approaches are common in laboratory applications. For longer staffs, it is more common to use wire which is helically wound on an insulating member which contributes the necessary structural strength. In either configuration, the overall resistance of the gage is decreased as more of the wire becomes short-circuited with immersion. The helical winding allows finer wires to be used (increasing resolution), increases the resistance per unit length of wave staff, and reduces the possibility of wire breakage from stress contributed by the flexing of the staff itself.

Step-resistance staffs utilize a vertical array of closely spaced electrodes. For either type of staff, structural strength is a concern if large tidal ranges are present.

For ocean wave measurements, the insulation and strength contributing materials are selected for their fouling resistance and their ability to quickly shed water films as each wave recedes. For short-period measurements such as made in ship wave studies, the fouling question may not be so important. Alternating current is used to drive wave staffs used in salt water to avoid corrosion effects which could occur if direct current were used. Resistance staffs can be designed and fabricated by users to be in compliance with their individually designed electronic circuitry for driving the staff and for data acquisition and processing.

Step-resistance staff gages have been used in a number of ship wave studies in the United States; three are listed here. Sorensen (23) used a gage with 0.2-foot steps in a study of ship waves conducted in the Oakland Estuary; the U.S. Army Corps of Engineers (29) used gages with the same interval in a study of ship waves in the Detroit and St. Clair Rivers. Bhowmik et al. (3) used a pole-mounted gage with finer, 0.05-foot, increments in the studies of waves generated mostly by barge tows in the Mississippi and Illinois Rivers; they present details of their circuitry in the referenced report.

b. Capacitance staffs. One conductor is internal to the staff, running the length of the staff and sealed from the water by a covering of insulating material which serves as the dielectric. The outer water serves as the other conductor. The capacitance is proportional to the length of the vertical staff immersed, hence to wave height, and is expressed by the relationship

$$c = \frac{2\pi eh}{\ln(d_2/d_1)} \tag{3-1}$$

where c is the capacitance, e is the dielectric (insulation) permittivity, d_2 and d_1 are the outer diameter of the staff and diameter of the inner conductor, respectively. The capacitance, and hence sensitivity, is seen to increase as $(d_2 - d_1)$ becomes small, i.e., with thin insulation. The thickness of the insulation is a compromise between durability and fouling effects; improved electronics permits use of a heavier insulation.

c. Electromagnetic staffs. Two types of electromagnetic staff have seen fairly wide use; they are both commercially available units.

A transmission-line wave staff, marketed by the Kelk Co., Toronto, Canada, is composed of two concentric metal tubes, spaced apart by insulators, which serves as a vertical waveguide for electromagnetic pulses moving vertically up and down the annular space between the tubes and bouncing off the water surface at the immersion level of the staff. The active element is a bistable diode which produces the pulses when it receives pulses reflected from the water surface. The device is vented to allow rapid equalization of water levels.

A staff produced by the Baylor Corporation, Houston, Texas, consists of two vertical stainless steel wire ropes held apart by mounting blocks and intermediate spacers. An oscillator at the top of the staff sends a continuous radio-frequency wave down the ropes, and associated circuits measure the standing wave ratio (which is proportional to the length of the exposed staff).

These gages seem to behave well. No cost data were obtained for this report. In both cases, the entire package would be obtained commercially.

2. Pressure Transducers

Pressure transducers, mounted at or near the bottom, are frequently used to record wave-induced pressures in shallow water. According to Ribe (22), the maximum recommended depth is about 50 feet. The problem is that bottom pressures do not directly reflect wave heights, because pressures induced under a wave are highly attenuated with depth below the water surface and are a function of total water depth, transducer elevation, and wave period (or wave length). The pressure at a sensor elevation $-y$ with respect to the mean water level (see Fig. 2-1), under sinusoidal monochromatic waves, and expressed in terms of the equivalent height term of pressure head is

$$\frac{p}{\gamma} = K_p \eta - y \qquad (3\text{-}2)$$

where η is the water surface displacement from the mean level and K_p is the pressure response factor defined as

$$K_p = \frac{\cosh \frac{2\pi}{L}(d+y)}{\cosh \frac{2\pi d}{L}} \qquad (3\text{-}3)$$

As d/L increases, and as y approaches -d (i.e., is located near the bottom) K_p decreases. Further, as real waves are rarely sinusoidal, errors are introduced. Also, as pointed out by Eagleson and Dean (9), at a given elevation y the pressure response factor is different for different wavelengths and so damping is selective. Sinusoidal components must be obtained by Fourier analysis, and the individual components must be corrected by the pressure attenuation relation.

Other problems faced by pressure transducers include transducer noise, resolution error, tide effects, and possible non-wave pressures such as might be caused by turbulence and currents depending on the transducer orientation. As opposed to wave staffs, hard-wiring to shore-based electronics would be underwater.

3. Inverted Echo Sounders

These upward directed sonar devices have a subsurface projector-receiver transducer. Pulses reflected from the water surface are processed electronically, return-trip transit times of the acoustic pulses are measured, and variations in the round-trip transit time are interpreted as a measure of the surface waves above the transducer. Both self-contained and hard-wire linked systems are commercially available.

Use of this type of sensor has been aimed more at ocean wave measurement rather than to wave measurements in shallower, or relatively protected, inland water bodies such as Puget Sound. For example, Ribe (21) describes one commercial device as having a beam width narrow enough so that waves of T = 7 seconds (L = approximtely 250 feet) can be recorded in depths of 2,000 feet.

4. Wave Buoys

The big advantage of buoys is that they allow measurements in deep water where no mounting structures are available. The disadvantage of these devices is the incomplete knowledge of their dynamic response in high, steep waves.

a. Spar buoys. A spar buoy is a long, vertical cylinder with usually 70 percent or more of its length always submerged, with the upper, surface-piercing portion serving as the sensor. The lower end of the buoy is usually weighted for stability and also is usually equipped with a damping plate to reduce vertical oscillations caused mainly by buoyancy force changes as waves move by the buoy and its immersion changes. Resistance-wire wave staffs are most commonly employed. Relationships between overall length, weight, and strength depend on such questions of wave height frequency to be encountered and measured and how the buoy will be transported, deployed, and retrieved.

Colburn et al. (6) described a representative large spar buoy used for ocean wave measurements. It had a 47-foot overall length, with a 4-inch diameter main body, and a 2-inch diameter surface-piercing mast section containing a 10-foot long capacitance-type wave gage, and a 4-foot diameter damping plate equipped with a cylindrical rim. The natural period of oscillation in heave was estimated to be nearly 33 seconds, long with respect to periods of anticipated waves. A battery powered digital cassette recording device was mounted on the spar buoy, thus eliminating the usual tethering or telemetering problems.

The wave sensors used in the present study were spar buoys, and are described later in this report. They are essentially the same unit which has been used in earlier wave studies, associated with floating breakwater studies, in western Washington and in Alaska. A description of an early system incorporating these resistance staff units was given by Adee et al. (1). These spar buoys also have operated with cassette recorders.

b. Wave follower buoys. The most common type of sensor used in wave follower buoys is an accelerometer. If the accelerometer is the only sensor, the buoy measures wave height but not direction. The accelerometer signal is integrated twice to provide a signal output proportional to displacement (wave height). Wave direction as well as height information can be obtained through combinations of accelerometers, gyros, and a compass. The accelerometer-type buoy is relatively portable, can operate without mooring system requirements, and is comparable in cost to other commercially available wave instruments. The engineering of the units varies with accuracy requirements.

Perhaps the non-directional buoy most widely used on a worldwide basis is the Datawell Waverider, produced by Datawell-b.v. of the Netherlands. It also is perhaps the most sophisticated commercial unit. It consists of a stainless steel sphere of 0.7 or 0.9-meter diameter containing the accelerometer, signal-processing circuitry, and radio transmitter for telemetry, all battery operated. Tether designs vary according to wave, tide, and current conditions at the site. The accelerometer is gimballed to keep it vertical under wave action on the buoy. Datawell provides correction relationships for errors at the high- and low-frequency ends of the wave spectrum. The response of the

Waverider and other accelerometer buoys to very high and/or very steep waves has not been fully established. In many cases, the Waverider has provided information on ocean waves where no other data sources were available.

The NOAA Data Buoy Office has equipped their 12-meter diameter discus buoys used for environmental monitoring with accelerometer-based wave measurement systems. Given the size of the buoys, they would not be appropriate for measurements on relatively protected, inland waters. These buoys use non-gimballed accelerometers.

Other gimballed accelerometer wave buoys include the Environmental Devices Corp., Marion, Massachusetts, Type 949 WAVE-TRAK device, which has a cylindrical accelerometer housing attached below a spherical float and thus acts as an inverted pendulum, and a unit developed by the National Research Council of Canada.

Another type of wave follower is one which measures water surface displacements by sensing pressure changes at a transducer suspended below the buoy. The transducer has to be far enough below the water surface that wave induced pressures, as indicated in Eq. (3-2), have been attenuated so that pressure changes measured by the transducer are mainly the result of vertical motion of the buoy.

5. Others

Shipborne wave recorders have received most of their use in Britain. The recorder consists of two packages attached to the inside of the hull, near midship and well below waterline. Each package contains a pressure transducer (which senses pressures through a hole drilled in the hull) and an accelerometer. Measurement capability depends on how well the characteristics of the system are known for the particular ship in which it is installed for a variety of wave conditions and ship speeds. This device would not, of course, provide information on waves generated by the ship.

Downward directed sonic instruments are widely used for making depth measurements in calm water but are not widely used for ocean wave measurements.

The development of laser-based wave systems is still proceeding.

Some information on these devices, as well as pertinent citations, are given in the report by Ribe (22).

C. Directional Wave Sensors

The question of wave direction measurements in natural sea states will be treated here briefly because it is not a major concern as far as the specific objective of the present study is concerned i.e., measurement of heights of waves generated by a few specific vessels (Puget Sound ferries). Nevertheless, there continues to be continued activity in developing wave direction measurements and techniques. Engineering and scientific needs for relatively simple and economical procedures for determining adequate directional properties of waves have been discussed by Dean (8). One problem is the large amount of information that is necessary to properly describe wave magnitude, frequency, and direction. Problems, advances, and applications of determining wave directional spectra were high-lighted in a 1981 American Society of Civil Engineers conference devoted to the topic (2); readers are referred to the conference proceedings for particulars.

1. Wave Staff Arrays

The most common type of instrumentation used for directional spectra determination are arrays of wave staffs. The staffs might be mounted on a pier, in the case of measurements in such near-shore locations, or can be restrained in position in deeper water by properly designed tethering, or mooring, systems. Resistance wire staffs on spar buoys of the same design as used in the ferry wave study have been deployed in a directional array to obtain wave directional spectra in a recent field study of behavior of a prototype floating breakwater in Puget Sound. Details of the array configuration, data processing, and results have been given by Ratnayake (20), who also lists pertinent recent references.

Pressure transducer and inverted echo sounder arrays have received limited use and investigation for directional measurement of waves. Again, cost and deployment advantages of wave staffs are important, in addition to direct measurement capacity of water surface displacements. Ribe (22) lists a number of spar buoy arrays which have been experimented with earlier.

2. Other Instrumentation

Buoy motions can be used for measurement of wave direction. The pitch-roll buoy, in addition to their vertical accelerations as measured by the Waverider, provides a measure of direction by measuring orthogonal components of wave slope with respect to some directional reference. The pitch-roll buoy is considered to be the simplest and most widely accepted directional buoy, but it does lack resolution and may be too complex for some purposes. Ribe (22) describes a number of such devices which have been developed by different organizations.

A variety of devices have been designed to derive wave directions from measurement of wave-induced forces on the instrument. These devices, a number of which are described by Ribe (22), are subject to drag coefficient dependency on Reynolds number and, more importantly, to attenuation of wave-induced velocities with depth below the water surface. Accordingly, it may be more practical to use a separate sensor (e.g., wave staff) to measure surface displacement, and use the force-vector device to correlate waves with direction.

Fast response current meters with a 360° directional capability and positive-negative sensing can be used to measure wave directions. They are subject, also, to velocity attenuation with depth; a staff measurement would be needed to get the wave height.

Techniques using radar or radar-laser combinations are still being developed. Two radars can be used together to produce images of wave patterns and wave heights. It sill remains to develop economical data recording and analysis techniques. Hammond (10) has discussed problems of adapting one radar system to taking measurements from a moving vessel.

3. Stereo Photography

This procedure is discussed separately because some efforts were made to use it to obtain supplementary data in the present study. The concept is simple, the accomplishment not easy. Simultaneous stereo photographic pairs must be obtained from two cameras of known spacing and height obove the water (usually mounted on two airplanes flying in formation) and with a distance scale in the photographs. Interpretation of the photographs requires special apparatus - i.e., stereo plotters.

Results of a study conducted off the Dutch coast in conncection with a JONSWAP program were presented in brief form by Holthuijsen (12). Cameras were mounted in separate helicopters. About 600 stereo photo pairs were obtained, of which 40 pairs were selected for analysis of waves under different wave generation situations. Although no details of the logistics are given, the author's acknowledgments indicate that this support was indeed significant and, by implication, expensive. Kinsman (16) has provided a good summary of why the execution of wave measurements by stereo photography is anything but simple. One important consideration (encountered in the present study) is that field conditions are completely out of control, and the availability of the required, specially equipped aircaft is useless unless sea, weather, and lighting conditions are satisfactory. Another difficulty is the lack of points in the photographs whose exact elevations, or exact elevations with respect to each other, are known. Stereo photographic analysis of ship waves generated by model ships in a laboratory tank, using fixed cameras, has been described by Sorensen (26).

IV. DESCRIPTION OF EXPERIMENT

This experiment involved the direct measurement of wave height at the sea surface, and the use of aerial photographs to provide additional, supporting data. This chapter will be divided into three parts. The first part will describe the instrumentation. The second part will describe the sea surface measurements and will present all such details as dates, times, locations, operating conditions and vessel data. The third part will discuss the photographic effort.

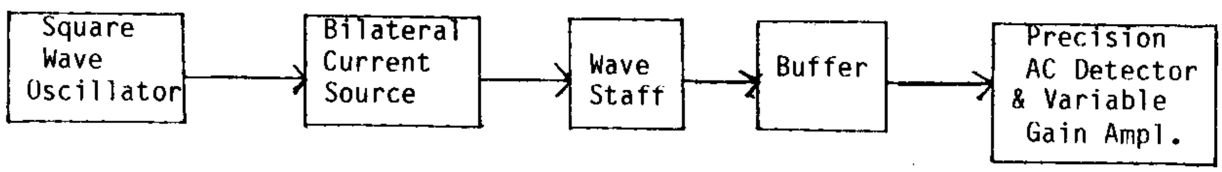
A. Instrumentation

The experiment was designed to measure waves at three distances from the sailing line of the vessels. Three wave measuring staffs were deployed from a 30 foot sailboat on a single mooring line as depicted in Figure 4-1. One end of the array was secured to a fixed buoy and the other end was held in position by the sailboat, which was operated under power to keep tension on the mooring line. The distances between wave staffs shown in Fig. 4-1 are nominal values for a straight, but unstretched mooring line. Under actual field conditions these distances could vary significantly and needed to be measured during the experiment.

An example of the wave staffs is shown in Fig 4-2. They are an electronic resistance type developed at the Civil Engineering Department of the University of Washington. They were chosen because of their accuracy, reliability, relative ease of deployment and availability. These staffs are the spar buoy type, with a damping plate mounted on the bottom to increase the buoy's resistance to vertical motion in the presence of waves. All electronics are located in the thinner top section; the bottom section provides buoyancy. In the configuration used in this experiment, shown in Fig 4-3, the staffs received their power from a generator on the boat maintaining the staff array, via an electrical cable attached to the mooring line.

All signal conditioning was accomplished by electronic circuitry inside the staff, where an output voltage was made proportional to the height of the water surface. The voltages from all three staffs were returned to the sailboat for recording via the same electrical cable. The following technical description of the wave staffs is taken from a report by Christensen, (5).

A block diagram of the wave staff and associated electronic circuits is shown below:



The wave staff itself consists of a length of PVC tubing which is spirally wound with a resistance wire, such that when it is immersed in sea water, the electrical resistance varies in direct proportion to the length of the exposed staff.

The electronic circuits driving the wave staff consist of a fixed frequency square wave oscillator, (having a precisely controlled output amplitude), driving a precision bilateral current source with an output current directly proportional to the input voltage. Thus, the wave staff is driven by a current source of constant magnitude, but one which changes direction with each half cycle of the square wave oscillator. The output of the wave staff then is a square wave voltage with a magnitude, (peak-to-peak), that is directly proportional to the length of exposed wave staff. This output is fed to a high input impedence voltage follower circuit which serves as a buffer between the wave staff and the AC detector circuit. The precision AC detector circuit uses two operation amplifiers in conjunction with two diodes to form a precision full wave rectifier circuit that is capable of operating at very low input voltages. Ordinary diode detector circuits cannot operate on AC signals of peak magnitude less than the forward voltage drop of the diodes and produce large conversion errors unless the signal magnitude is large with respect to the diode voltage drop. A gain control has been incorporated in the detector circuit so that full scale output can be set at any positive value up to +10 volts with a wave staff resistance of 300 ohms up to 3000 ohms.

Alternating current is used to drive the wave staff to avoid both the corrosion effects that would occur if direct current were used and the DC offset which occurs as a result of the use of dissimilar metals in a conducting solution. The latter is eliminated by use of AC coupling in the output from the wave staff.

Bench tests of the wave staff electronic circuits were made using a 1000 ohm variable precision resistor in place of the wave staff. The circuit was adjusted to produce an output range of 0 to 10 volts with the resistor varied from 0 to 1000 ohms. Linearity was determined to be 0.1% of full scale over this range.

The spar buoys were made of two PVC pipes coupled together near the center of the buoy. The lower section is a 15' x 6" pipe filled with styrofoam. The top section is 12' x 3" wherein the upper 8 feet is wound with a resistance wire which measures wave height. The wave staff electronics are mounted inside the top section, above the waterline with the remainder being filled with a foam core to add stiffness. The buoys also have a 2.5 foot diameter damping plate mounted on the bottom and are anchored using a dual point mooring system with the anchor lines attached at the center of drag on the buoy to prevent it from being pulled underwater in strong currents.

In 1975, one of these buoys was tested in the Puget Sound just north of Seattle. Its performance exceeded expectations both in terms of minimized response to the waves and accuracy of wave height measurement. The natural periods for heave and roll taken from these plots are approximately 18 and 14 seconds respectively which are well out of the range of maximum wave periods expected in this study (of ferry-generated waves). Visual observations of the buoy in waves in excess of 1 1/2 feet indicated no heave or roll motion, but some yaw about the anchor line caused by the current and wind. This motion resulted in less than a one foot variation from the buoy's horizontal position in calm water and appeared to have periods in excess of 30 to 60 seconds. For comparative measurements, the buoy was located about 30 feet from an existing one-inch diameter resistance wire wave staff mounted in a stationary piling. Autospectra computed from the data obtained from each of the two wave staffs were in close agreement.

The recording system comprised a Gould model 220 analog strip chart recorder, a Gould model 2200 analog strip chart recorder, and the Nicolet model 4094 digital oscilloscope.

The Nicolet oscilloscope contains a floppy disk so that in this application it was used as a digital data acquisition system. As configured it recorded a single channel. A manual switch allowed the operator to select which of the three buoys to record. Under normal circumstances it was possible to obtain a digital record of the ferry wake as it passed each of the wave staffs by a proper selection of channels. Each of the Gould models recorded two analog channels. The four channel total provided a complete paper record of each of the wave staffs as well as a paper record of the channel selected for the digital system.

B. Sea Surface Measurement

The experiment measured the wake of three different classes of ferries operated by the Washington State Ferry System. Figure 4-4 shows a side view of these vessels and the captions give the names of the vessels used in the tests along with some general dimensions. Notice that two different ferries were used to represent the Evergreen State class. The two vessels are essentially identical and the results for these two should be interchangeable. The three vessel classes represented in the tests comprise over half the total fleet operated by the state.

An individual vessel run involved sailing the ferry past one end of the array on a fixed course at a constant speed, in a direction as perpendicular to the mooring array as circumstances allowed. The problem was not only to measure the wave heights but also to be able to determine the distance from the sailing line of the ferry to each of the wave staffs (x_1, x_2, x_3 of Figure 4-1). To obtain these distances, each run included a record of the relative positions of the wave staffs, the distance of the ferry from the nearest staff and the angle between the sailing line of the ferry and the mooring array. This record was obtained from aerial photographs when possible, otherwise it was obtained by visual observation from the ferry and from the sailboat. Experience proved that changing wind and current could lead to significant differences in angle and position of the staffs over the course of a day. In addition, it was desired to measure vessel speed directly in preference to using sea trial performance data, which were available for only two of the three vessel classes. An effort was made to use a sequence of aerial photos of the same run to determine vessel speed. This turned out not to be very successful, and in most cases the ferry speed was determined indirectly from a record of the vessel's engine RPM and performance data. A detailed discussion of the determination of distance and speed is presented in Chapter V. Locations, times, distances, and speeds of all the runs are summarized in Table 6-1.

The tests began with the ferry Sealth, of the Issaquah Class, on 17 September 1984. The U.S. Coast Guard had given permission to tie the wave staffs to buoy "SF", off Pt. Jefferson, shown in Figure 4-5. The wave staffs were strung out to the north, with the sailboat holding the north end. This direction happened to be in line with both the current and the wind during the tests that day. The Sealth started its runs on either the east or west side of Puget Sound, and would pass just south of "SF' as it moved across the Sound to the other side. The direction of each run is noted in Table 6-1.

The light, southerly wind did not generate any significant wind waves, permitting a clear, uncluttered output signal. The wave staffs and recording gear worked reliably all day long.

The ferry Tillikum, of the Evergreen State class, was tested on 19 September 1984, at the same site used for the Sealth. The wave staffs were strung out to the south this time, with the sailboat holding the south end, because of a north wind. This wind was strong enough to create a significant sea state, producing very noisy output signals. Furthermore, failures in the signal conditioning circuitry eliminated the first and third wave staffs, so that data could be acquired only at the middle distance. Because of these problems the test was cancelled after four runs, and none of the Tillikum data are used in this report.

The sea state encountered during the Tillikum runs, and the fact that availability of a ferry of the desired ferry class could not be guaranteed until later in the year when weather conditions might be poorer, led to a decision to select a more sheltered site on the northwest side of Blake Island, shown in Figure 4-6. On 23 October, the wave staffs were tied to one of several Washington State Park Department mooring buoys that are permanently anchored near shore (shown by arrow in Figure 4-6), and were strung out to the west to make a line perpendicular to the shore. This test differed from the earlier ones in that the sailboat holding the wave staffs in position was at the end closest to the passing ferries, but the spacing of the buoys relative to the ferry remained the same. The ferry runs passed in a generally north or south direction, parallel to the west shore of Blake Island.

The ferry Yakima, of the Super Class, was tested during the morning of the October 23. The ferry Klahowya, of the Evergreen State Class, was tested in the afternoon, providing data that were to have been collected from the Tillicum. The runs are tabulated in Table 6-1.

All equipment worked well during the tests. The morning runs occurred in light winds with very small wind waves. By the afternoon the wind had increased, generating enough of a sea to show up on the trace but not so high as to hide the ferry waves. An unexpected difficulty arose, however, due to a strong northerly current running through the operation area, parallel to the shore. This current, probably an eddy off the main Puget Sound tidal current, forced the line of wave staffs to angle out northwest from the shore by varying degrees throughout the tests. During the Yakima runs the angle between the ferry course and the mooring line (angle a of Fig. 4-1) was estimated visually by an observer on the board the ferry. Most of the

Klahowya runs have aerial photography to determine the position of the wave staffs.

C. Aerial Photography

The Washington State photogrammetry section was scheduled to provide aerial photography of each of the runs. These photographs serve several purposes. So long as the waves produced by the vessel are clearly visible in the photographs, one can obtain by direct measurement estimates of the wavelengths of the waves and the angle the waves make with the sailing line of the vessel, information that can not be obtained from the wave staffs alone. The photographs also provide the best means of determining the distance between the vessel and the wave staffs. In addition, vessel speed was to be checked by measuring the change in vessel location in sequential photographs.

Photographs from a single aircraft can satisfy the above requirements, but while planning the photographic mission the possibility of obtaining stereo images of the sea surface came under consideration. The great advantage of stereo photographs is that they should provide measurements of wave height over a continuous region of the image, yielding much more data than produced by the three wave staffs alone. Operationally, stereo imagery of a moving surface requires simultaneous, overlapping photographs from two distinct points, ie., two aircraft flying in formation, as discussed in Chapter III. Neither the state photogrammetry staff nor any of the ferry wake staff had had any prior experience with this specific application. It appeared that the idea should work in principle, but that there were numerous practical challenges. Nevertheless, the possibility of utilizing a measurement technique that was more effective and cheaper than traditional methods spoke in favor of the additional effort of a second aircraft. A second aircraft with a suitable camera was available, and it was decided to attempt stereo photography of the ferry wake.

The discussion that follows is intended to provide a brief review of some of the operational considerations of the aerial photography mission. It is included for the record and because it may help future investigators planning to use the technique; in fact, at the time this report was prepared, no use had been made of the stereo photos. A more technical review of the general problem may be found in Moffitt (18). Fig. 4-7 is a sketch (greatly simplified) of the optics of an aircraft camera. The focal length, f_ℓ, and the size of the film plate, ℓ, are fixed by the camera design. The cameras used in this experiment take a square picture; by the law of similar triangles the length of a side of that square, L, is controlled by the height of the aircraft above the ground, H, according to the ratio:

$$\frac{L}{H} = \frac{\ell}{f_\ell} \qquad (4\text{-}1)$$

In the cameras used in this experiment, f_ℓ is 6 inches and ℓ is 9 inches. A picture taken at a height of 3000 feet, for example, would have a field of view that was 4500 feet on a side.

The choice of altitude for a photo mission must satisfy competing requirements. The camera must be high enough so that the field includes adequate reference points. It must be low enough to provide sufficient visible detail. Stereo photography imposes the additional requirement that there be overlapping photos to provide the parallax that produces a stereo image. Sixty percent is considered the optimum overlap between adjacent photos. Normally, this is achieved, when a still or stationary ground surface is to be measured, by one aircraft taking a sequence of photos along a straight track. The rate at which pictures are taken is matched to the speed of the aircraft and the altitude to produce the desired overlap.

In the case of a moving water surface, however, the overlapping photographs must be taken at the same time to avoid allowing the surface to change form in the interval between photos which supposedly are taken simultaneously from the two aircraft. In this experiment a voice countdown procedure over the radio was used for communication between the two aircarft to synchronize the photographs.

The desire to keep the photo overlap near the optimum sixty percent means that the two aircraft must maintain a fixed distance apart during the photo run, the distance depending upon the altitude. The operational challenges may be summarized as follows: the aircraft must manage to get over target area (ferry passing the wave staff string) at the same time as the subject vessels, while holding a constant relative position, with both cameras in the same vertical axis orientation, and must take their photographs simultaneously. Each day's experience during the experiment led to changes in the way these problems were attacked.

The first plan had the aircraft flying at 12,000 feet on the September 17 tests of the Sealth to assure that each photograph would have some known land features in it, to aid the stereo analysis. At that altitude the aircraft were positioned far enough apart that they relied on electronic navigation to stay on course and maintain formation. The aircraft courses were laid out at right angles to the ferry courses, and the pilots depended on a starting signal from the ferry and their own visual judgement to make an interception in the target area.

These first attempts at stereo wave photography were not successful, primarily due to the failure of some navigation equipment on board one of the aircraft. Overlapping pairs of photographs were obtained for only one of the ferry runs that day, but the combination of high altitude and poor lighting proved unusable. Fortunately, for most of the runs at least one of the aircraft did get the photographs needed for measuring distances, angles, and ferry speed. This last point is considered in more detail later.

The next photo missions, on 19 September, started with the same plan as on the 17th, and the first two ferry runs were photographed from an altitude of 12000 feet. Because of cloud cover and because it was becoming apparent that there would be little or no sea surface data because of the natural sea state produced by the winds for the day, the last two runs were photographed from 3000 feet to improve the resolution of the pictures. These two runs produced the only photographs of the entire experiment which had any chance of working as stereo pairs.

Based on the experience of the first two days, the photo mission for the final test at Blake Island was considerably revised. The plan put the aircraft at 2400 feet, with the idea that the vessel itself would provide adequate elevation and horizontal distance reference points. This altitude also kept the aircraft below the Terminal Control Area for the Seattle - Tacoma International Airport; the presence of controlled airspace proved to be an important consideration in making operational plans. The aircraft flew the same course as the ferry, coming up on the vessel from the rear. The two aircraft flew in line rather than trying to keep position abreast. The pilots reported that this approach made their task considerably easier; the higher percentage of acquired pairs at Blake Island affirmed this.

Unfortunately the weather nullified the improved efficiency of the operation. The tests at Blake Island started in a low overcast with light rain, preventing any aerial photography at all during the Yakima runs. The overcast did not lift enough to permit flying until the last half of the Klahowya runs, and even then the flat, grey lighting reduced the contrast on the sea surface to the point where ferry wake was invisible in all but a few photographs.

The poor lighting was a disappointment not only to the researchers but to the photo crews as well, who had worked hard at learning to perform a new and difficult task, only to be denied the chance to produce results. The photographic effort at Blake Island was not wasted, however. The photos provided the means of determining distances from the ferry to the wave staffs on a day when a nearshore current forced the staff array into an extreme angle with respect to the course of the vessel.

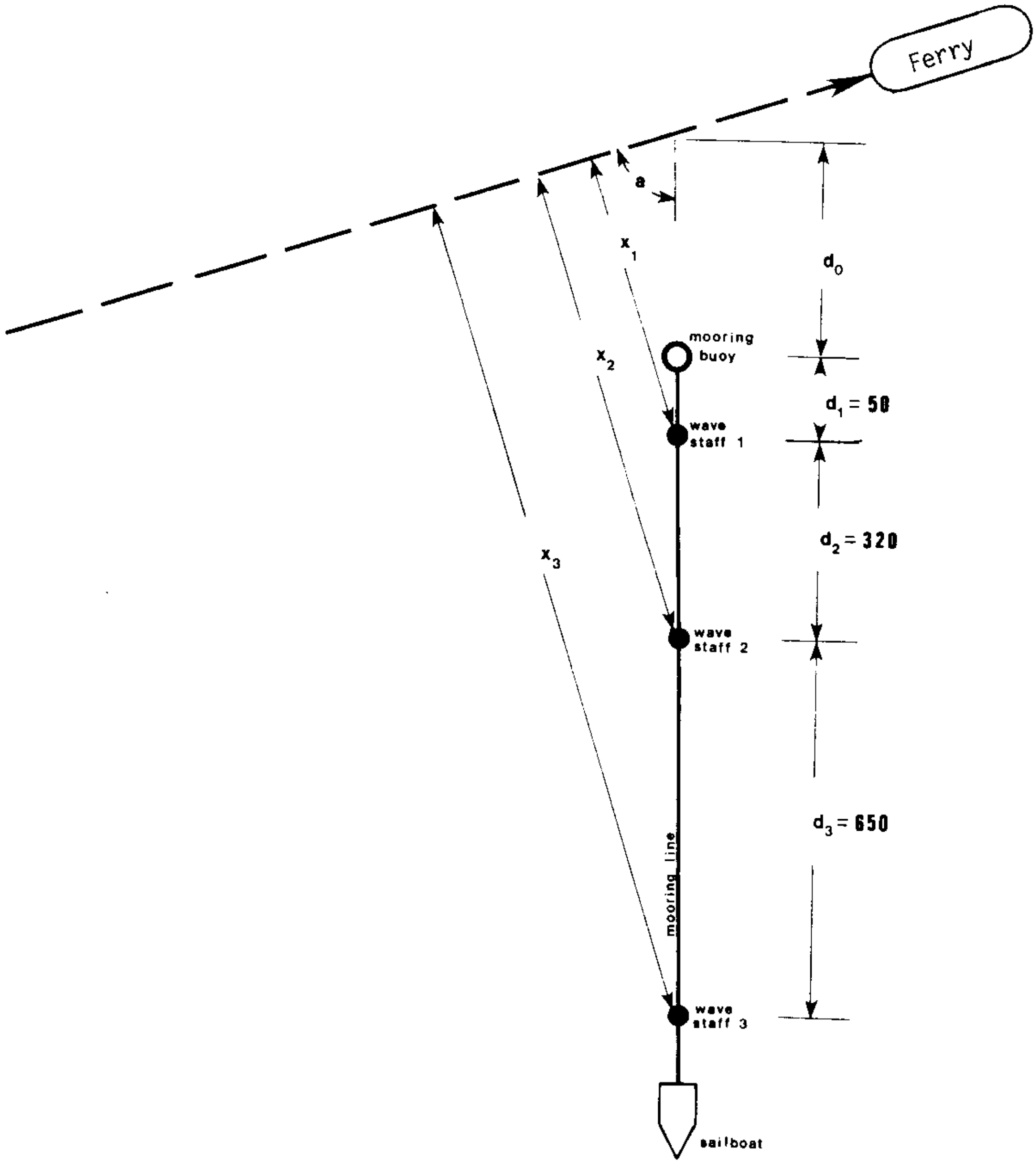


FIGURE 4-1

Deployment of the wave staff array on a mooring line stretched between an anchored mooring buoy and a sailboat under power.

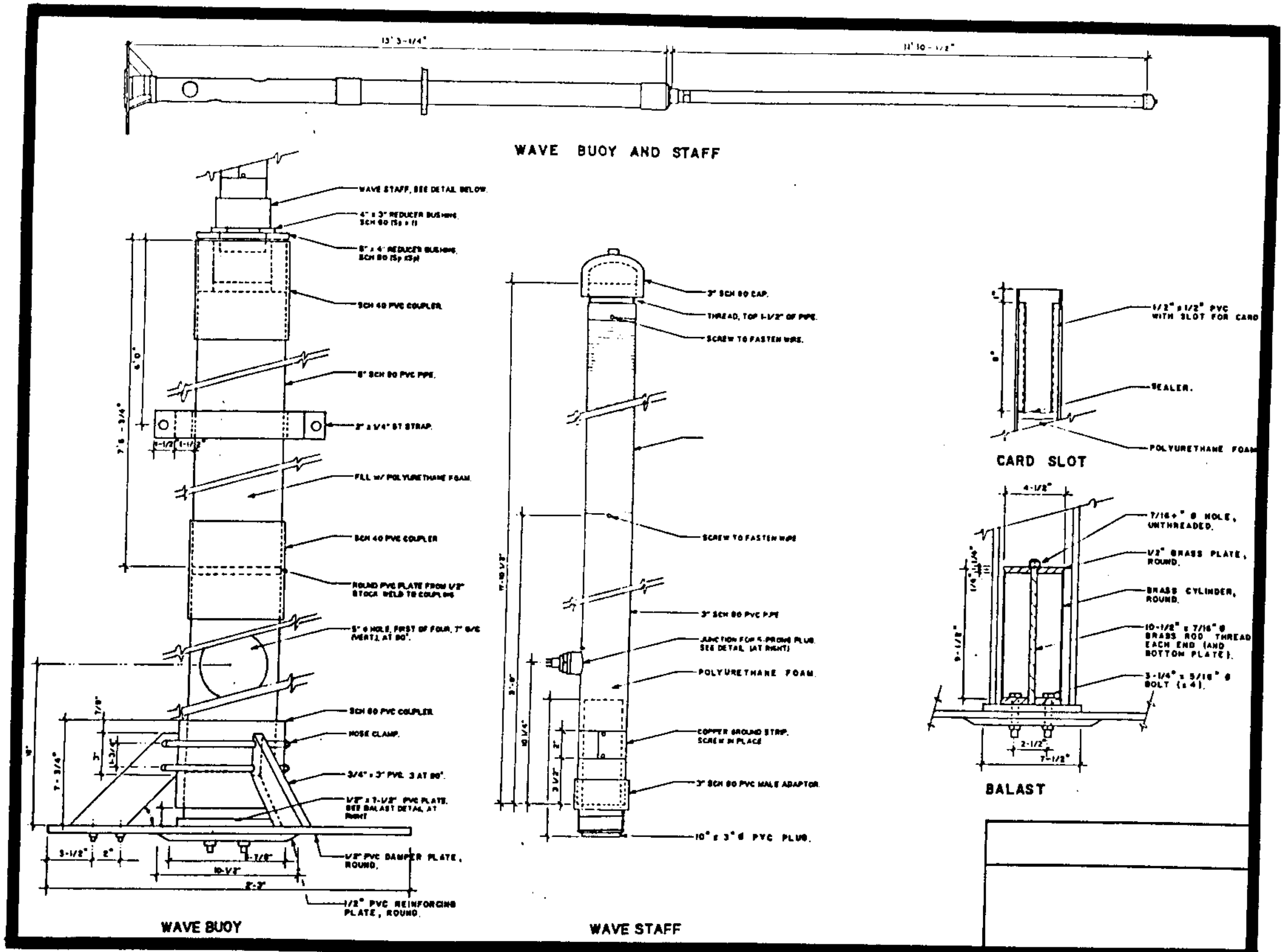


FIGURE 4-2 Schematic of the wave staff and wave buoy.

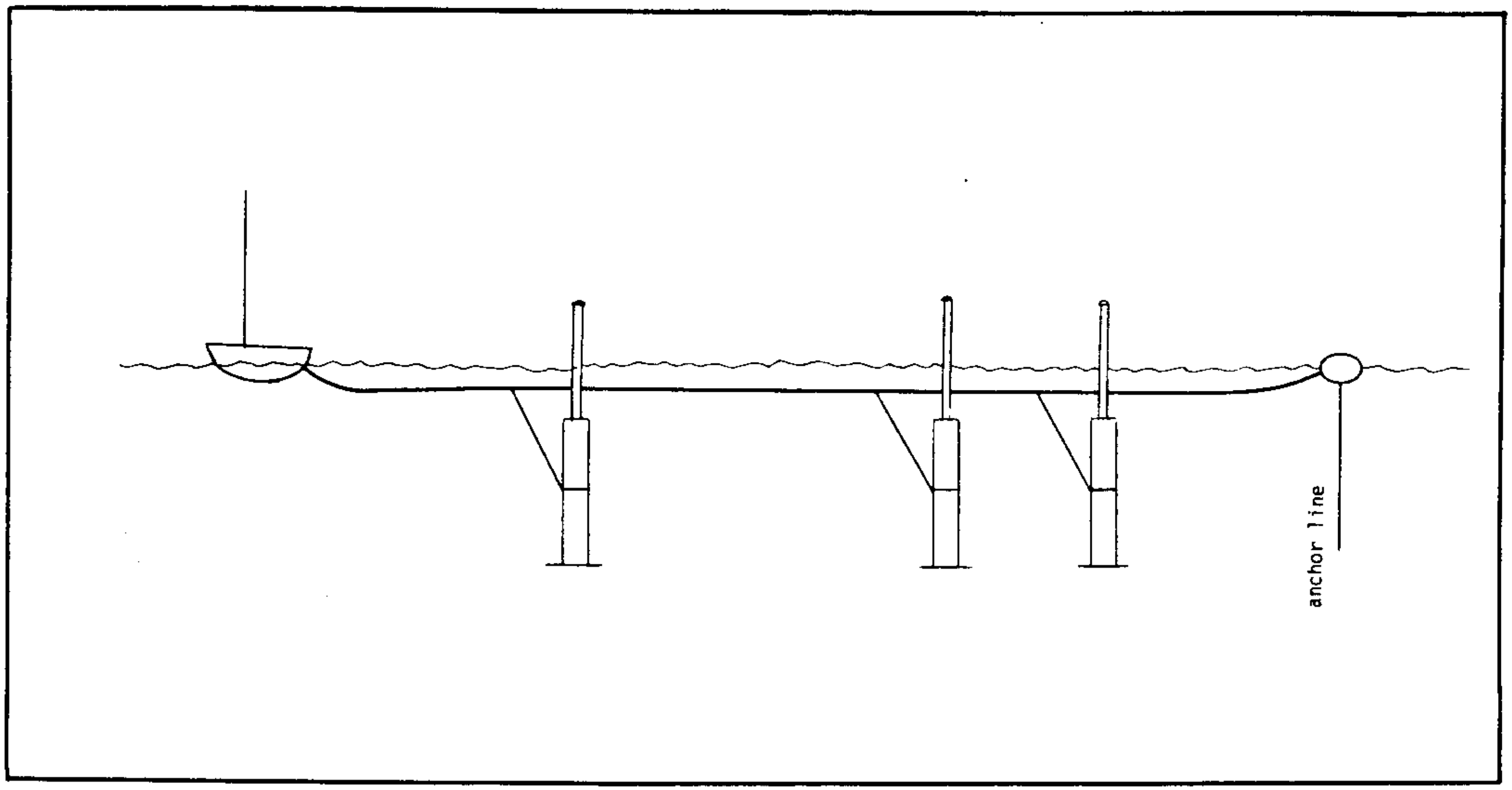
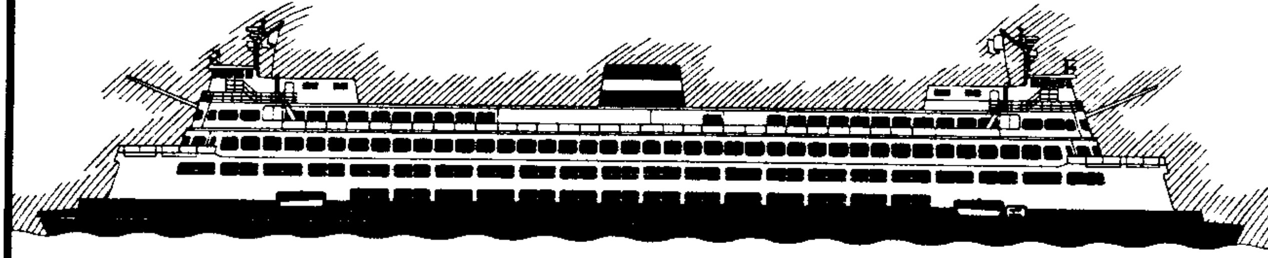


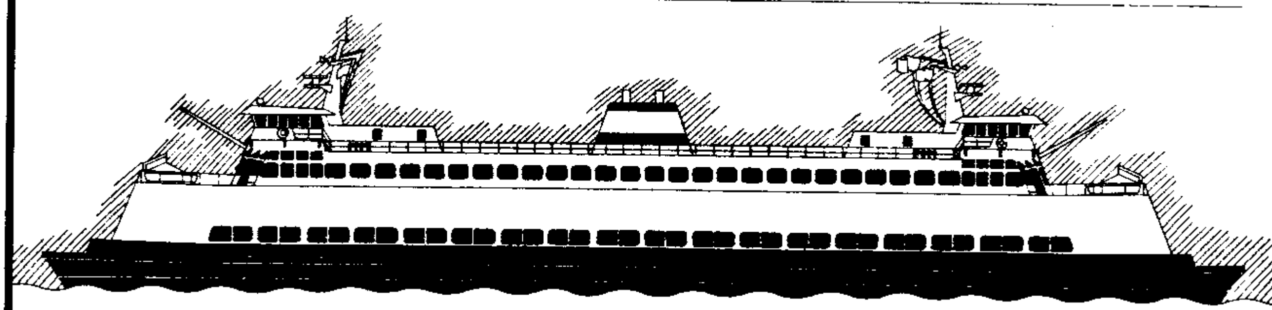
FIGURE 4-3 Schematic of wave staff deployment.

Super Class



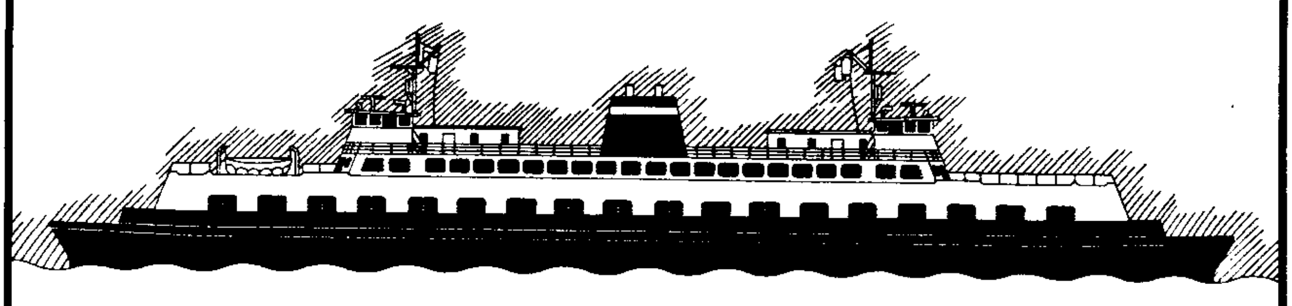
Name	City Built	Yr Built	Length	Beam	Draft	Auto Deck Clearance	Speed (knots)	No of Main Engines	Propulsion	Autos	Pass	Gross Net Tonnage
MV HYAK	San Diego	1967	382'2"	73' 2"	17'3"	16'	17	4	Diesel Elec	160	2500	2704/1214
MV KALEETAN	San Diego	1967	382'2"	73' 2"	17'3"	16'	17	4	Diesel-Elec	160	2500	2704/1214
➤ MV YAKIMA	San Diego	1967	382'2"	73' 2"	17'3"	16'	17	4	Diesel-Elec	160	2500	2704/1214
MV ELWHA	San Diego	1967	382'2"	73' 2"	17'3"	16'	17	4	Diesel-Elec	160	2500	2704 1214

Issaquah Class



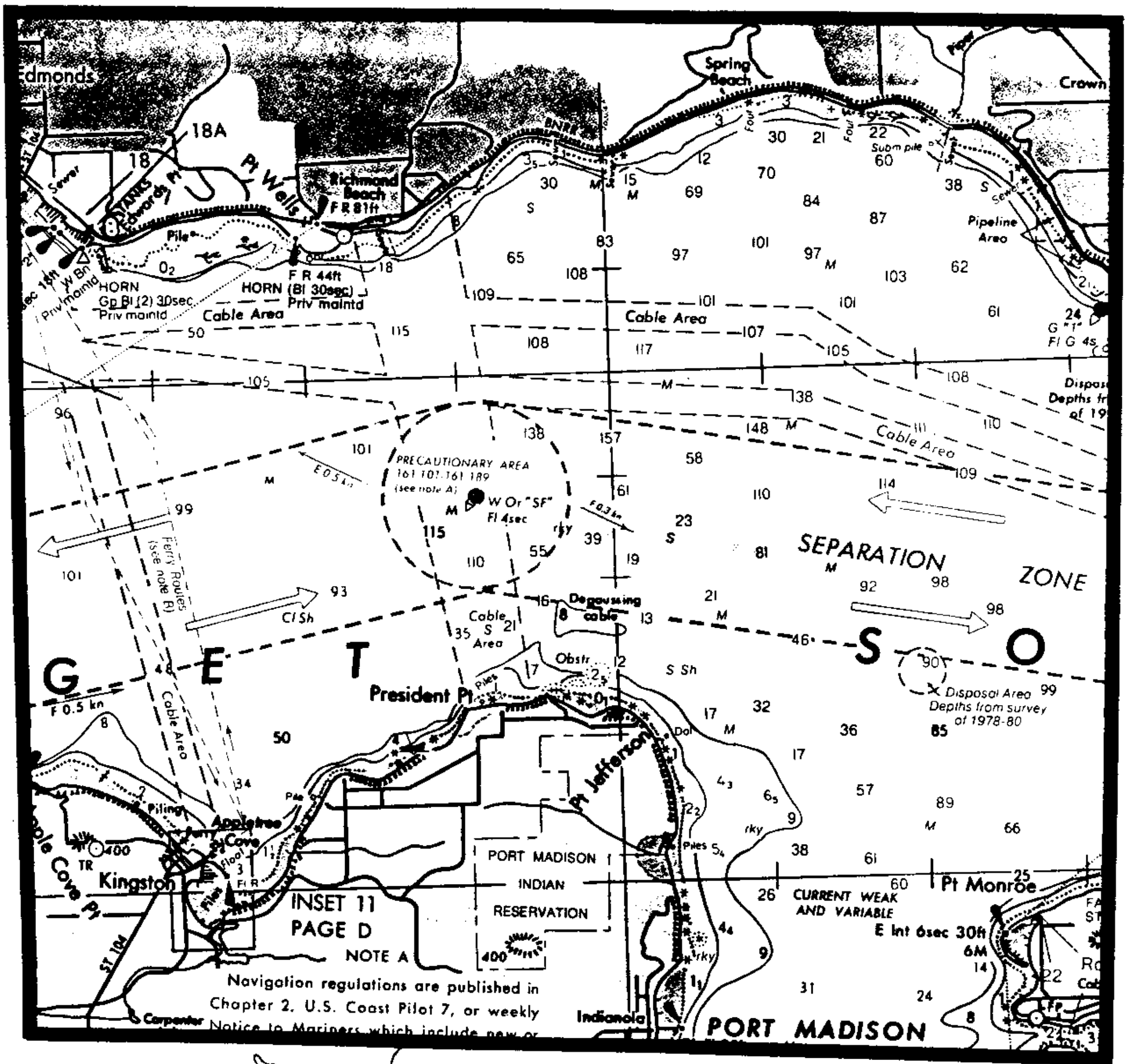
Name	City Built	Yr. Built	Length	Beam	Draft	Auto Deck Clearance	Speed (knots)	No of Main Engines	Propulsion	Autos	Pass	Gross Net Tonnage
MV ISSAQUAH	Seattle	1979	328'	78'	15'6"	16'	16	2	Diesel	100	1200	2469 1749
MV KITTITAS	Seattle	1980	328'	78'	15'6"	16'	16	2	Diesel	100	1200	2469 1756
MV KITSAP	Seattle	1980	328'	78'	15'6"	16'	16	2	Diesel	100	1200	2475 1755
MV CATHLAMET	Seattle	1981	328'	78'	15'6"	16'	16	2	Diesel	100	1200	2477 1772
MV CHELAN	Seattle	1981	328'	78'	15'6"	16'	16	2	Diesel	100	1200	2477 1772
➤ MV SEALTH	Seattle	1982	328'	78'	15'6"	16'	16	2	Diesel	100	1200	

Evergreen State Class



Name	City Built	Yr Built	Length	Beam	Draft	Auto Deck Clearance	Speed (knots)	No of Main Engines	Propulsion	Autos	Pass	Gross/Net Tonnage
MV EVERGREEN STATE	Seattle	1954	310'	73'	15'	12'6"	13	2	Diesel-Elec	100	1000	1495/1017
➤ MV KLAHOWYA	Seattle	1958	310'2"	73'2"	15'6"	13'10"	13	2	Diesel-Elec	100	1140	1334/907
➤ MV TILLIKUM	Seattle	1959	310'2"	73'2"	15'6"	13'10"	13	2	Diesel-Elec	100	1140	1334/907

FIGURE 4-4 From the Ferry Fleet Guide issued by the Washington State Ferry System. The vessels used in the test are marked by arrows.



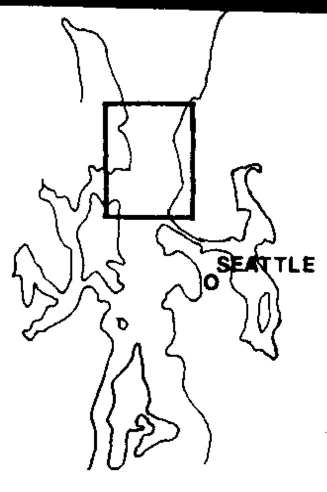
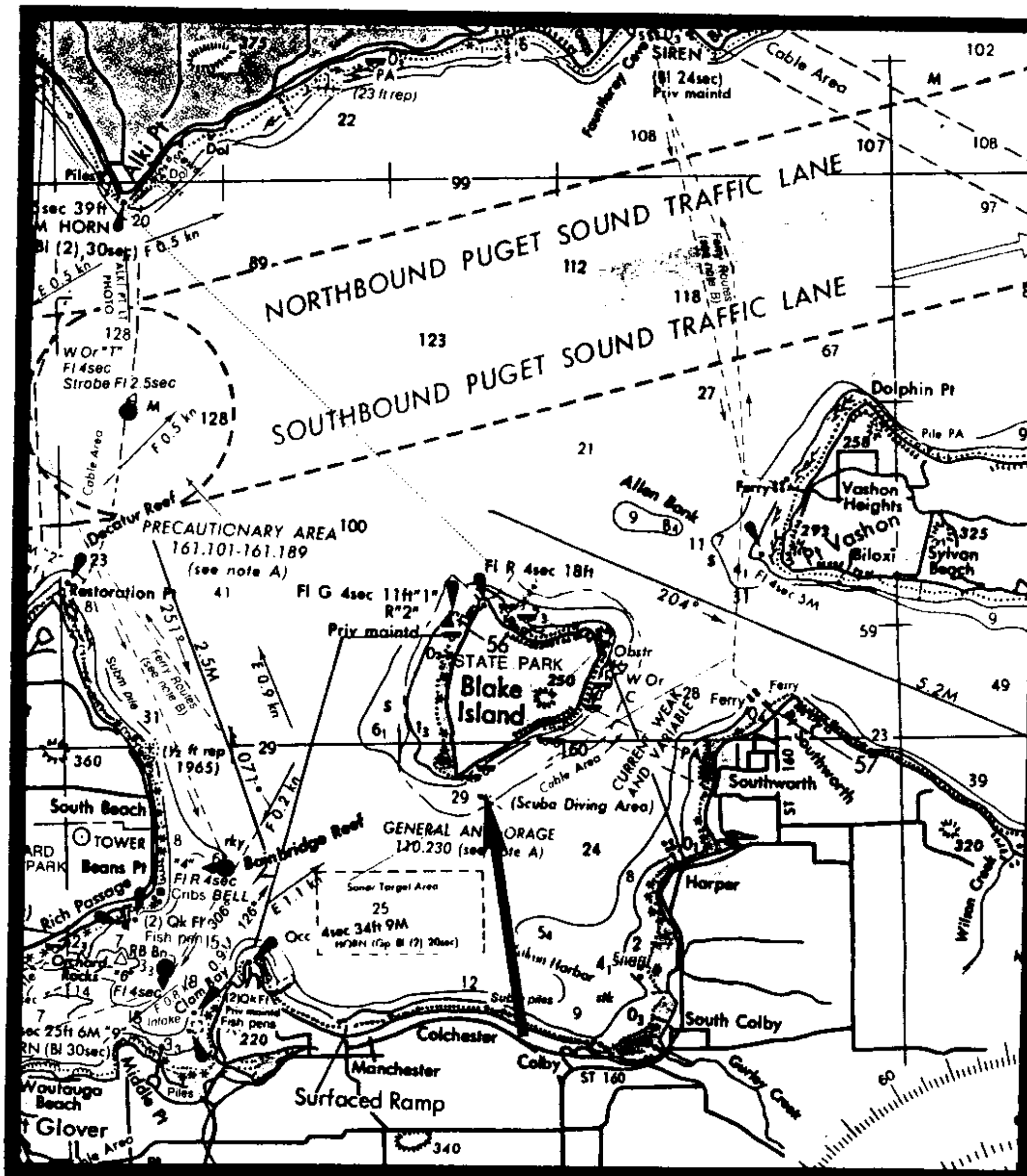


Chart of the test area on 17 September 1984. Chart area is outlined in the inset.

FIGURE 4-5



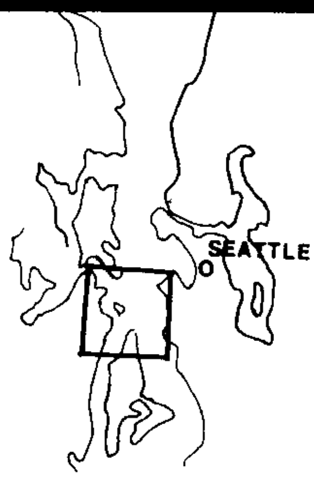


Chart of the test area on 23 October 1984. Mooring buoys are marked by an arrow. Chart area is outlined in the inset.

FIGURE 4-6

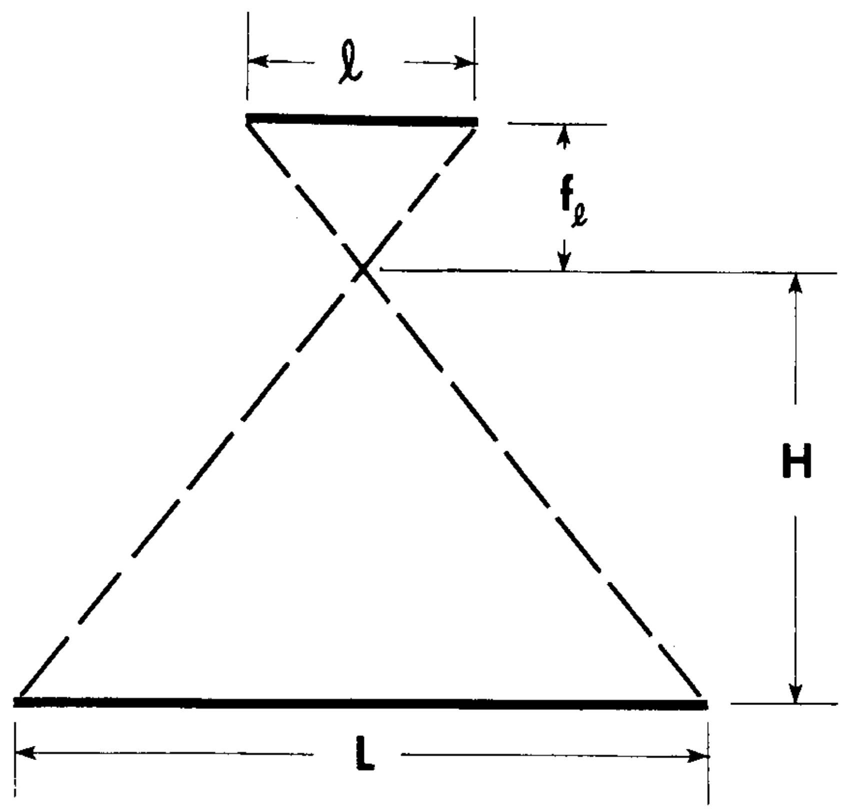


FIGURE 4-7 Schematic of aerial camera optics.

V. DATA REDUCTION

This chapter will be divided into two parts. The first part will describe the calibration and analysis of the sea surface data. The second part will discuss the use of the photographs in measuring the relative positions of the wave staffs and vessels.

A. Sea Surface Data Reduction

1. Calibration

The electronics in the wave staffs produce a voltage that is linearly proportional to wave height. It is this voltage that is recorded, in digital or analog form, and it can be converted to actual wave height by a simple multiplying constant which must be determined for each wave staff.

On 17 September, a calibration procedure was performed immediately after the staff array was deployed in the morning. Each staff in turn was manually forced to oscillate vertically through known distances about its static buoyant position in the water. The calibration constant was obtained by comparing the amount of rise and fall of the staff to the amount of variation in the recorded voltages. This procedure requires relatively calm water in order to work.

Figure 5-1 shows the trace on one of the analog strip charts of the calibration procedure of 17 September. The range from peak to peak on this strip chart represents a two foot excursion on the wave staff, which is greater that the highest ferry wave encountered during the experiment.

No calibration was performed on 19 September because of the high sea state and because of the failure of the signal conditioning electronics on staffs one and three. These electronics, located inside the staff, rarely have failed in service. The essentially identical nature of the failures suggests a common cause, possibley a voltage surge in the power line. Repair was effected simply by replacing the electronics.

On 23 October, the current at Blake Island forced the research crew to concentrate on maintaining the staff array in position to the exclusion of any calibration procedure. A calibration was performed the next day at the dock at Shilshole marina. All components were connected as they had been during the field test; each staff was lowered over the side of the work sailboat and held vertically at various submergence levels while the strip chart recorded a trace. Fig. 5-2 shows one of the traces from this calibration. The calibration constants used in the data analysis are shown in Table 6-1. The higher values obtained for 23 October reflect a change in the electronics after the staff failures on 19 September had been repaired.

2. Waveform Analysis

Figure 5-3 shows the trace from run 6 (Yakima) on 23 October. Figure 5-3a is from the staff closest to the ferry, Fig. 5-3b the middle staff and Fig. 5-3c from the farthest staff. Details of time and speed for this run may be found in Table 6-1. The trace was chosen for general discussion because it shows a prominent wake without much background noise. A more difficult trace, and the means for dealing with it, will be discussed below.

Care must be taken in interpreting these traces. The "up" in the calibration of Fig. 5-1 refers to the position of the wave staff in water rather than the water on the staff. This means that when the strip chart is held in the same orientation as it was recorded, the tops of the waves are at the bottom of the trace and the time scale runs from left to right. For Fig.

5-3 the traces were turned upside down, so that the tops of the waves are at the top of the traces, and the time scale runs right to left.

These traces are typical of those measured for the Washington State ferries, and for ship waves in general. The wave train is composed of a series of numerous peaks, the highest peaks usually being in the first half of the series. It should be remembered that wake is produced by both the bow and stern of vessels, and sometimes the propellor. The wake measured by an observer is a composite of the diverging bow and stern waves, transverse waves, and propeller effects which, at the staff locations in the present study, is dominated visually by the diverging waves. The resultant may show many variations. Even the same vessel making several runs at the same speed will not produce identical waves each time, although a pattern should appear. Generalizations about ship waves need to be drawn from a body of data rather than single measurements.

Following the practice of Sorenson (25), the wave heights presented in Table 6-1 are derived by taking the height of the maximum wave found in a wave train. In Fig. 5-3a, for example, the maximum height is taken to be five divisions (mm) of the strip chart scale, which represents .05 volts. The calibration, shown in Table 6-1, is 3.29 feet/volt. The wave height, then, is:

$$0.05_{\text{volts}} * 3.29 \text{ ft/volt} = 0.82 \text{ foot.}$$

The value of 0.82 ft. is shown in Table 6-1 as the unfiltered wave height for the first staff of run 6 on 23 October. Heights were derived for all runs in this manner (manual scaling of the strip chart records) and entered as unfiltered wave heights in Table 6-1. Gaps in the unfiltered wave heights usually mean that the wake could not be distinquished from the background wind waves. There was also an instance of failure during one run when a staff was fouled by kelp.

In order to maintain a consistent analysis, wave heights were measured using only the front, or leading side of a wave, i.e., maximum trough to following crest height difference in the record. In nearly all cases this side showed the greatest height, but there were a few cases where a greater height could have been measured on the back side (crest to following trough).

Not all traces presented vessel wake as clearly as Fig. 5-3. Figure 5-4 shows the trace from the (nearest the ferry sailing line) first staff during run 10 (Klahowya) on 23 October. The waves outside the region marked as ferry wake are much closer in height to the wake itself than are the corresponding waves in Fig. 5-3. In realty, whatever is measured as wake is the combination of both ship waves and the background wind waves. As the wind waves increase in height, they not only make the ship waves harder to pick out, but their potential for distorting the waves one is trying to measure increases proportionally. In the language of signal analysis, the unwanted wind waves are referred to as "noise"; the greater the noise the greater the distortion.

Mathematical techniques are available that can reduce the level of noise in the data. Known as "filtering", these techniques are described at length in many textbooks and papers, including Bloomfield (4), and Jenkins and Watts (14). They allow the analyst to remove from the data wave components of selected frequency. When the frequency of the unwanted noise is sufficiently different from the frequency of the wave that is being sought, then it may be possible to eliminate or reduce the noise while retaining the rest of the information.

In this analysis, the noise caused by the wind waves had a frequency of approximately 1 Hz., (period T = 1 second) while the ship waves had frequencies that ranged from 0.25 to 0.4 Hz (2.5 second to 4 second periods). After considerable experimentation, a filter was selected that rejected components above 1 Hz. and below .08 Hz. The latter is the approximate natural frequency of the wave staff in vertical oscillation, and was incorporated to eliminate any very long period rise and fall of the wave staffs caused by changing tension on the mooring line.

The filtering was performed on the digital records acquired by the digital data acquisition system, using a Compupro dual processor microcomputer. The filtering calculations were performed using the Fast Fourier Transform technique. The filtering software was part of the Simple Statistical Program, a time series analysis package developed for the U.S. Army Corps of Engineers at the University of Washington. This software package is described in Christensen (5).

Figure 5-5a shows the ferry wake segment of the wave train of Figure 5-4. Whereas Figure 5-4 is a copy of the analog trace, Fig. 5-5 is plotted from digital data and shows more high frequency detail because the digital data acquisition system has a higher frequency response than the analog system. Figure 5-5b shows the same data as Fig. 5-5a after filtering. This same filter was applied to all the data that had been recorded by the digital system, and the resulting wave heights are entered in Table 6-1, under the column heading of filtered wave heights. Gaps in the filtered heights occur where digital data were not available, either because of operator error or because the angle between the wake and the staff array caused the wake to pass through the array too quickly to record more than one channel of digital data.

B. Photo Interpretation

The original plan called for the aerial photographs to be used in determining vessel speed as well as the distances of the wave staffs from the vessel sailing line. Relatively few speed pairs were obtained, however, and those were not suitable for an accurate speed measurement. The time intervals between photographs combined with the resolution ($\pm$ 1 second) of the camera clock visible in the photographs produced unacceptable measurement errors. As a result, where available, speeds were taken from vessel sea trial data, typically in the form of propeller shaft rotation rate vs. vessel speed. These data had been taken very accurately. Their use was considered acceptable because the vessel drafts observed on the September 17 and October 23 tests were almost identical to those in effect during the sea trials. Photographs were used to estimate the speed of the Klahowya.

The photographs did prove very useful in determining the distance from the wave staffs to the vessels. Figure 5-6 shows a photograph from run 11 (Sealth) on 17 September, taken from an altitude of 6000 feet. The ferry is moving from west to east across Puget Sound and has just passed south of the Coast Guard buoy "SF". Both the Coast Guard buoy and the sailboat show clearly in the photograph but the wave staffs themselves do not. This turned out to be true for all photographs regardless of altitude.

There are three problems to be solved in finding the distances from the wave staffs to the vessel. First the scale of the photograph must be determined, since the scale given in the photo annotation is only nominal. The scale usually was measured from the length of the ferry, which is known. Then the location of the wave staffs must be fixed; this usually was done by interpolation from the fixed buoy to the sailboat. Finally the sailing line of the ferry must be determined. Unless evidence in the photo indicated otherwise, the ferry course was assumed to be straight, and the sailing line was found by extending a straight line along the centerline of the vessel. With this information the distances then may be found.

Different methods were used in finding the distances for different runs. Table 6-1 indicates the method used by number. These numbers correspond to the numbered sections below, which explain the specific method for each run.

(1) A photograph was used, its scale being measured from the ferry. To find the location of the wave staffs, first the distance from the Coast Guard buoy to the sailboat (see Fig. 4-1) was measured. This distance usually differed from the total nominal distance of 1020 feet (Fig. 4-1) because the mooring line would stretch under the tension applied by current and the sailboat. The actual values of d_1, d_2 and d_3 (Fig. 4-1) then would be found by linear interpolation. For example, if the mooring line had stretched ten percent (as determined from a photo), as often happened, then the values of d_1, d_2 and d_3 would be 55, 352, and 715 respectively. Next the sailing line of the ferry was determined by extending a straight line back from the ferry. Then the distance from the sailing line to the Coast Guard buoy, d_0 (Fig. 4-1), was measured directly from the photograph, along with the angle, a (Fig. 4-1), between the staff array and the sailing line. x_1, x_2 and x_3 then were calculated by simple trigonometry.

(2) This is the same as method 1, except that the distance between the sailing line of the ferry and the Coast Guard buoy was estimated by an observer on the ferry rather than measured from the photograph.

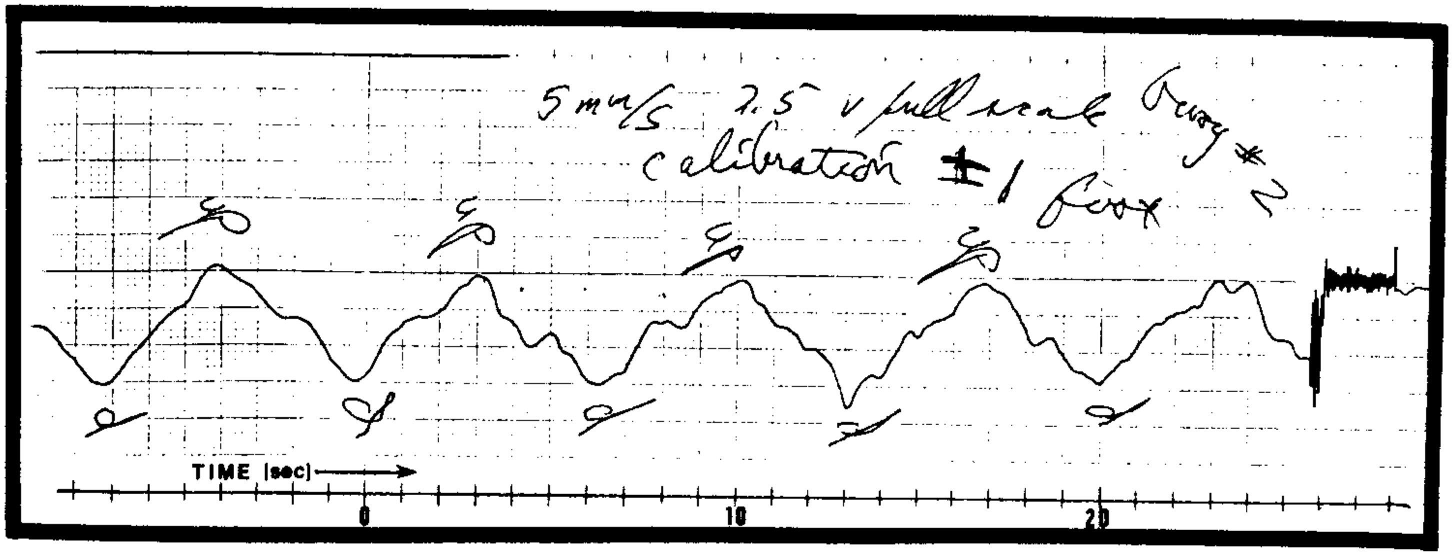
(3) No photographs are available for these runs. The distance from the ferry to the Coast Guard buoy was assumed to be 250 feet. The location of the wave staffs was assumed to be the same as on adjoining runs where photographs had been available. The angle, a, was assumed to be ninety degrees.

(4) A photograph was used. Fig. 5-7 shows the photo used on run 17 (Klahowya) on 23 October. Notice the extreme angle between the sailing line of the ferry and the line of the staff array. The scale, measured as usual from the ferry, is much larger than on previous days, leading to a change in the normal procedure for finding distance. First the distance from the sailboat to the mooring buoy was measured. The location of the wave staffs along the mooring line were identified by linear interpolation, and plotted on a transparency overlaying the photograph. Next the sailing line was determined by extending a straight line back from the ferry. Then the distance from the sailing line to each of the wave staffs was measured directly from the photograph, rather than calculated as in method (1).

(5) A photograph was used; but because part of the staff array was not included in the photo, a highly modified version of method 4 was employed. The scale was measured from the ferry. The distance to the buoy 3 was determined as in method (4). The distance to buoy 1 was assumed. The distance to buoy 2 was determined by linear interpolation, using the distances of buoys 1 and 3 and the nominal staff separation along the mooring line.

(6) No photographs are available for these runs. The distance from the ferry to the sailboat, and the angle a (Fig. 4-1), was estimated by an observer on

the ferry. The buoy positions were determined by assuming a ten percent stretch. Then x_1, x_2 and x_3 were calculated by trigonometry.



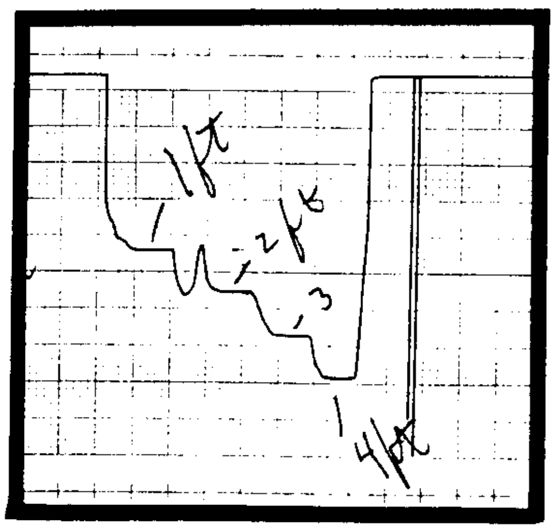


FIGURE 5-1 Copy of the analog calibration trace for wave staff one, 17 September 1984. The location of zero on the time scale is arbitrary.

FIGURE 5-2 Calibration of 23 October 1984.

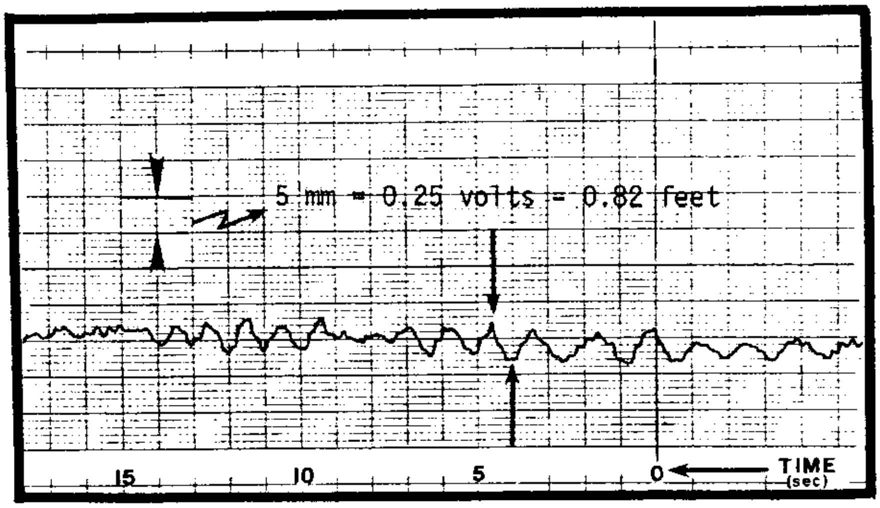


FIGURE 5-3a

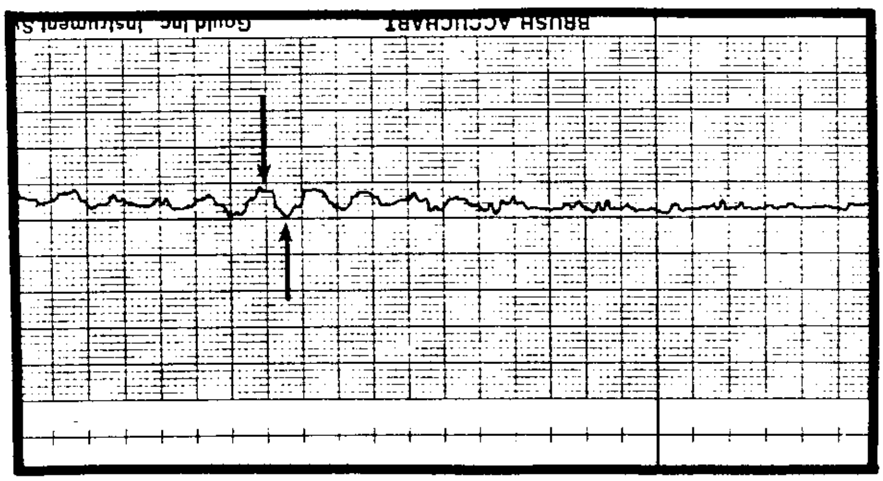


FIGURE 5-3b

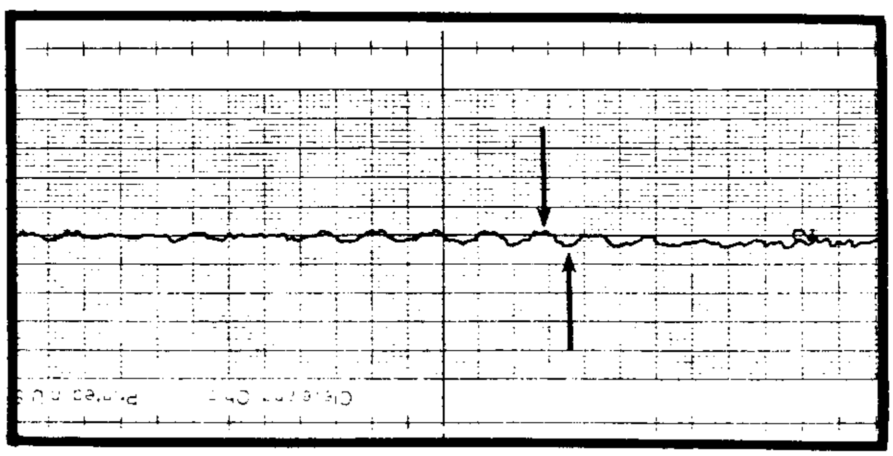


FIGURE 5-3c

FIGURE 5-3 Trace from run 6 (Yakima), 23 October 1984.

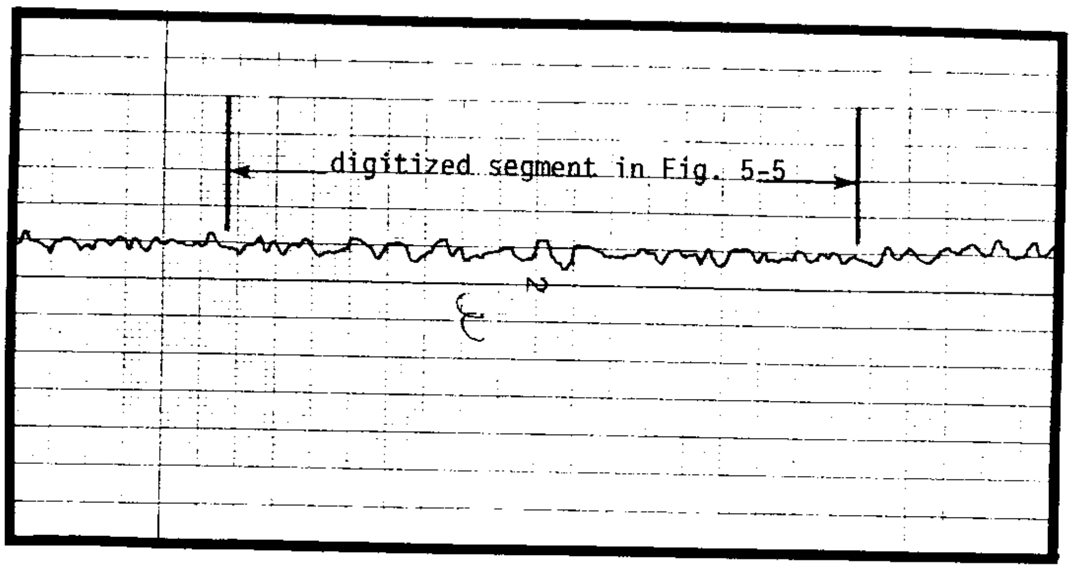


FIGURE 5-4 Trace of wake staff 1, run 10 (Klahowya) on 23 October 1984. The digitized segment shown in Fig. 5-5 is inside the brackets.

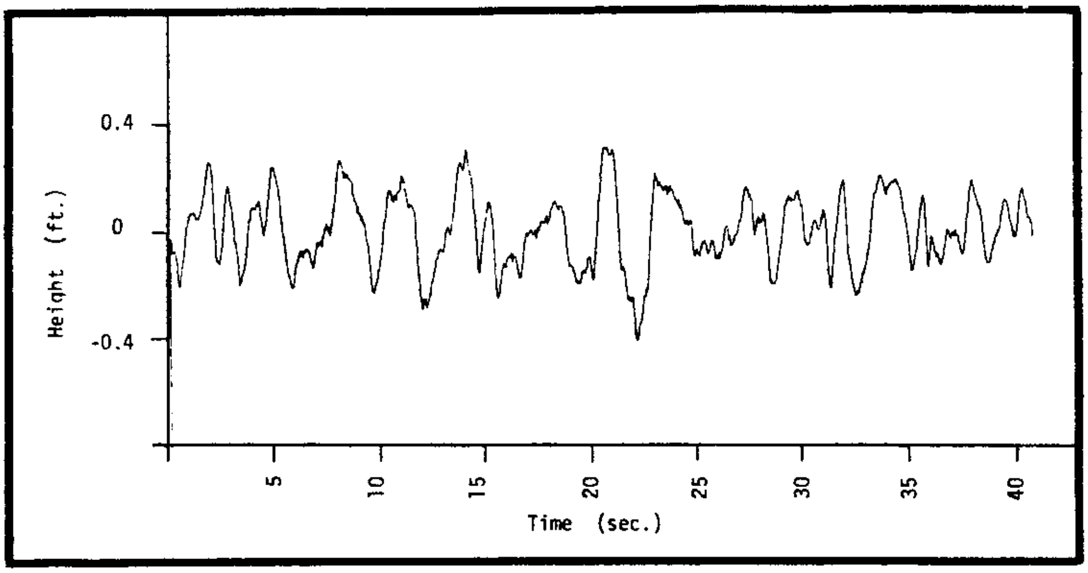


FIGURE 5-5a Unfiltered

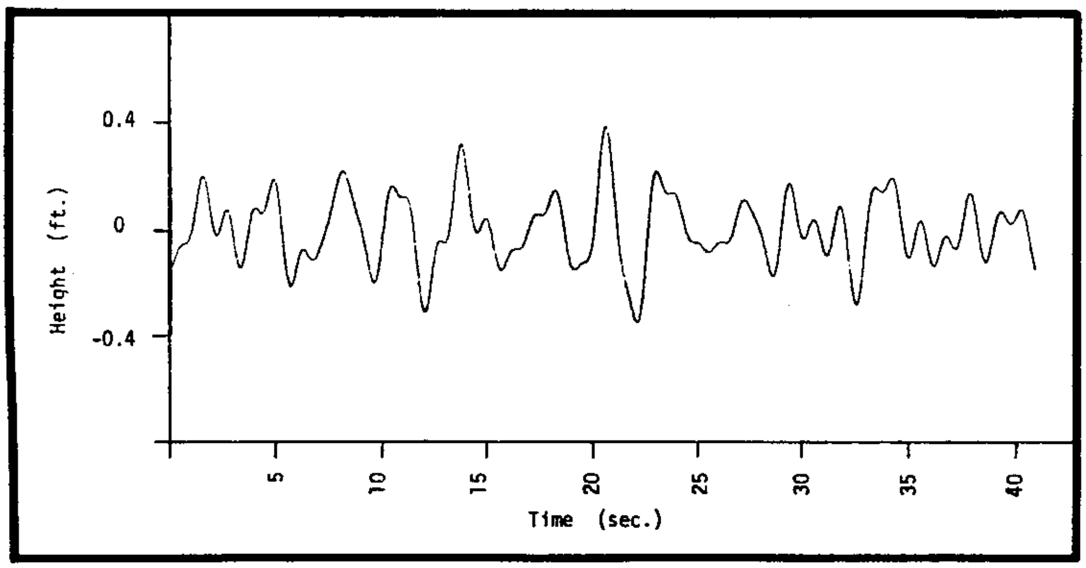


FIGURE 5-5b Filtered

FIGURE 5-5. Digitized segment of run 10 (Klahowya), 23 October 1984. See Fig. 5-4.

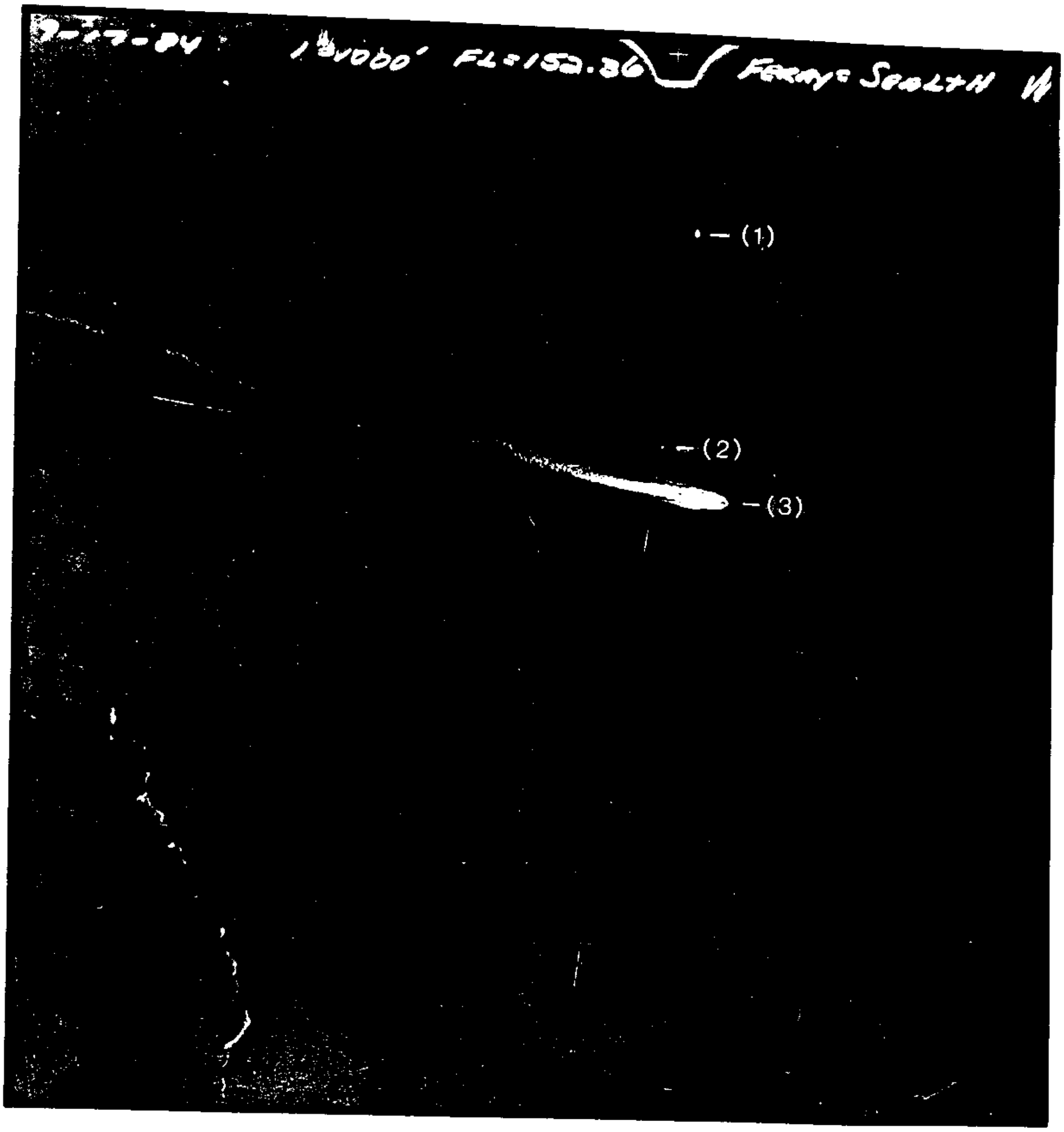


FIGURE 5-6 Photograph of run 11 on 17 September 1984.

(1) sailboat

(2) Coast Guard buoy

(3) Ferry Sealth

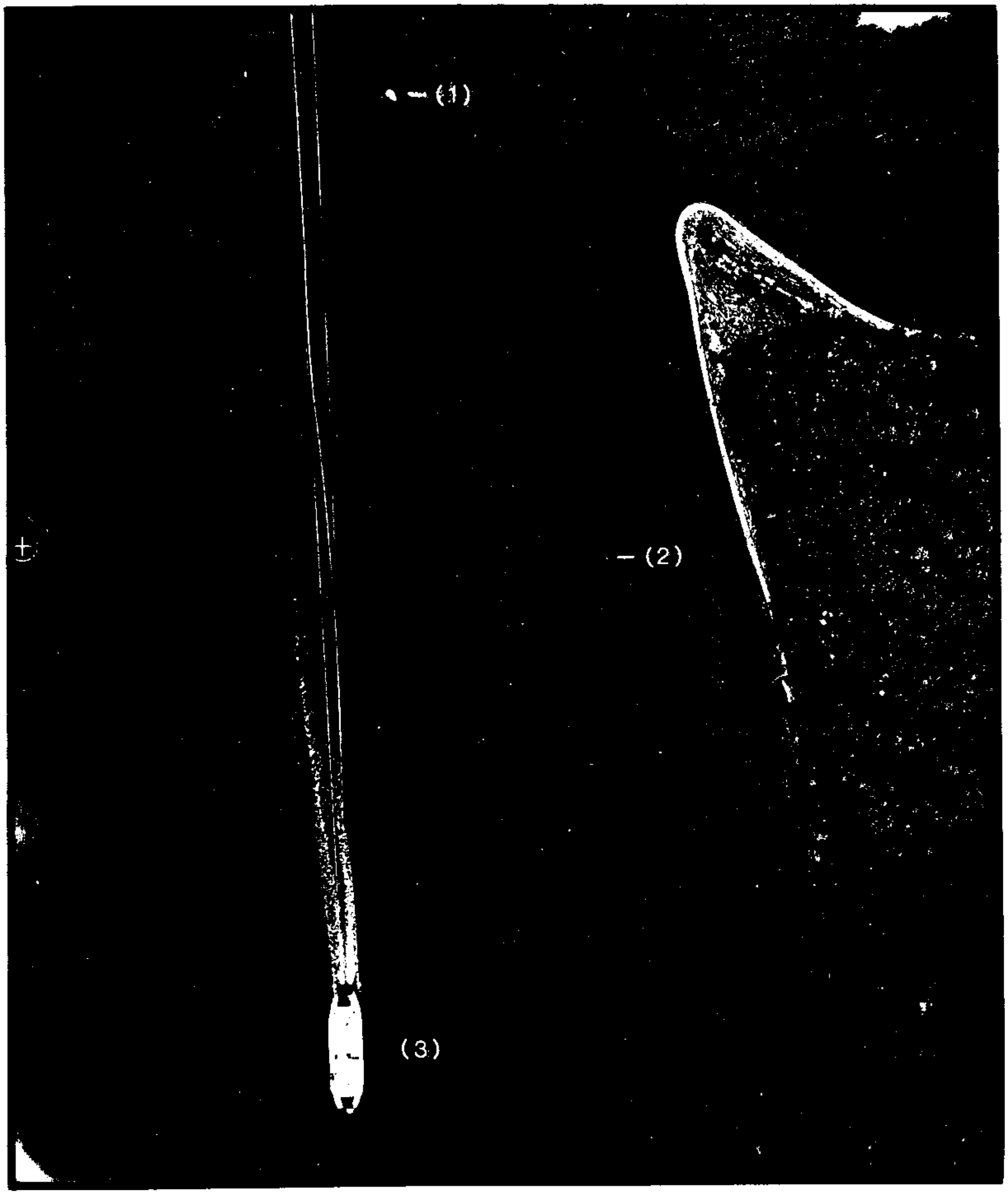


FIGURE 5-7 Photograph of run 17 on 23 October 1984.

(1) sailboat
(2) mooring buoy
(3) Ferry Klahowya

VI. RESULTS

Table 6-1 presents a summary of the results of the wave analysis for the ferries Sealth, Yakima and Klahowya, as well as items describing each of test runs. The "DIR." column refers to the vessel's general direction of travel during each run. "Time abeam" refers to the time the ferry Sealth passed abeam of the Coast Guard buoy "SF" and the time the Yakima and Klahowya passed abeam of the sailboat. The vessel speed was determined as indicated in the prior chapter, section B. Both the recorded propeller shaft RPM and the associated speed are shown, as available.

The wave staff data list the distance from the sailing line, unfiltered wave height and filtered wave height, where available. Wave height data may not be available for a particular run because ferry waves could not be distinguished from the wind waves, because of equipment failure, operator error or, in the case of some of the filtered data, because the circumstances of the particular run did not allow the data to be recorded digitally, as described in section V-A. The number in parentheses next to the staff label is the calibration constant used for that staff on that test day.

The method by which distance from the sailing line was determined for each of the runs is indicated by a number that corresponds to a numbered paragraph describing the particular method. These numbered explanations are found in section V-B. Although the distance is recorded to within ten feet, certainly none of the methods were that accurate. The estimated resolution of distance is given in the final column of Table 6-1. It is believed that the greatest source of error is in the distance from the ferry to the first staff. Therefore the error for a particular run will be in the same direction by approximately the same amount for all three staffs.

Figs. 6-1, 6-2 and 6-3 show the results of Table 6-1; both the filtered and unfiltered data are combined on each plot. Figs. 6-1a, 6-1b, 6-1c and 6-1d show Sealth data for speeds of 18, 17, 15 and 10 knots respectively. Figs. 6-2a, 6-2b and 6-2c show the Yakima data for speeds of 16.3, 14.2 and 10.9 knots respectively. Note that the single Yakima run at 14.5 knots has been plotted on the 14.2 knot graph. Figs. 6-3a and 6-3b show the Klahowya data for the estimated speeds of 13 and 10 knots respectively. The single run at 110 RPM was not plotted.

The considerable scatter in the data is typical of ship wave measurements. Errors in the measurement of distance will account for only a small amount of the scatter; even large adjustments in the distance values are not going to change the general pattern, because at the larger distances of concern variation of wave height with distance is observed to be small. In the case of the Sealth data, extraneous wake contributes to the scatter in the wave height determinations. During the Sealth runs observers were struck by the amount of wave activity in Puget Sound that could be attributed to passing vessels. Since such waves would exist at approximately the same frequency as the waves to be measured, it would be difficult to filter them out of the data. The ferry runs were delayed until visible waves from larger passing vessels had cleared the area, but wake from small craft could not always be identified or avoided.

It was hoped that the filtering scheme would reduce the amount of scatter in the data by reducing the effect of the wind waves. While there is some reduction in scatter in a few of the graphs, in general the filtered data is not significantly more regular or repetitive than the unfiltered data.

The scatter in the data cannot be attributed entirely to wind or other extraneous causes. Ship waves, like waves in general, are not entirely regular and repeatable. Identical runs at identical speeds are not guaranteed to produce identical results in field tests. For this reason it is important to base predictions on as large a source of data as can be acquired.

Curves have drawn through the points of Figs 6-1, 6-2 and 6-3 to represent the trend of the data. The curves were fitted by hand rather than by using any statistical method, as the data were not sufficiently numerous to justify use of statistical techniques. Most of the curves show a trend that is consistent with model data (references 15, 25) and ship wave data (reference 23). Fig. 6-1a is a good example. The wave height decreases rapidly with distance over about the first 500 feet from the sailing line. After that distance the attenuation of wave height with distance is small, and provided that it can be distinguished for other waves, a measurable wake will persist for a long distance from its source. The trend of Fig. 6-1a has been observed for many different types and sizes of vessels over a large range of speeds.

Exceptions to the normal trend also may be found, as for example, in Fig. 6-1d. Here the data suggest the highest ship wave at this speed is to be found at about 500 feet from the sailing line. While it is possible that more data points would establish a different pattern, there is no reason to reject the data presented. It should be remembered that the changes in wave height being presented in these figures amount to only a few inches. Anomolies in relative values at this scale are much more likely than if the data involved larger waves.

Figures 6-4a, 6-4b and 6-4c show the results as a graph of wave height versus the speed of the vessels at distances of 300, 600 and 1200 feet respectively. All three ferries are shown on each plot for comparison. Note that the points shown on Fig. 6-4 do not come from Table 6-1 but have been selected from the curves that were fitted to the data in Figs. 6-1, 6-2 and 6-3; Fig. 6-4 is simply a cross-plotting of the curves in Figs. 6-1, 6-2, and 6-3.

Figure 6-4 presents the desired summary of the field measurements. Relative wave heights generated by the three representative vessels - Sealth (Issaquah Class), Yakima (Super Class) and Klahowya (Evergreen State Class) - can be compared readily. The results can be used as a guide to vessel operation on specific routes on Puget Sound if wake generation is a concern.

TABLE 6-1a Summary of results for 17 September 1984.

RUN NO.	VESSEL	DIR.	TIME ABEAM	SPEED		STAFF 1 (2.50)			STAFF 2 (2.50)			STAFF 3 (2.86)			METHOD of FINDING DISTANCE	RESOLUTION of DISTANCE (Ft.)
				RPM	Kt.	Distance (Ft.)	Unfiltered Height (Ft.)	Filtered Height (Ft.)	Distance (Ft.)	Unfiltered Height (Ft.)	Filtered Height (Ft.)	Distance (Ft.)	Unfiltered Height (Ft.)	Filtered Height (Ft.)		
1	Sealth	E	1105	125	10	730	0.74	0.63	1100	0.54	0.44	1850	0.47	0.42	(1)	50
2	Sealth	W	1130	125	10	180	0.50	0.52	550	0.50	0.55	1280	----	----	(1)	50
3	Sealth	E	1151	125	10	300	0.75	----	680	0.64	----	1400	0.57	----	(2)	50
4	Sealth	W	1204	125	10	300	0.61	0.56	650	0.63	0.59	1400	----	----	(1)	50
5	Sealth	E	1221	155	15	330	0.92	0.85	700	0.68	0.65	1450	0.63	0.56	(1)	50
6	Sealth	W	1242	155	15	300	0.78	0.69	650	0.53	0.56	1400	0.72	0.56	(3)	50
7	Sealth	E	1251	170	17	300	1.00	1.04	650	0.94	0.89	1400	0.84	0.75	(3)	50
8	Sealth	W	1258	170	17	300	1.20	1.14	650	1.05	0.92	1400	1.05	1.02	(3)	50
9	Sealth	E	1312	180	18	300	1.50	1.42	650	0.90	0.88	1400	0.83	0.84	(3)	50
10	Sealth	W	1335	180	18	330	1.31	----	680	1.00	----	1430	1.00	----	(3)	50
11	Sealth	E	1354	180	18	330	0.99	1.04	680	0.91	0.86	1430	0.88	0.81	(1)	25
12	Sealth	W	1417	180	18	250	1.25	----	580	1.13	----	1200	1.14	----	(1)	25
13	Sealth	E	1425	170	17	300	0.81	0.75	580	0.69	0.69	1180	0.89	0.86	(3)	50
14	Sealth	W	1448	155	15	300	1.00	0.97	580	0.64	0.57	1150	0.72	0.61	(1)	25

TABLE 6-1b Summary of results for 23 October 1984.

RUN NO.	VESSEL	DIR.	TIME ABEAM	SPEED		STAFF 1 (3,29)			STAFF 2 (3.50)			STAFF 3 (3.42)			METHOD of FINDING DISTANCE	RESOLUTION of DISTANCE (Ft.)
				RPM	Kt.	Distance (Ft.)	Unfiltered Height (Ft.)	Filtered Height (Ft.)	Distance (Ft.)	Unfiltered Height (Ft.)	Filtered Height (Ft.)	Distance (Ft.)	Unfiltered Height (Ft.)	Filtered Height (Ft.)		
1	Yakima	S	1103	150	16.3	390	0.73	0.71	750	0.39	0.53	1450	0.26	----	(6)	50
2	Yakima	N	1109	150	16.3	390	0.49	----	750	0.48	----	1450	0.43	----	(6)	50
3	Yakima	S	1118	150	16.3	380	0.63	0.74	740	0.48	----	1430	0.43	0.53	(6)	50
4	Yakima	N	1126	130	14.2	380	0.74	0.71	720	----	----	1380	0.32	0.44	(6)	50
5	Yakima	S	1135	130	14.2	380	0.70	0.67	700	0.88	0.90	1340	0.42	0.46	(6)	50
6	Yakima	N	1143	133	14.5	370	0.82	0.69	680	0.70	----	1290	0.43	----	(6)	50
7	Yakima	S	1155	110	10.9	370	0.61	0.67	680	0.73	0.69	1290	0.31	0.45	(6)	50
8	Klahowya	N	1308	150	13	370	0.99	0.92	680	0.70	0.90	1290	0.25	0.48	(6)	50
9	Klahowya	S	1315	150	13	370	0.69	0.77	680	0.83	0.86	1290	0.82	0.67	(6)	50
10	Klahowya	N	1336	130	10	370	0.61	0.72	680	0.35	0.61	1290	0.36	0.37	(6)	50
11	Klahowya	S	1343	130	10	500	0.57	0.47	810	0.44	0.46	1420	----	----	(6)	50
12	Klahowya	N	1354	130	10	380	0.74	0.67	630	0.44	----	1130	0.43	----	(6)	50
13	Klahowya	S	1406	130	10	340	0.99	0.87	460	0.71	0.77	700	0.46	0.41	(6)	50
14	Klahowya	N	1415	150	13	340	0.86	0.82	460	0.53	----	700	0.51	----	(6)	50
15	Klahowya	S	1428	110	--	150	0.63	----	250	0.84	----	500	----	----	(4)	50
16	Klahowya	N	1438	150	13	240	1.18	1.24	360	0.88	----	600	0.65	----	(6)	50
17	Klahowya	S	1447	150	13	270	1.00	1.02	410	0.87	0.94	670	0.91	0.96	(4)	50
18	Klahowya	N	1455	150	13	310	1.42	1.46	490	1.05	----	840	0.73	----	(6)	50
19	Klahowya	S	1503	130	10	420	0.74	0.79	570	----	----	850	0.55	0.53	(4)	50
20	Klahowya	N	1512	130	10	310	0.59	0.59	490	0.53	----	840	0.47	----	(6)	50
21	Klahowya	S	1521	130	10	250	0.63	0.63	500	0.85	0.79	1000	0.57	0.56	(5)	50

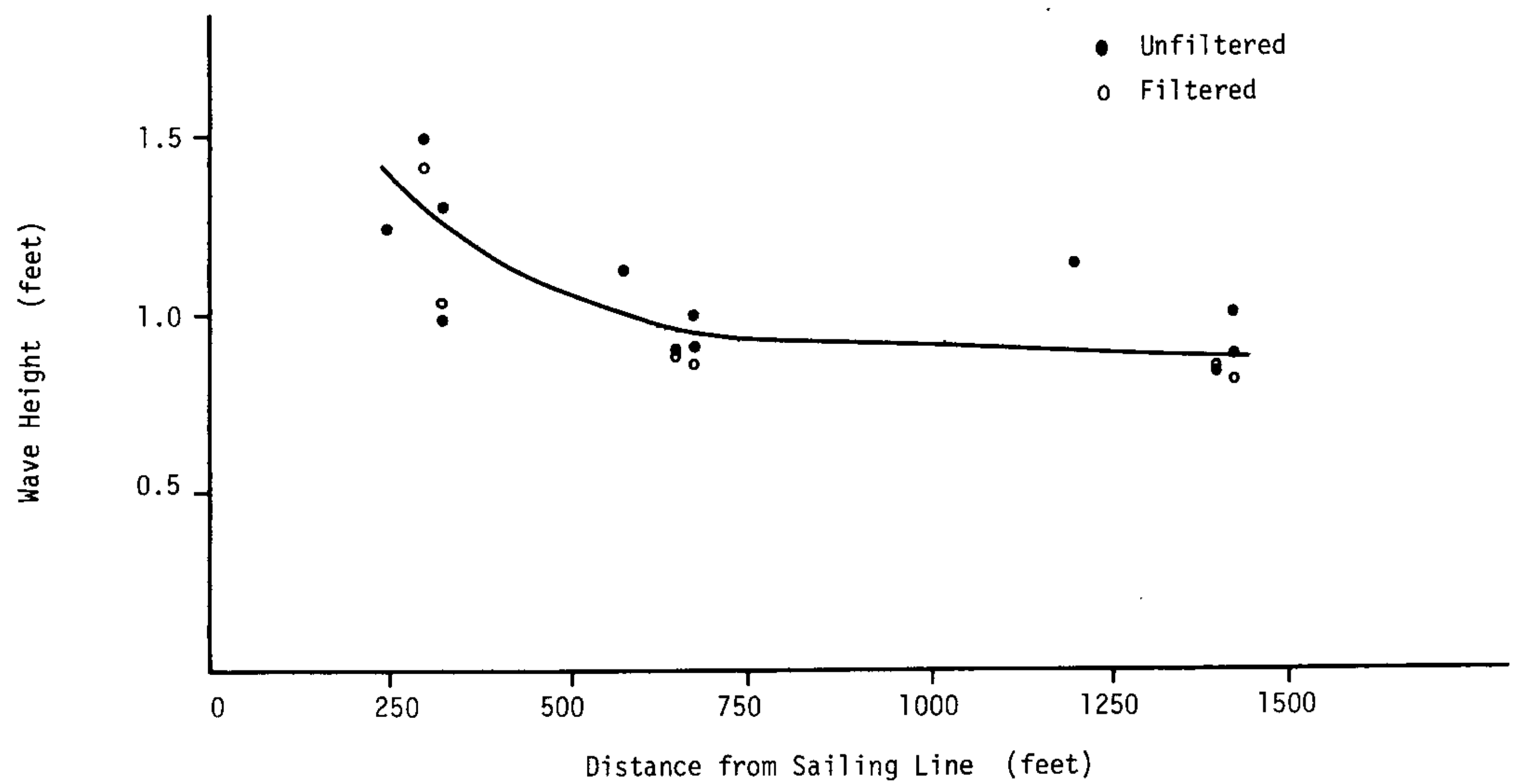


FIGURE 6-1a Plot of Sealth data at 18 knots.

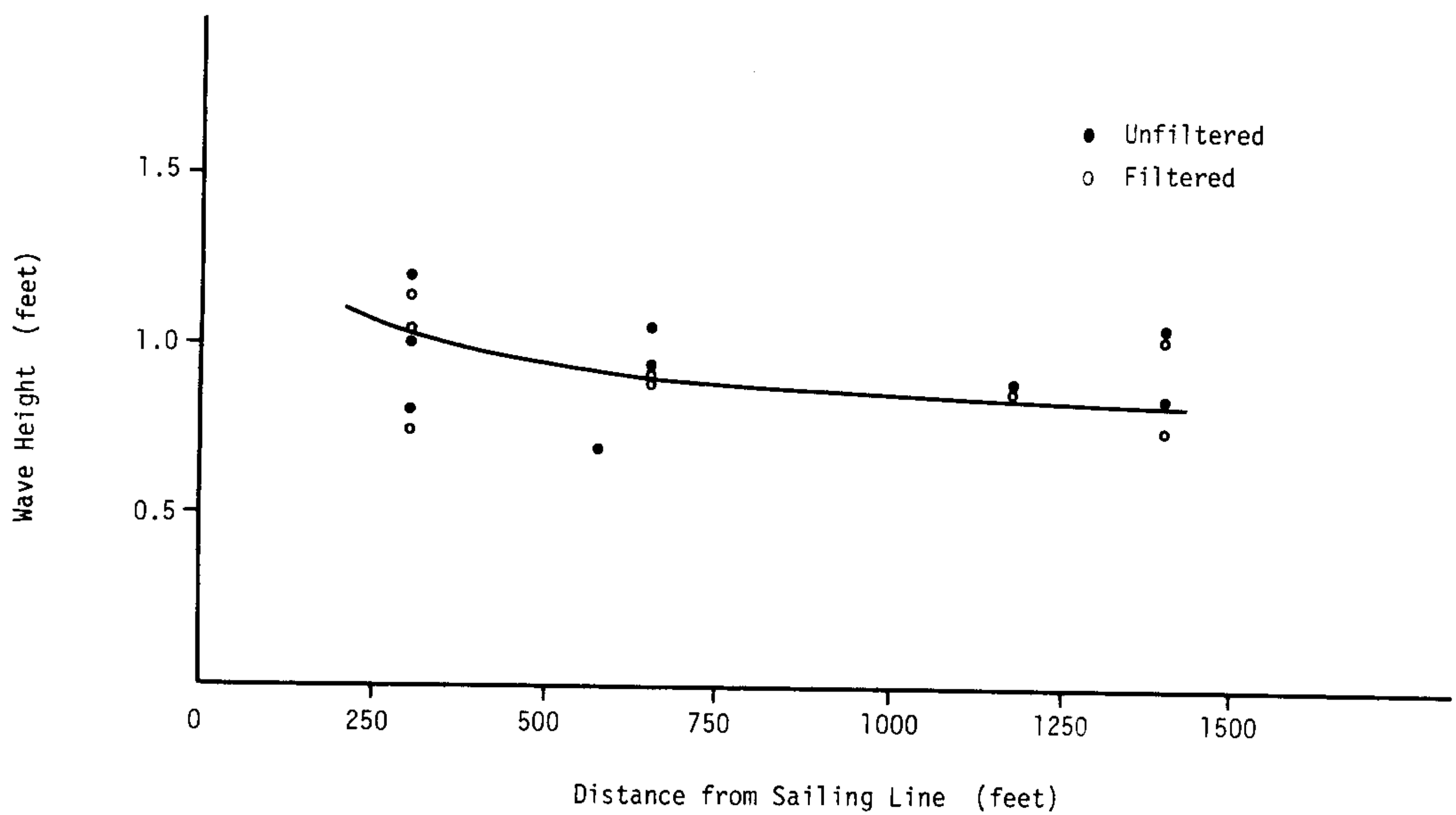


FIGURE 6-1b Plot of Sealth data at 17 knots.

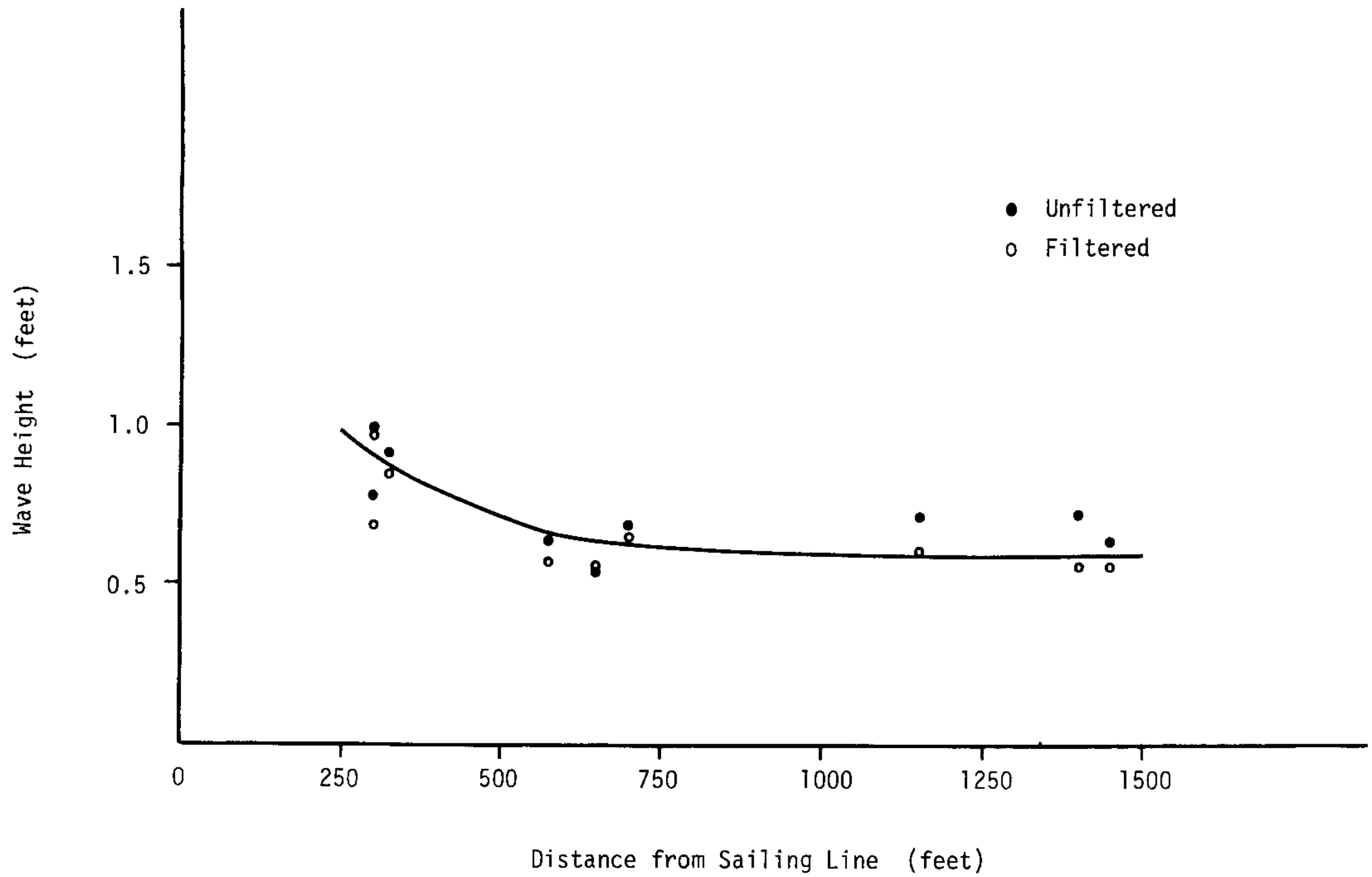


FIGURE 6-1c Plot of Sealth data at 15 knots.

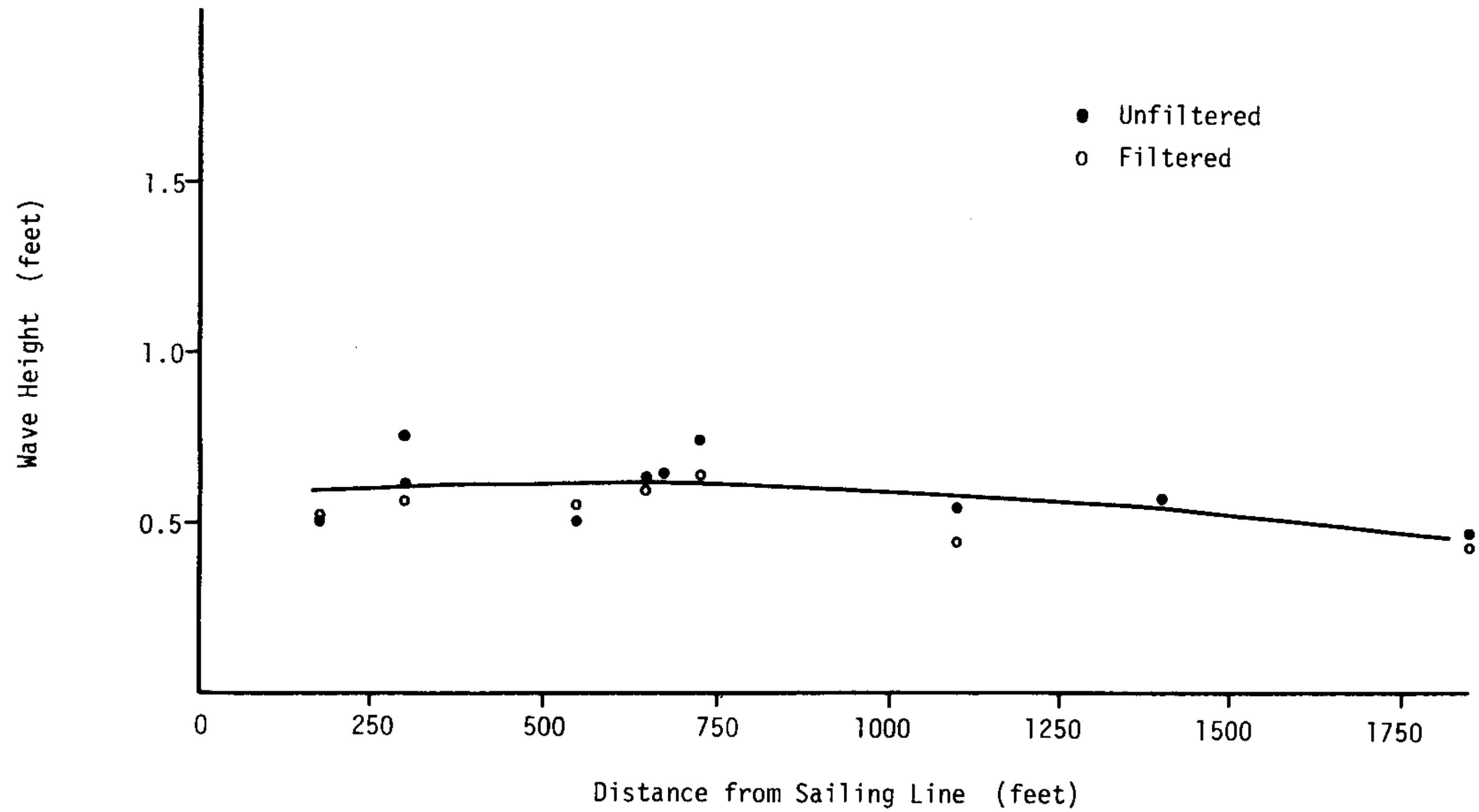


FIGURE 6-1d Plot of Sealth data at 10 knots.

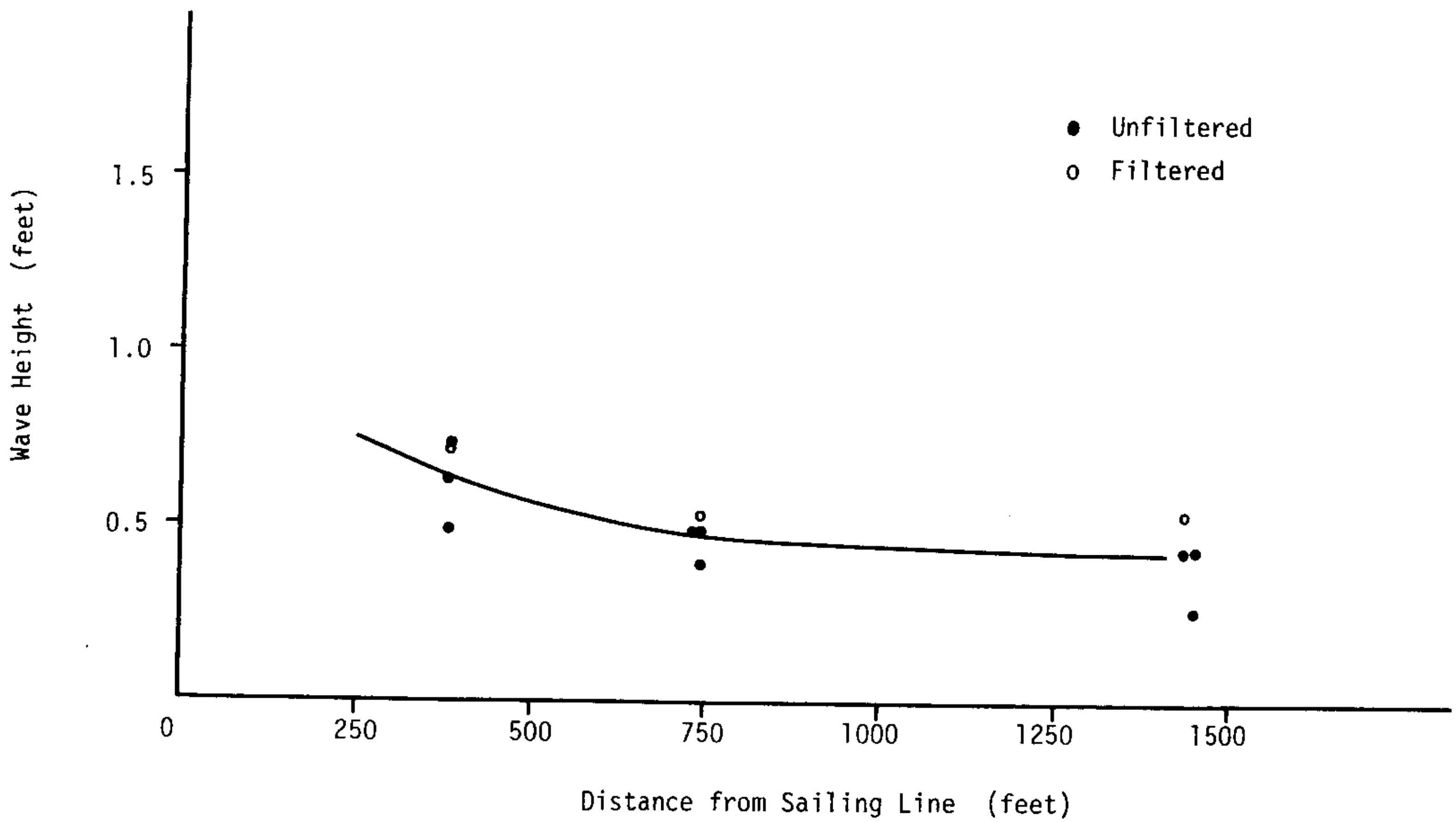


FIGURE 6-2a Plot of Yakima data at 16.3 knots.

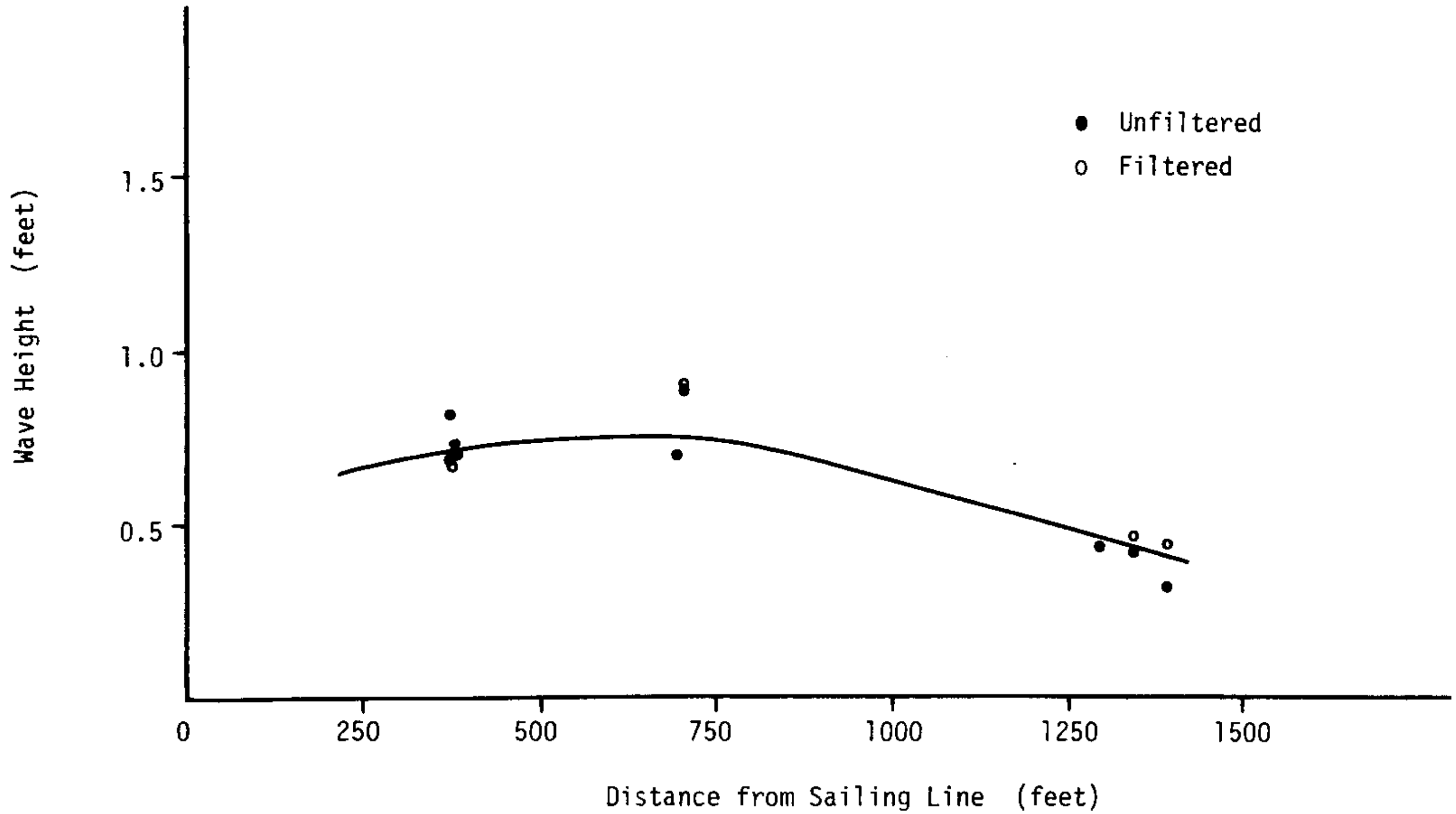


FIGURE 6-2b Plot of Yakima data at 14.2 knots.

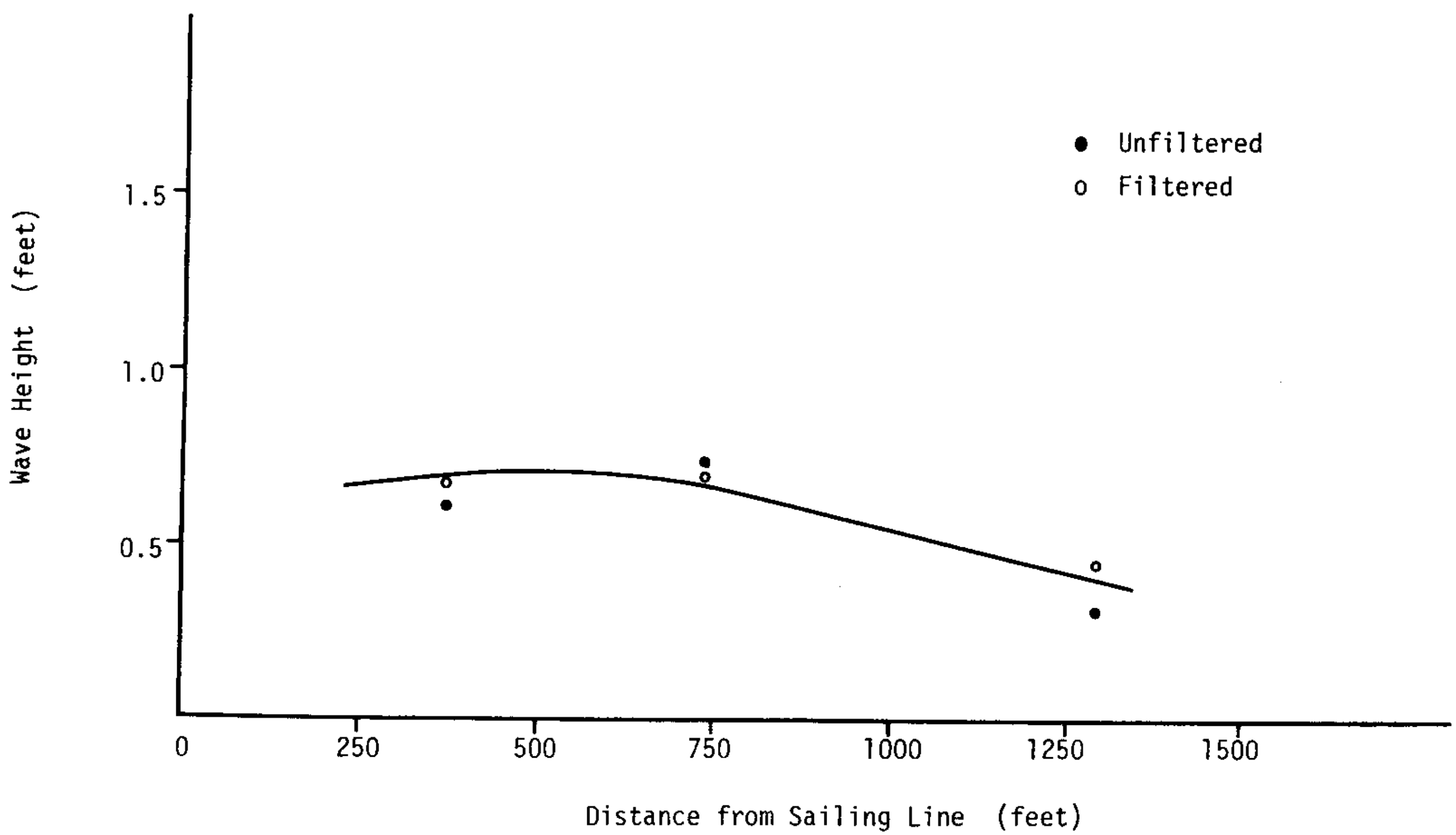


FIGURE 6-2c Plot of Yakima data at 10.9 knots.

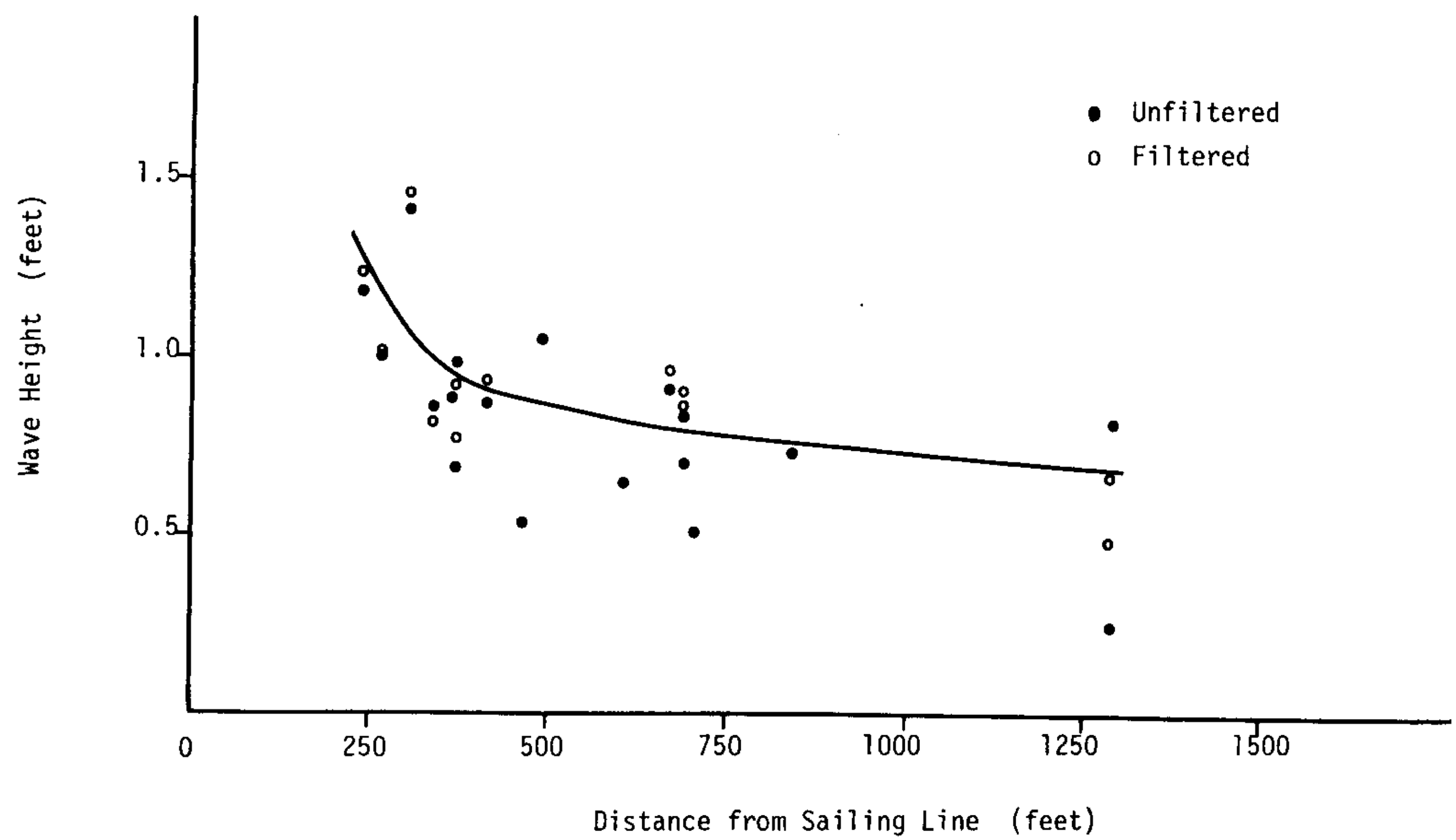


FIGURE 6-3a Plot of Klahowya data at 13 knots.

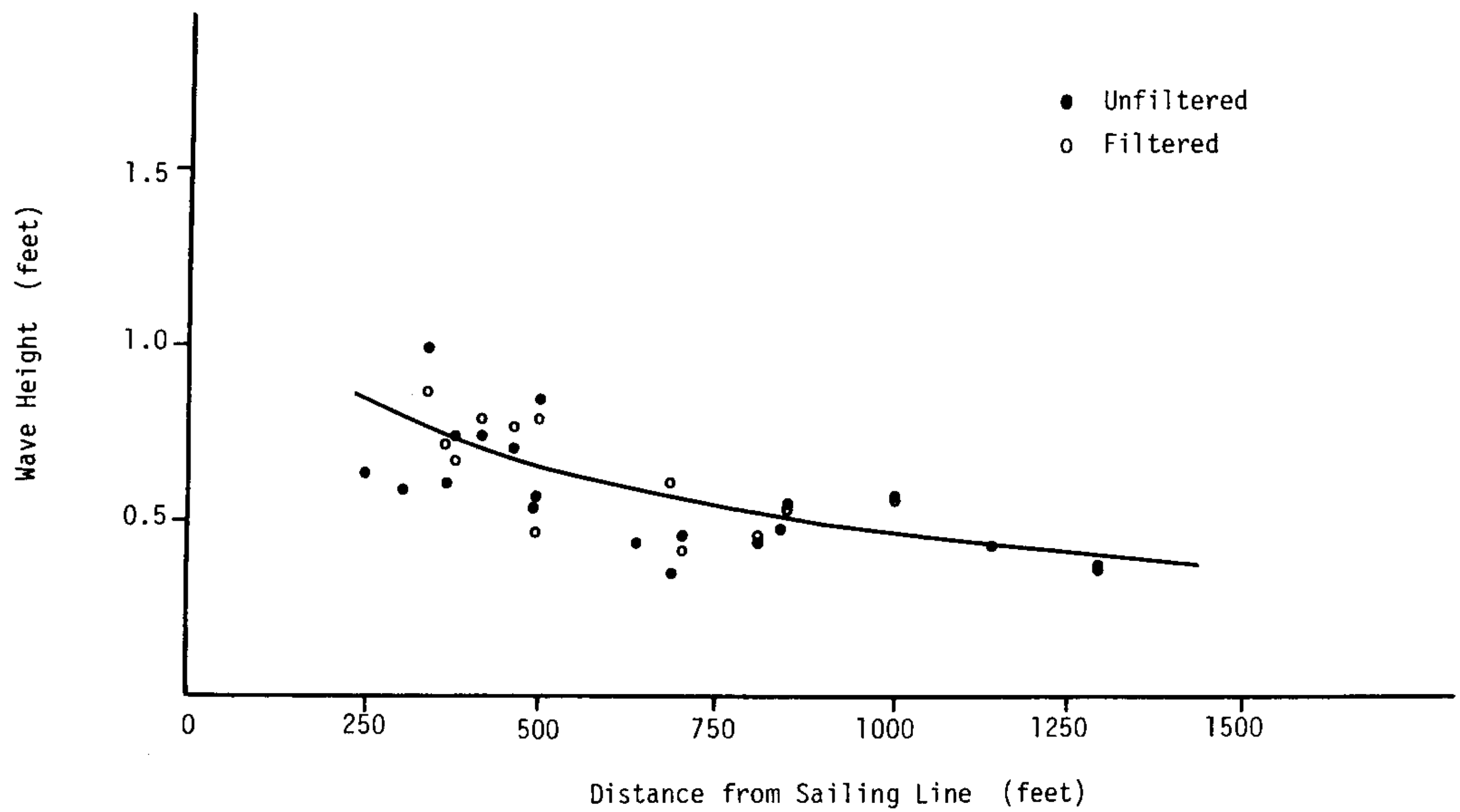


FIGURE 6-3b Plot of Klahowya data at 10 knots.

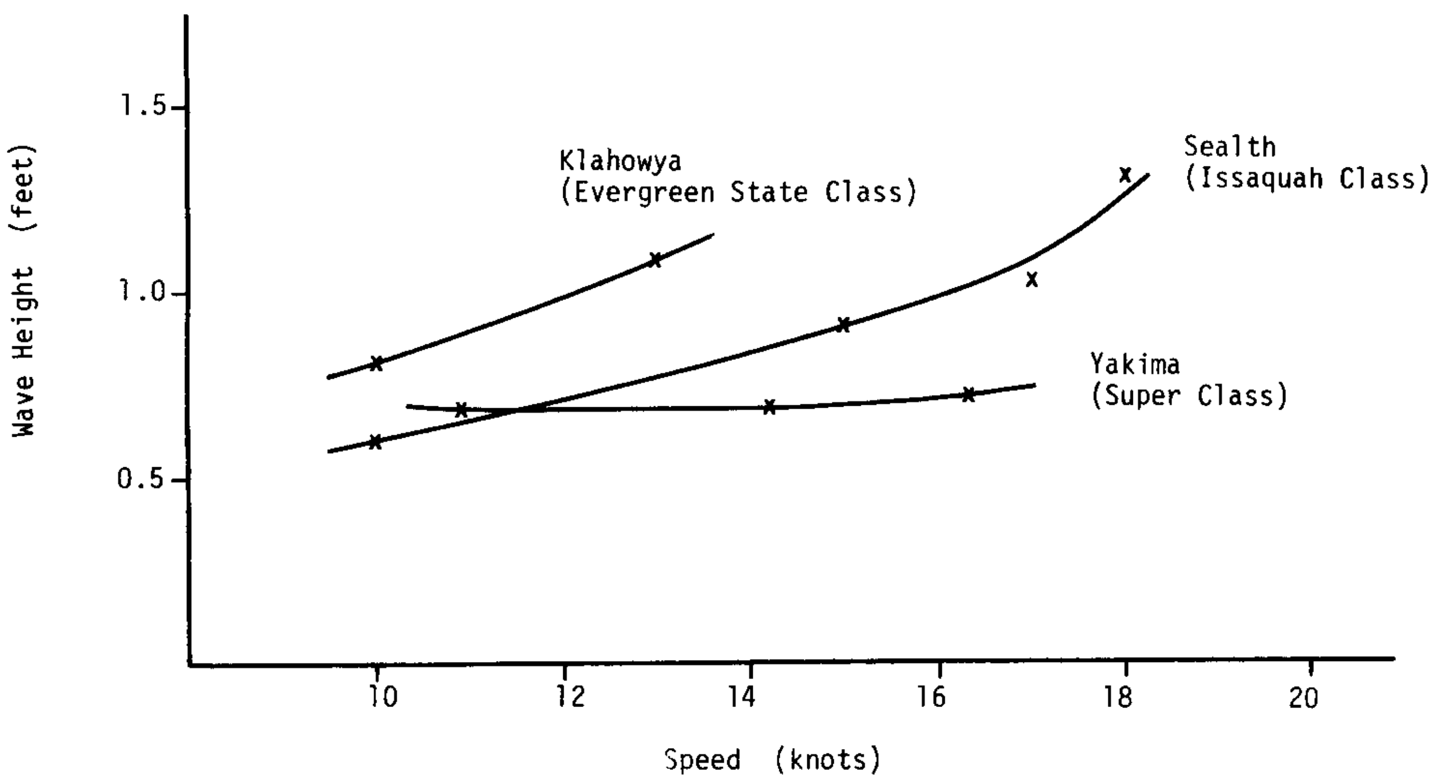


FIGURE 6-4a Wave Heights at 300 Foot Distance from the Sailing Line. From Wave Height vs. Distance Curves, for each Class.

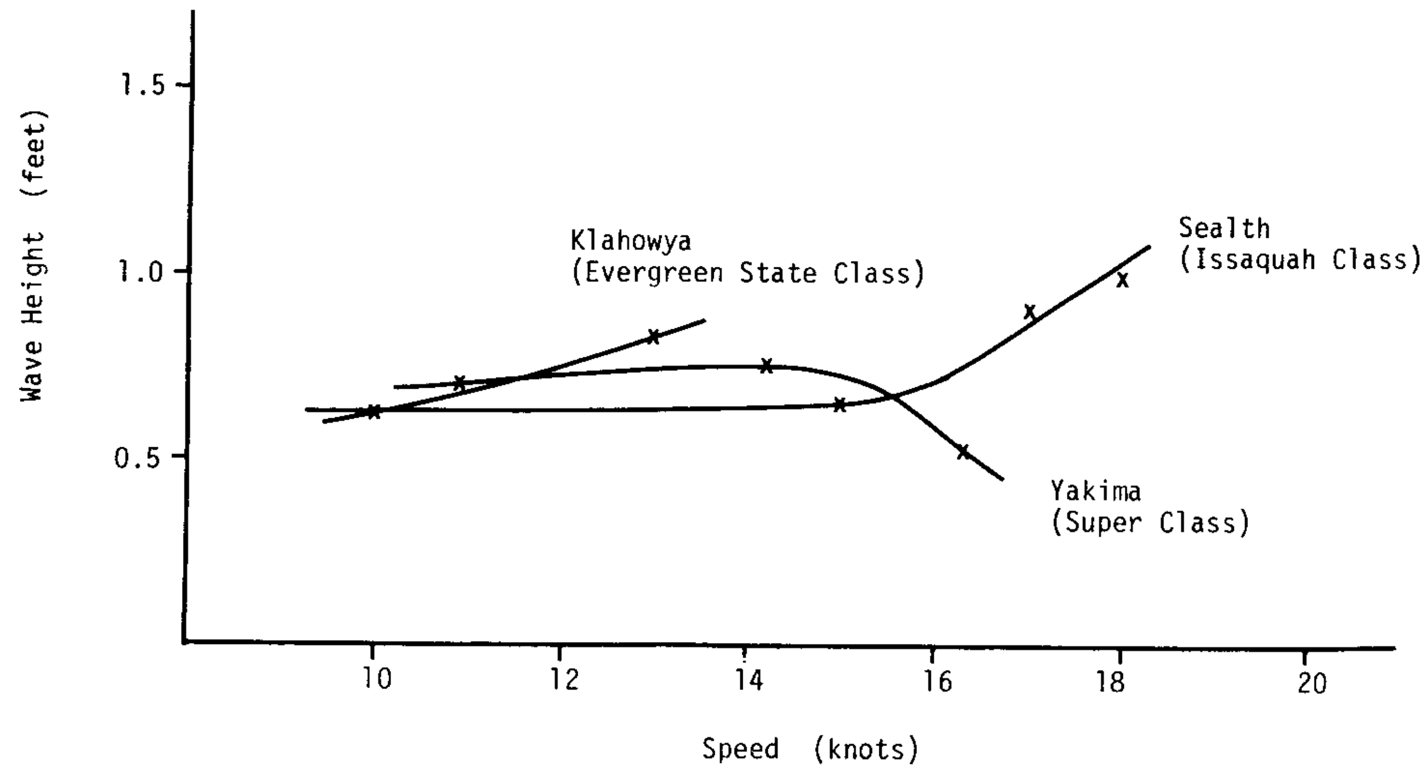


FIGURE 6-4b   Wave Heights at 600 Foot Distance from the Sailing LIne. From Wave Height vs. Distance Curves, for each Class.

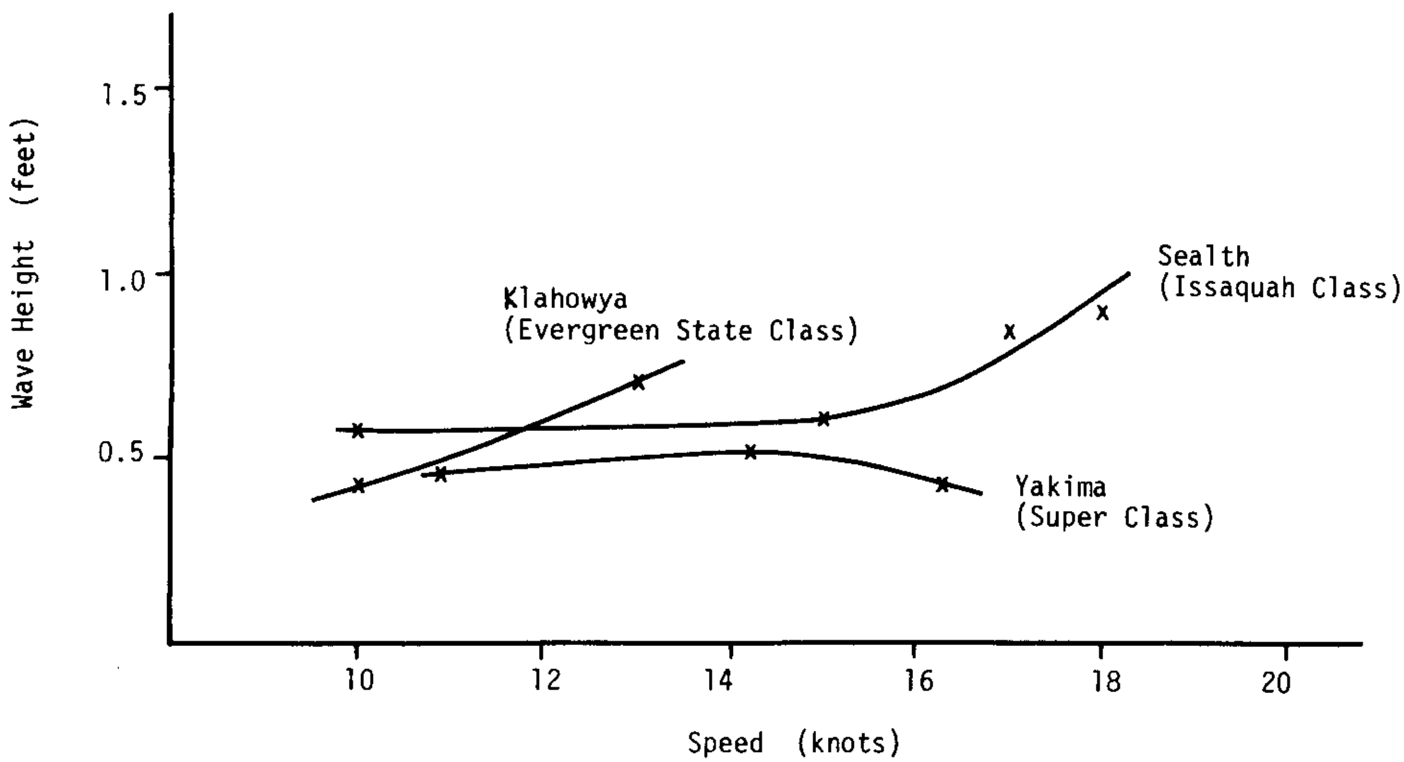


FIGURE 6-4c Wave Heights at 1200 Foot Distance from the Sailing Line. From Wave Height vs. Distance Curves, for each Class.

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