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Wave Sensor Survey

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Washington, D.C.

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WAVE SENSOR SURVEY

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ABSTRACT: A study of selected scientific and engineering literature was conducted by the NOAA/NOS Test and Evaluation Laboratory to survey the state-of-the-art of wave measurement technology. Secondary references to earlier work can be found in the selected literature. Brief descriptions of representative wave sensors and their principles of operation are given.

INTRODUCTION

Measurement of the complex characteristics of ocean wave phenomena is generally accepted to be one of the great challenges in oceanography today. Data sampling, reduction, and analysis techniques become more diverse and sophisticated with advances in the response and capabilities of wave instruments. The objective of this report is to greatly reduce the efforts of investigators who must make use of the wave-measurement instruments.

An extensive literature survey and study were combined with experiences by personnel of the Test and Evaluation Laboratory, National Ocean Survey, to determine the present status of ocean wave sensors and to catalog the available literature in a logical pattern. Most of the reported wave sensors are described briefly. (Radar-based sensors, an extensive and complex area of measurement technology, are briefly mentioned.*) In nearly all instances the approach used in this report was to summarize use, experiences, and characteristics of each specific type of sensor and to relate this information to reports documenting analysis or experience.

The study is part of a general effort by the Test and Evaluation Laboratory in support of wave measurements by the National Ocean Survey.

*Theoretical and observational studies of radar wave measurements are being made by NOAA's Wave Propagation Laboratory at Boulder, Colo.

An earlier study, the "Waves Sensor Technology Assessment," determined the characteristics of commercially available, wave-measurement instruments.

I. VISUAL ESTIMATION OF WAVE CHARACTERISTICS

Estimation of wave characteristics by an observer is a widely applied method. The estimate, both of height and direction, is available almost immediately.

Some studies indicate that visual estimates are related to the significant wave height (average height of the highest one-third of the waves). Some of these relationships are shown in fig. 1 and are described by Ross (1967), Weigel (1974), Hogben and Lumb (1967), and Paape (1969). Although some relationships have been established, a thorough study of the situation is lacking. Pierson (1967) indicates that the reporting system for routine shipboard observations introduces a large bias. No universal method of correcting for biases has been adopted. Visual observations are usually confined to a significant height and direction of principal swell.

Visual estimation can be refined with telescopes for observing buoys, pilings with marked scales, and so on (Charlton 1974).

Observations via satellite could eliminate much of the need for visual observations.

II. NONDIRECTIONAL WAVE SENSORS

Waves are generally short crested and chaotic, but, at any specific location and time, they will frequently obey (to some degree) a variance governed by some underlying statistical (stochastic) relationship. Usually this relationship has some directional basis, possibly very complex. Wave instruments capable of resolving some of these directional characteristics are discussed in section III. The nondirectional methods sum the contributions from all directions. For many purposes, this is an adequate amount of information.

A. Wave Staffs

A staff sensor is a vertical member piercing the water surface and having an output which is a function of water level on the staff. Measurement procedures are fairly simple and economical. Staff measurements, however, can be influenced by the staff supporting structure, especially for the larger waves.

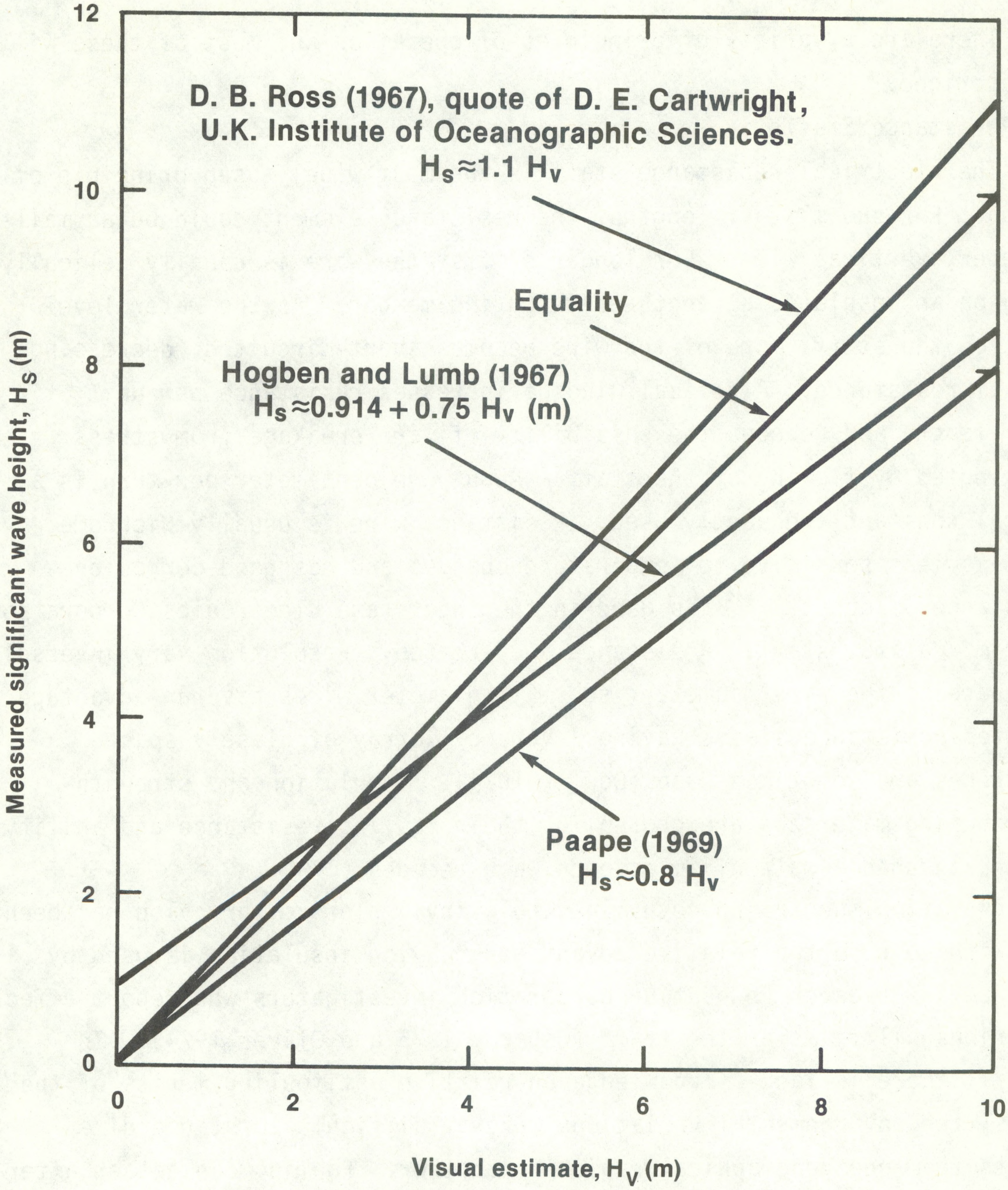


Figure 1.--Studies of visual observations of ocean waves (estimates from averages of large numbers of observations).

There are a variety of principles of operation and most of these will be described.

1. Resistance Staffs

The electrical-resistance staff is the most widely used principle of design. For short staff lengths, the resistance element could be a small-diameter, vertical wire. For longer staffs, the wire is usually helically wound on an insulated strength-contributing member. As the water level rises on the staff, more of the wire becomes short-circuited, decreasing overall resistance. A helical winding increases resistance per unit of staff length and reduces the possibility of wire breakage from stress contributed by flexing of the staff. About one centimeter per turn is a helical constant frequently used. Resistance wire is usually Nichrome, which is less sensitive to temperature changes and has good corrosion resistance. Tophat A (R) is used in the Interstate Electronics Corporation, Anaheim, Calif., staff. Resistance and, thereby, resolution vary inversely as square of the wire diameter, so small-diameter wires have an advantage.

Step-resistance staffs having a vertical array of closely spaced electrodes are sometimes used (Bowler 1974). Insulation and strength-contributing materials are chosen for their fouling resistance and ability to quickly shed a water film as each wave recedes.

Insulation such as polyethylene, polyvinyl chloride, or nylon has been used with no reported relative advantages. Nylon insulation is used by Nova Scotia Research Foundation Corporation investigators who report effects of various oil films on the staff (Osborne 1975 and Oliver 1974). In general, there is lack of knowledge on relative antifouling merits of the staffs; the environmental variations make it difficult to standardize results from one geographical region to another. Fouling can attach after an initial pollutant or biological film forms, so initial fouling resistance may not be sufficient. Resistance staffs almost always use an alternating current to prevent water polarization effects at the staff and resultant signal drift. When not restricted by any other design consideration, frequencies on the order of 1 kHz are selected with no indication of any tradeoffs with accuracy. No widely used staff uses the 60 kHz line frequency, yet 30 or 60 Hz is used in electromagnetic current meters with no significant polarization effects at the electrodes. Electronic filtering might be more difficult at this lower frequency.

2. Capacitance Staffs

The sensor (staff) consists of an internal conductor running the length of the staff and sealed from the ocean water by a covering of insulating material. This provides one conductor and the dielectric, while the outer water provides the other conductor. Thus capacitance will be proportional to level of the water on the staff and is governed by the relationship (Slater and Frank 1947),

$$C = \frac{2\pi\varepsilon h}{\ln(d_2/d_1)},$$

where C is the capacitance, h is water height, ε is the dielectric (insulation) permittivity, d_2 is the outer diameter of the staff, and d_1 is the diameter of the inner conductor. For a thin dielectric, $d_2/d_1 \rightarrow 1$ and C (per unit length) is large (good sensitivity). Early capacitance staffs frequently used thin insulation, but this technique was a compromise with durability and fouling effects (Anderson et al. 1972). Improved electronics designs have made it possible to use thicker insulation.

3. Electromagnetic Staffs

In addition to the impedance-measuring resistance and capacitance staffs, the Canadian National Research Council has developed a transmission-line wave staff (Zwarts 1974 and Ribe 1977). The staff, composed of two concentric metal tubes insulated from each other with plastic, spacer screws, is essentially a vertical waveguide for electromagnetic pulses traveling up and down the space between the tubes and bouncing off the water surface at the staff immersion level. The active element is a bistable tunnel diode producing transmitted electromagnetic pulses upon reception of pulses reflected from the water surface. The staff, vented to allow rapid water-level equalization, serves to focus the electromagnetic energy and to minimize interference. Kelk Co., Toronto markets this staff.

In worldwide use, the Baylor Corporation, Houston, Tex., model 19595 wave staff consists of two 1.3-cm-diameter, vertical, stainless steel wire ropes held 23 cm apart by top and bottom mounting plates and intermediate plastic insulator blocks. An electronic oscillator at the top of the staff transmits a continuous, radio-frequency (600 kHz) electromagnetic wave down the wire ropes. Associated circuits measure the standing-wave ratio, which is proportional to the length of the exposed staff. The staff sensitivity is proportional to the characteristic impedance of the staff which is primarily inductive at this frequency. The impedance is determined by the geometry of the staff design and is proportional to the logarithm of the ratio of the distance between the wire ropes (conductors) and the wire-rope diameter.

B. Pressure Transducers

Pressure transducers, mounted at or near the bottom, are commonly used to sense wave-induced pressures in relatively shallow water. (The maximum recommended depth is about 15 m). Individual pressure transducer designs can be studied for accuracy characteristics, but performance is more related to signal processing and recording systems than to any sensor principle. (The primary consideration in measurement of waves by measurement of wave-induced pressures is the capability to retrieve the surface wave record). Wave-induced pressures are highly attenuated with depth and are a function of total water depth, transducer depth, and wave period or wavelength. The function has been established for long-crested sinusoidal-shaped waves as follows (Kim and Simons 1974):

$$K' = \frac{P}{\eta_o} = \frac{\cosh\left[\,2\,\pi(D-h)/L\,\right]}{\cosh\left[\,2\,\pi D/L\,\right]},$$

where P is the wave-induced pressure, units of wave height,

η_o is the wave height,

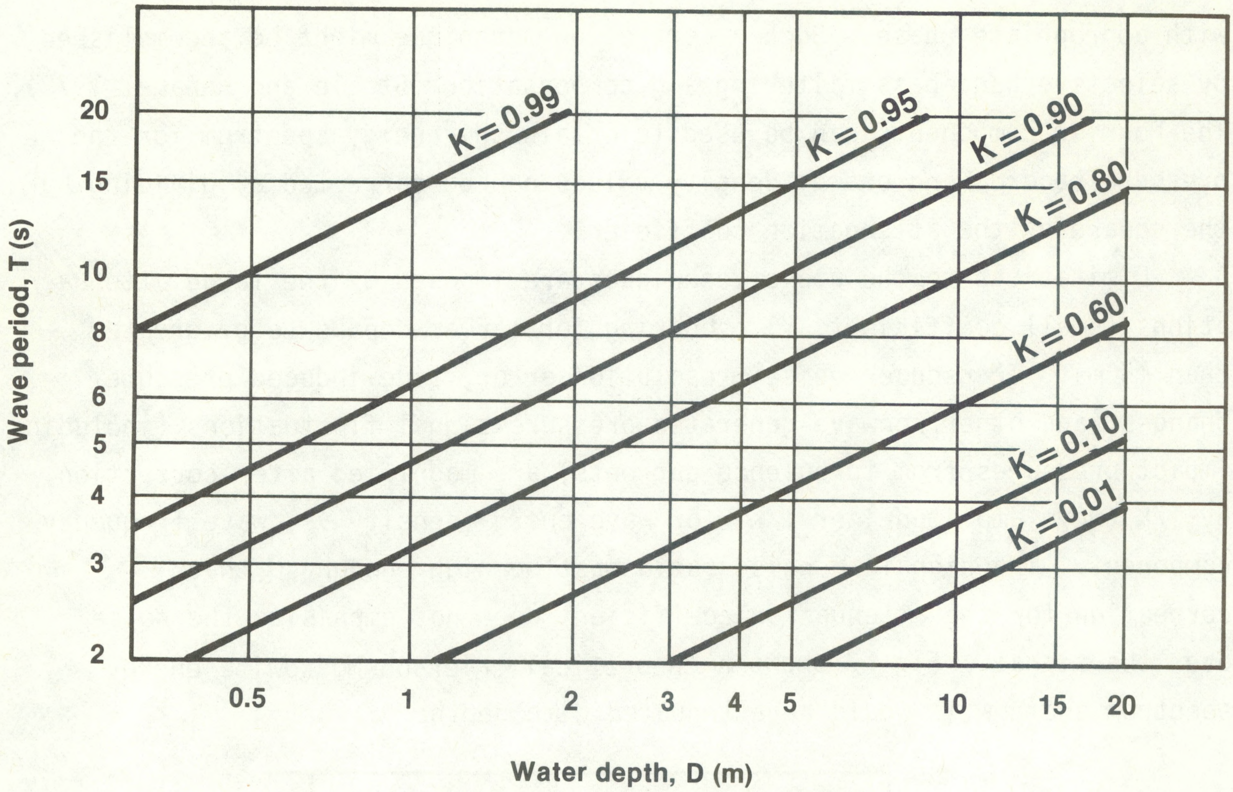
K' is the pressure attenuation ratio (1/K' = correction factor),

D is the water depth,

h is the transducer depth, and

L is the wavelength.

The attenuation terms and procedures for their use are provided in fig. 2. However, because ocean waves are rarely long crested, regular, and near-sinusoidal, errors of the order of 10 to 30 percent are introduced (Harris 1972 and Esteva and Harris 1970). Successful procedures for attenuation correction and decreasing this error involve digitizing the pressure record and obtaining the sinusoidal components by Fourier decomposition. Individual components are then corrected by the attenuation relation and reconverted



K = ratio of pressure at depth to wave-induced pressure at the surface.

For pressure transducer on the bottom, $K = \frac{1}{\cosh[2\pi D/L]}$

For transducer above the bottom, $K' = \frac{\cosh[2\pi(D\text{-}h)/L]}{\cosh[2\pi D/L]}$, with (D-h) the height (meters) of the transducer above the bottom. K′ can be obtained by dividing K, for transducer on the bottom, by a K value based on the (D-h) distance instead of depth.

Figure 2.--Attenuation of wave-induced pressure with depth.

with appropriate phase. Such a correction technique might be accomplished by selective band-pass filtering and compensation (Steele and Hananel 1978). The Fourier components can be used to obtain the energy spectrum for the pressure record, and energy density values can be corrected by dividing by the square of the attenuation coefficient.

Limitations to the above techniques are imposed by the large attenuations (small coefficient, K) occurring for larger depths (e.g. greater than 15 m). Transducer noise, resolution error, tide-induced pressure changes, and other nonwave-generated pressure signal fluctuations (including impact pressures from turbulence currents) are magnified after correction by 1/K (wave amplitude) or $1/K^2$ for wave energy density vs. wave frequency component. The signal-to-noise ratio must be high enough so that correction for the attenuation coefficient does not emphasize the noise over the signal. Fig. 3 shows a theoretical, Pierson-Moskowitz energy spectrum and how it would be attenuated with depth.

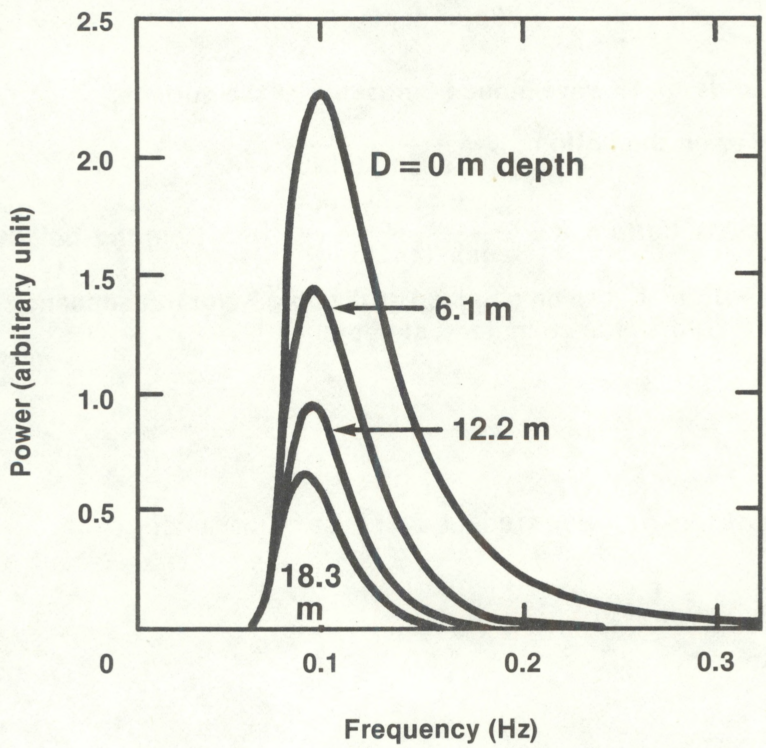


Figure 3.--Decay of a Pierson-Moskowitz surface power spectrum (from Kim and Simons 1974).

Pressure transducers are also suspended from buoys at much greater depths so that surface-induced pressures are negligible and the pressure transducer responds mainly to pressure changes resulting from vertical buoy motion. Suspended pressure transducers are described later in this section under wave follower buoys.

C. Inverted Echo Sounder

Inverted echo sounders (upward directed sonar) consist of subsurface piezoelectric, projector-receiver transducer with electrical oscillator to provide an acoustic carrier wave and pulse generator for electrical (and acoustic) modulation. Pulses reflected from the ocean surface are amplified, band-pass filtered, and processed, and, by one of several possible techniques, the transit time from acoustic-pulse transmittal to reception is measured. Variations in the transit time, properly interpreted, are a measure of surface waves above the transducer. Both self-contained and hard-wire linked systems are commercially available.

Errors can arise from a number of sources, some of which depend on the design of individual instruments and on emplantment conditions.

Fluctuations in sound velocity in the water column above the sonar transducer will be measured as fluctuations in water level. The sound velocity is dependent on water density which, in turn, is a function of salinity and temperature (Berryman 1967). Sound speed and, therefore, echo sounder sensitivity (signal output divided by wave height) will change about 0.23 percent (less sensitivity) for each 1°C increase in water temperature at 10°C, and a 0.1 percent increase in sensitivity will occur for a salinity change from 35 to 34 ppt. Small water-level changes (e.g. from tides) will not cause significant error unless they occur during a specific wave recording and corrections are not applied, for example, during energy spectrum computation. At the ocean surface, the appropriate relationship for sound velocity (C) in meters per second versus temperature (T) in °C and salinity (S) in ppt is (Wilson 1960)

$$C = 1449 + 4.6T - 0.055\,T^2 + 1.39\,(S-35).$$

A frequent occurrence in measurement of ocean waves is to encounter relatively constant temperature above a thermocline, changes of possibly 5°C to 10°C in 10 m through the thermicline, and again relative stability below the thermocline (fig. 4). Under these conditions, most of the wave action occurs in the water of near-zero temperature gradient above the thermocline, and wave height can essentially be computed from surface sound speed. A significant question to consider is possible vertical motion of the thermocline during passage of a wave which could possibly affect the accuracy of wave measurements.

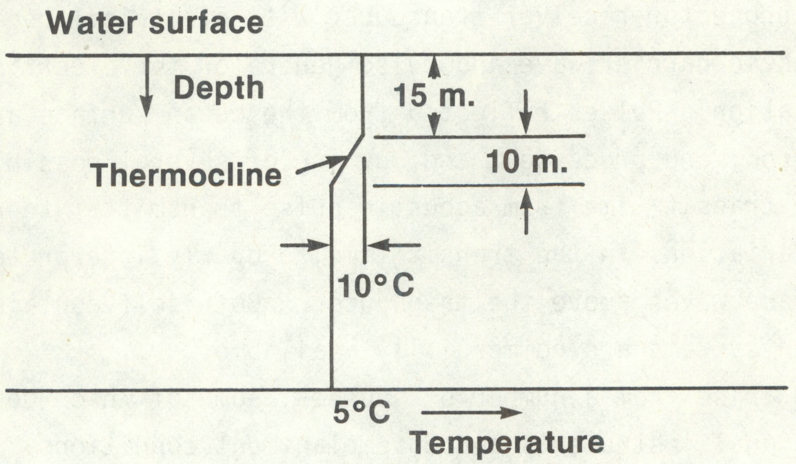


Figure 4.--A plausible water temperature variation.

Increasing transducer depth causes loss in resolution capability. See, for example, comparison spectra in fig. 4 of Ribe and Russin (1974) for higher frequencies.

Fish near the projector can sometimes produce sufficient echo to cause erroneous measurements. Some echo sounders provide a brief low-gain time interval immediately after projecting each sound pulse to eliminate such false returns.

As shown in fig. 5, ambient noise at the 200-kHz carrier frequently used for upward sonar is not a problem.

Combined acoustic-pulse attenuation and spreading losses do not impose large transducer acoustic intensity requirements unless the sonar is designed for great implantment depths. Note point at top of fig. 6, which indicates 53 dB round-trip power loss for a representative 100 m depth. An additional power loss occurs at pulse reflection from the ocean surface and is dependent on surface irregularity.

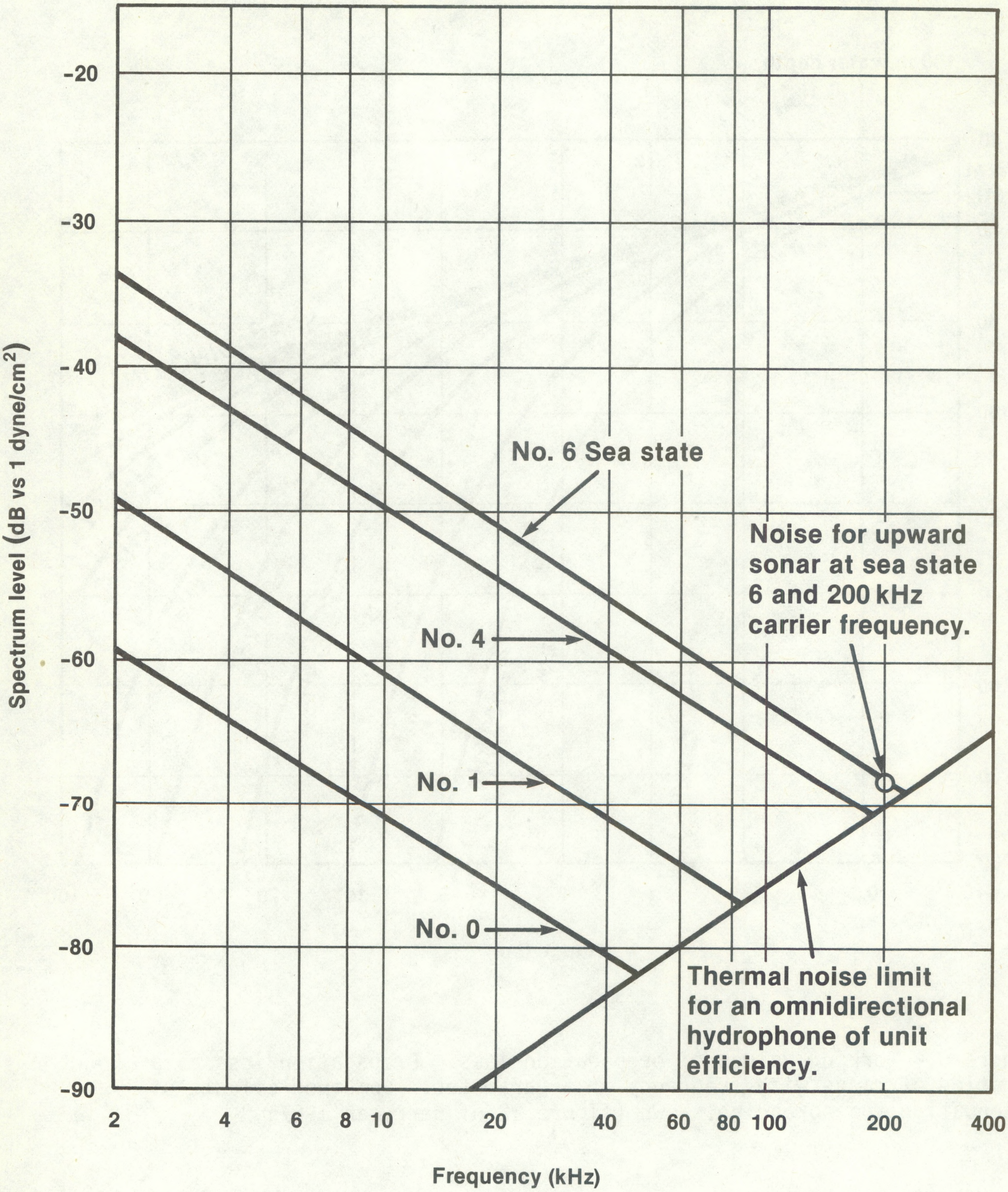


Figure 5.--Deep-water ambient-noise levels -- Knudsen curves.

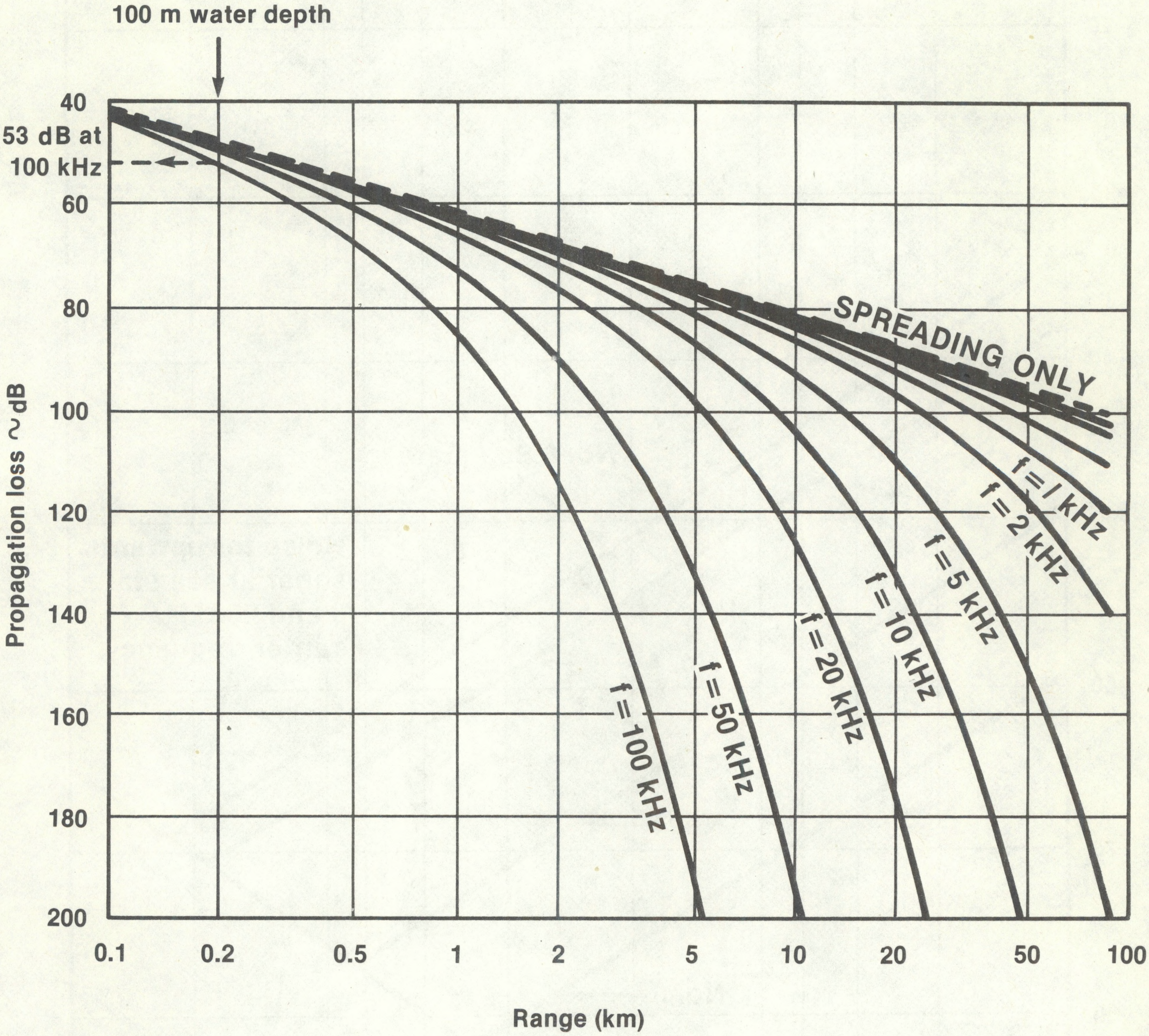


Figure 6.--Working values of propagation loss. Propagation loss as a function of range with frequency as a parameter. Combined effects of attenuation and spreading shown (figure 12 of Berryman 1967).

D. Wave Measurement Buoys

The great advantage of buoys is the ability to measure waves in deep water where no mounting structure is available. Principal categories of wave buoys are spar buoys and wave-followers. A great disadvantage is the lack of knowledge of dynamic response of the various designs for very high and steep waves, conditions where good measurement capability is needed.

1. Spar Buoys

The spar buoy is a long, vertical cylinder with possibly 70 percent of its length always submerged and approximately the upper 30 percent of the buoy acting as the wave-sensing section. The lower end of the buoy is weighted for stability and usually has some damping plate arrangement to greatly reduce undesirable vertical oscillations. The oscillations can be caused in part by changes in the buoyant force with wave-generated changes in water level on the buoy. The damping can be provided by a horizontal damping plate (with a weight beneath) at a depth where there is nearly no wave motion. The sensor has most often been a resistance-type wave staff, either helically wound or with step contacts (Kerr 1964, Pearlman 1964, and Colburn et al. 1974). The spar buoy design makes compromises between length and maximum wave height measurement and between diameter of upper section for strength and combination of overall weight and frequency response to wave stimulus (ref Kerr, Pearlman, Colburn, and Warsh). Slender upper-section diameter and heavier weight provide resonant frequency in the low range where not much wave energy is present. Longer lengths provide greater stability and higher-wave capability but are a compromise with the slender upper section and strength and ability to implant and retrieve the buoy. The final compromise depends on the intended use.

2. Wave Follower Buoys

The most frequently used sensor in a wave-follower buoy is an accelerometer. If the accelerometer is the only sensor, the buoy measures height but not direction. Combinations of accelerometers, gyros, and a compass can provide both height and directional information. Less frequently, a wave-follower buoy uses a pressure transducer suspended at depths of 100 to 500 ft (30 to 150 m) to measure buoy motion. Buoys have also been tethered with an elastic member, and tension of the elastic member was used as a measure of waves. (To our knowledge, this method is not frequently used).

(a) Accelerometer Sensors

Most useful and popular for deep-ocean wave measurements, the accelerometer buoy can be relatively portable, comparable in cost to other wave instruments, and, in some instances, operate with no requirement of a mooring system. Because of the frequent necessity to obtain high accuracy, accelerometer buoys are often extensively engineered, but the design concept allows fabrication of simpler, less expensive buoys suitable for many purposes (Marks and Tuckerman 1960). A gimbal mounting system for the accelerometer can provide about 4 percent maximum increase in accuracy of wave height measurement (Tucker 1959). Wave heights tend to be measured too low for no gimbals in the mounting system, which causes the accelerometer to tilt along with the buoy.

Datawell-b.v. of the Netherlands - In worldwide use, the Datawell Waverider is among the most sophisticated and widely used of the nondirectional accelerometer buoys. It consists of a stainless-steel sphere (0.7 or 0.9 m diameter) containing the special-design accelerometer, solid-state signal-processing circuitry, and a radio transmitter for telemetry, all operated by batteries. The sphere is balanced for static flotational stability. The buoy can be free floating with a stabilizing weight, usually a length of chain attached to the bottom of the buoy. A variety of tethers have been designed, most using a Datawell-supplied elastic cord in an anchor line attached to the bottom of the buoy. Tether design varies according to water depth at the installation site and other conditions, including tide, current, and wave range.

The accelerometer is gimballed by an original design to assist in maintaining vertical attitude under wave action on the buoy. The accelerometer signal is a variable resistance in an a.c. bridge circuit. This signal is amplified and twice integrated to provide an analog signal proportional to displacement (wave height). The signal processing includes high-pass filtering to prevent drift in the wave record. Errors occur at the high-and low-frequency ends of the wave spectrum resulting in frequency-dependent amplitude changes and phase shifts (Datawell 1967). Datawell provides graphs and correction relationships for these errors. Corrections are most easily made for energy spectrum calculations. Corrections for measured wave shapes would be more complicated. All the possible effects of the variety of tethers are not understood.

The British National Institute of Oceanographic Sciences has tested the large-amplitude response of the Waverider at low frequencies on a large ferris wheel, and the response was approximately as predicted (Draper et al. 1974). Six Waveriders have been tested on a 13-m-diameter ferris wheel by NOAA's Test and Evaluation Laboratory (study unpublished at this time). The Waverider should follow somewhat of a circular motion under action of each wave, but this is not documented for the variety of possible tether arrangements. The response of the Waverider and other accelerometer buoys to very high and/or steep waves has not been established (Datawell 1977). Comparison tests for such waves are difficult since the Waverider and the "standard" are usually not measuring the same wave. This is an important problem since high waves are the basis for structural design and might have their own statistical relationships (Ezraty 1977). For many purposes, the Waverider provides essential wave information where there are no other sources.

<u>NOAA Data Buoy Office</u> - The National Oceanic and Atmospheric Administration's Data Buoy Office (NDBO) has installed accelerometer-based wave measuring systems on most of their environmental monitoring, 12-m-diameter discus buoys, and development is continuing. Model tests and extensive analysis establish the validity of the procedures and designs. Description of the wave measurement and data acquisition and processing techniques is provided by Steele et al. (1975). The buoys have nongimballed, servo accelerometers with the output analog integrated twice to provide displacement. Estimates predict that less than two percent error in wave height is caused by elimination of gimbals and that reliability is increased. Detailed description of the wave measurement system is provided by Michelena et al. (1974). Further information is available from the Director, NOAA Data Buoy Center, Bay St. Louis, MS. 39520.

<u>Environmental Devices Corp.</u> - Also based on the principle of a gimballed accelerometer, the Environmental Devices Corp., Marion, Mass., Type 949 WAVE-TRAK buoy has a spherical float with the cylindrical accelerometer housing attached 4 feet below via a length of pipe. The accelerometer

housing has a vertical crossfin attached to increase attitude stability. Buoy motion is that of an inverted pendulum during wave passage. Period of the inverted pendulum is about 0.07 seconds and the buoy-accelerometer hydrodynamic design provides about 0.6 of critical damping. Middleton et al. (1976) provide an extensive description of the buoy design and derivation of a transfer function from buoy output to wave energy.

National Research Council of Canada - The Canadian Nationa Research Council has developed a wave buoy with gimballed accelerometer which, so far, has been used principally for wave measurements for the Canadian government (Bowler 1973 and 1974). Present models use an accelerometer of commercial manufacture. The buoy has a somewhat flattened bottom and includes a section of weighted pipe projecting downward from the bottom to increase stability. This would seem to tend to maintain the buoy vertically, while the philosophy of the Waverider is for the buoy's vertical axis to be perpendicular to the water surface.

Trident Engineering, Inc. - With low cost and expendability as prime goals, Trident Engineering, Inc., Annapolis, MD. has developed a buoy where the accelerometer and processing electronics are in a cannister suspended about 15 m below the water surface and the styrofoam, spherical float (Reynolds, et al. 1974). The accelerometer consists of strain gauges on a cantilevered beam with a weight fastened to the free end. Acceleration signals are radio or wire-link transmitted. Locating the accelerometer in deeper water provides greater accelerometer attitude stability. Signal processing includes double analog integration.

(b) Suspended Pressure Transducers

Ocean Applied Research Co. (OAR) San Diego, Calif., manufactures a free-floating, surface-following buoy, model WMS 806 that measures water elevation changes by sensing ambient pressure changes with a transducer suspended via electrical conductors below the buoy (Gaul and Brown 1966 and Gaul and Brown 1967). The transducer should be far enough below the buoy so that the wave-induced pressures have been attenuated to negligible amounts. This ensures that the hydrostatic pressure changes measured by the transducer are mainly the result of vertical buoy motion. Attenuation vs depth is a function of wave period or wavelength (fig. 7),

$$\frac{P_z}{P_o} = e^{-kz},$$

where P_z is wave-induced pressure at depth z and $K = \frac{2\pi}{L}$ = wave number, with L the wave length. P_o is the wave-induced pressure at the surface.

A relationship which provides estimates of wave period (T) as a function of length for deep-water waves is:

$$T^2 = \frac{2\pi L}{g},$$

with g the acceleration of gravity.

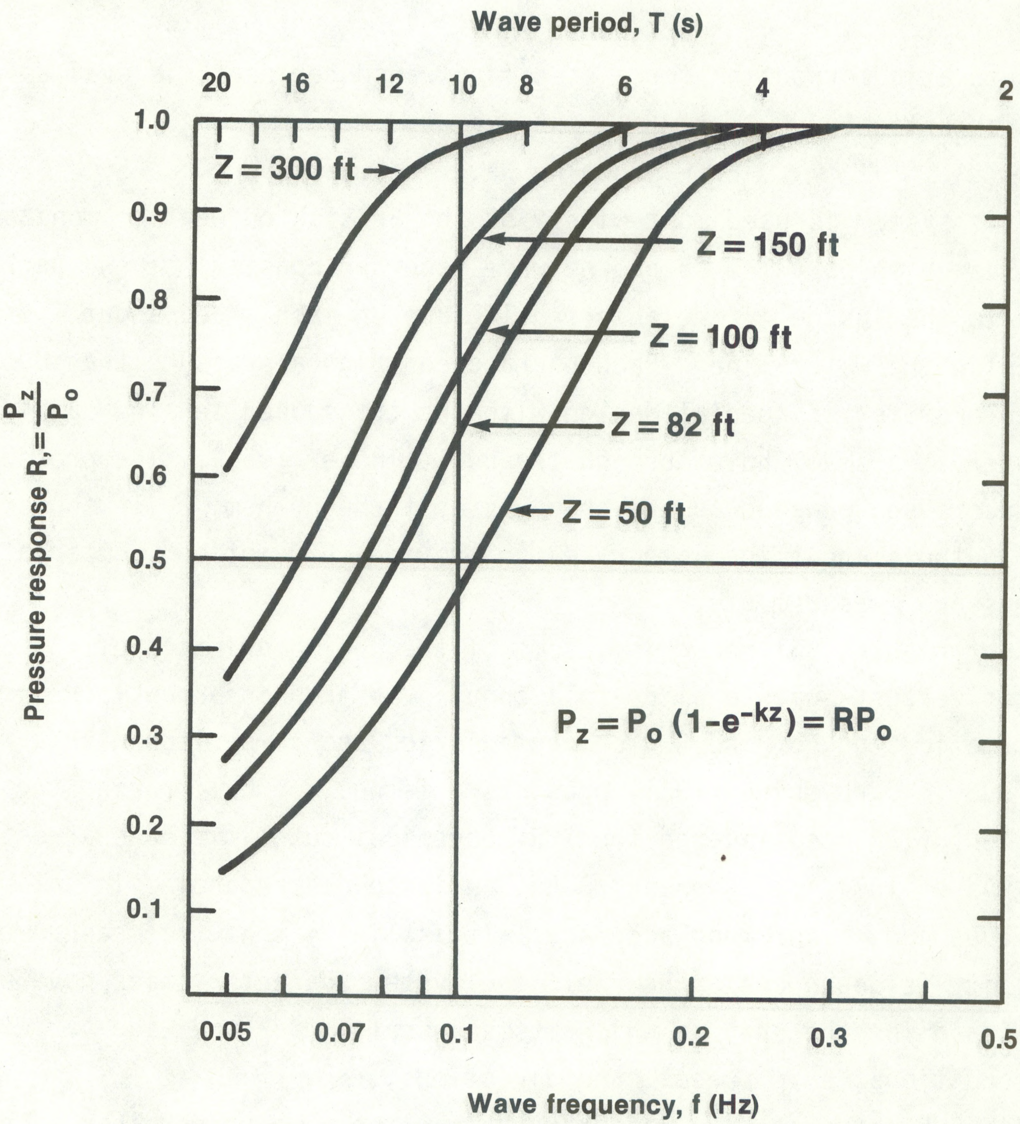


Figure 7.--Pressure response for selected mean depths of a free-floating, wave-meter transducer (from Gaul and Brown 1967).

This buoy design measures pressure changes at depth due to vertical buoy motion which is equivalent to the difference between surface pressure change (wave height) and wave induced pressure; that is,

$$\Delta P = P_o - P_z = P_o (1-e^{-kz}).$$

The square of the ratio $\Delta P/P_o$ can be used as a transfer function to convert the energy spectrum from buoy pressure measurements to the surface wave spectrum.

Fig. 7 indicates that substantial corrections to such wave pressure measurements are required unless the transducer depth is greater than about 100 meters.

Automatic correction for a specific transducer depth is available from OAR as an option.

E. Shipborne Wave Recorder (SWR)

This system is used most widely by the British on weather monitoring and research ships. The shipborne wave recorder consists of two packages welded to the inside of the ship's hull, one on each side, about midship and well below the water line. Each package contains a pressure transducer and an accelerometer of special design with the transducer sensing outside water pressure via a small hole through the hull (Tucker 1956). The pressure transducers sense waves as the ship passes through them, while the accelerometer outputs are twice integrated to provide ship-motion compensation for the pressure measurements.

Cartwright (1961) describes some of the characteristics of the SWR and comparative tests with a pitch-roll buoy. Van Aken and Bouws (1974) present a systematic study of the SWR characteristics and comparison with a Wave-rider buoy. Darbyshire (1961) presents a method for calibrating the SWR. Cartwright (1963) considered the SWR convenient but limited as a research tool. As of 1974, Van Aken and Bouws indicate discrepancies in calibration techniques and measurement accuracy. It is likely that the measurement capability is dependent on how well the system characteristics have been established for the ship in which it is installed for the wide variety of wave conditions, ship speeds, and directions.

The SWR provides wave measurements routinely where no other wave measurement technique might be used. A large number of measurements have been made with it.

F. Downward Directed Sonic (DDS) Instruments

With downward directed sonic instruments, a piezoelectric transducer is pointed at the water from above. Variations in transit time of acoustic pulses to the water surface and back are a measure of water-level variations including waves. The transit times can be measured electronically by several methods. DDS instruments are widely used for water level measurement in calm water but are much less widely used for ocean wave measurement. Definite advantages for wave measurement include fairly low power, compact and lightweight components, relatively simple electronic circuitry, and no contact with the ocean.

This technique possesses similarities to the inverted echo sounder (upward directed sonar) discussed in paragraph IIC. Sound speed (C) in air is nominally 1,100 ft/sec compared to 4,800 ft/sec in water. In air, C is dependent only on temperature, whereas salinity, temperature, and pressure effects exist in water. The longer transit times in air are a little easier to measure and the environment is less harsh, but sound speed (C) in air is likely to vary more rapidly than in water. The relation for air is:

$$C = 20.05 \sqrt{T} \text{ m/sec or } 65.78 \sqrt{T} \text{ ft/sec}$$

with T in degrees Kelvin. For small air-temperature changes, the DDS instrument output will increase 0.17 percent per degree Celsius decrease. The higher the air temperature, the lower is the recorded ocean wave compared to true wave and referenced to mean water level. In addition to the temperature effect on DDS output, it is possible to have noise interference and occasional loss of signal from the surface. Both these problems might be eliminated in a good design.

Western Marine Electronics Corp of Seattle, Washington provided a prototype modification of their model SLM15 Water-Level monitor for evaluation by NOAA (Ribe 1976). Similar instruments have measured waves, but this modification frequently lost signal in wave-tank tests. An air-temperature compensation probe was accurately matched to the sound speed relationship but had a time constant too slow to follow typical air temperature fluctuations. The time constant could probably be decreased fairly easily.

Weist (1973) describes ultrasonic water-level sensors used on Boeing Co.- designed hydrofoil ships which might have wave measurement capability. Kaplan and Ross (1968) discuss tests of an RCA Corp. ultrasonic wave sensor combined with a vertical accelerometer for obtaining wave measurements from the bow of a ship. They provide a list of other references.

G. Laser-Based Wave Systems

Reports by W. J. Pierson (1976) and Krishman and Peppers (1974) provide a very good review of the use of lasers in ocean-wave measurement.

In general, at least two techniques are used: measurement of the transit time of the light-beam modulation directed downward at the ocean and measurement of the time variation of the reflected radiance from the ocean surface as a measure of the wave statistics (Cox and Munk 1954). Studies of the relationship between a laser beam and reflection characteristics of the ocean surface are provided in a number of symposium proceedings and periodicals. Laser systems are mainly used for research, and there seems to be no special standardization of instrumentation or techniques. Procedures are still evolving.

III. DIRECTIONAL WAVE SENSORS

At the present time, there is considerable activity toward development of wave directional measurement devices and techniques. There is a great need for a relatively simple and economical device or technique with adequate directional resolution (Dean 1974). The large amount of information necessary to properly describe the wave magnitude, frequency, and direction is a basic problem. Uncertainties enter into the results from instrumentation characteristics, limits on sampling rate, randomness of the waves being sampled, and techniques of data processing and analysis (Bennett 1971). Frequently the result is a best estimate, and estimates of uncertainty in the measurement are sometimes based on previous application to theoretical examples. There do not seem to be any good estimates of the effect of instrument characteristics on errors or of the uncertainties in the results from the use of various data processing and analysis techniques. Panicker and Borgman (1974) provide a good summary of the status of capabilities and relationships for data analysis.

Instrumentation most frequently used is arrays of wave staffs. Certain types of radar hold promise. There are indications that more pitch-roll-type directional buoys will be used, especially in deep-water and farther from shore where directional measurements are infrequently made. Datawell Company will soon manufacture a pitch-roll buoy patterned somewhat after their Waverider. Environmental Devices Corp. of Marion, Mass. is developing a directional buoy.

A. Wave Staff Arrays

Although new devices such as solid-state, two-axis current meters and instruments to measure force vectors from wave induced currents (paragraphs III D. and E.) provide convenient and relatively economical methods for measurement of wave amplitude and direction, greater effort and attention is directed toward wave-gauge arrays (Dean 1974, Weigel 1974, and Pannicker 1974). Wave staffs and pressure transducers are used in almost all the arrays, the staffs having the advantages of providing true wave heights unattenuated by the water depth.

Tsuchiya and Yamaguchi (1974) installed an array of four capacitance staffs at the end of a long pier at Ogata, Japan on the Japan Sea.

Dean (1974) estimates directional accuracy effects for littoral drift where a high premium is placed on directional accuracy. It might be noted that the directional uncertainties of deeper water are somewhat reduced as the wave reaches shallower water; refraction directs the waves in toward the shore as seen in fig. 8. However, other influences in shallow water have not been thoroughly analyzed and quantified (Wood 1976).

Oakley and Lozow (1977) study design characteristics and sensitivity of arrays of up to five sensors for both conventional and maximum-likelihood data analysis techniques. Effects of errors in array spacing, instrument noise, and resolution of delta-function inputs are considered in a theoretical manner. This provides a frame of reference for relative merits of the techniques. Their use of a delta function might be too severe a test to be representative.

Davis and Regier (1977) provide extensive insight into the properties of the resolution of arrays for the various data-analysis techniques.

Der and Watson (1977) provide description and analysis of a Canadian array of 14 capacitance staffs in Lake Ontario.

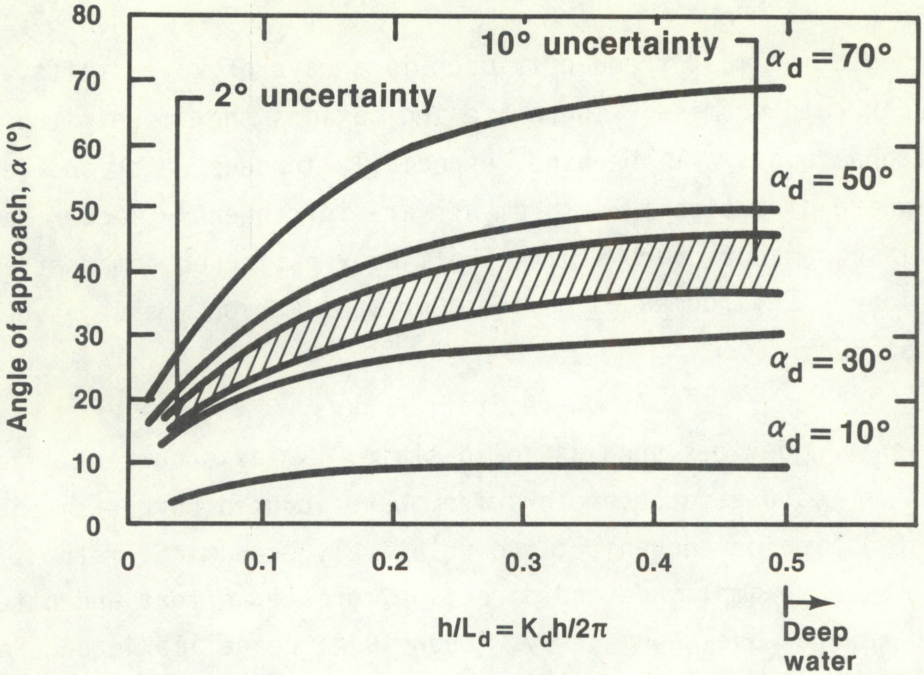


Figure 8.--The change in the angle of approach α with water depth h for representative deep-water angles of approach α_d, where L_d= deep-water wave length and K_d= deep-water wave number. Modified from Kinsman (1965).

B. Other Arrays

Pressure-transducer and inverted-echo-sounder arrays can be used for directional measurement of waves. Other sensors such as downward-directed laser and radar would be feasible for arrays, but no reporting on such systems was discovered in the literature search. Small, economical, X-band radar transducers and low power (infrared) lasers are now available for such purposes, but no studies of their use have been located or are indicated. Tsuchiya and Yamaguchi (1974) mention installation of two inverted-echo-sounder arrays but present no description or test results.

Pressure transducers were used in an array located off Pt. Mugu, Calif. Borgman and Panicker (1970) and Panicker and Borgman (1974) provide the necessary transfer functions. Results of Pt. Mugu array wave measurements are reported by Panicker (1971). Esteva (1976) analyzes measurements from the same array and uses computer simulation to isolate some of the sources of measurement uncertainty in three-gauge arrays.

C. Buoys

The original concept of using buoy motions for measurement of wave direction was developed by Barber (1946).

1. Pitch-Roll Buoys

In addition to the vertical accelerations, as measured by the Waverider accelerometer buoy, the pitch-roll buoy provides a measure of direction by measuring orthogonal components of wave slope (pitch and roll) with respect to some directional reference.

The buoy provides the basis of calculating in-phase and out-of-phase components of the displacement and slope spectra which, in turn, allow determination of the first five coefficients in a finite Fourier series expansion of the wave energy as a function of direction at a number of representative wave frequencies. The angular resolution (capability of separating two spectra peaks) of such a system has been stated to be $\pm 44°$ by Stewart (1974). For closer-spaced peaks, the buoy will still provide a mean direction. Pitch-roll buoy design is a compromise between large enough size to prevent capsizing in high waves and ability to respond to the smaller and higher frequency waves.

Each of the various pitch-roll buoy designs has a number of characteristics such as noise and resonances which enter into the record. It is necessary to extensively analyze the system and make design and data processing/analysis compensations.

(a) British Institute of Oceanography

Pitch-Roll Buoys were developed by the British National Institute of Oceanography that is now part of the Institute of Oceanographic Sciences (Longuet-Higgens et al. 1961). This original buoy was a cast aluminum disc, ellipsoidal in cross section and 6.5 ft in diameter. The sensors consisted of a gimballed accelerometer similar in design to the Tucker Shipborne Wave Recorder (Tucker 1956) plus pitch and roll sensors based on gyroscopes. (No further description of the pitch-roll sensors is contained in the Longuet-Higgens reference.) In addition, for study of wave generation, air turbulence, and other concepts, a microbarograph was installed at the top of the buoy. Recording was internal with a 12-channel galvanometer-recording camera. The buoy was maintained in a relatively constant alinement with the wind by use of a drogue (sea anchor) and pellet (small float which supports the drogue) harness. The buoy was usually not tethered.

Two later versions of the buoy were a hollow plywood disc and a fiberglass reinforced plastic toroid (Cartwright and Smith 1964). Potentiometers were used to sense pitch and roll movement of the gimbals supporting the gyro for the accelerometer. A specially designed compass was installed to provide buoy yaw reference.

(b) Hudson Labs

The Hudson Lab (Columbia University) buoys were designated VARP for gyro stabilized Vertical-sensing Accelerometer and Roll-Pitch indicators and later VARP-MAG for prototypes where a gyro-stabilized, fluxgate magnetometer was added for heading reference. Most tests were conducted with the buoy, a styrofoam disc 3 ft in diameter and 4 in thick, having no magnetometer but using a fin to stabilize direction with respect to the wind. The sensors were contained in a cylindrical housing in the center of the buoy. Power and signal were provided by hardwire link from a ship. Theory is reported by R. A. Saenger (May 1969 - part I) while engineering and data processing is covered in part II. The transducer instrumentation is reported by Goldberg and Goldberg (1969). W. Jordan (1969) described the mechanical design, construction, calibration, and field deployment.

The buoy was used extensively by the U. S. Naval Research Laboratory to measure ocean surface conditions for reference in low-frequency, underwater-sound, surface-scattering experiments, and Saenger (1972) presents some of the test results together with a useful summary of the buoy design and characteristics, theory of measurements, and a guide to what might be expected with respect to accuracy.

(c) Scripps Institute of Oceanography

Between Dec. 1968 and Dec. 1973, Scripps Institute of Oceanography worked under contract with the Office of Naval Research to develop and test a pitch-roll buoy (Stewart 1974). The buoy is a 5-ft (1.5-m)- diameter disc of polystyrene foam between plywood end plates. The buoy is free floating and records the digital data internally on computer-compatible magnetic tape. The sensors are a gyro-mounted accelerometer for vertical accelerations and a gyrostabilized magnetic compass (a north-seeking gyro with position determined by use of a resistance potentiometer). Tilts are also measured with resistance potentiometers. An above-water fin provided directional stabilization with the wind. Power is provided by six, 20 ampere-hr, gel-cel, lead acid batteries providing about 20 hr operation time. Time controlled, intermittent operation extends this to a considerably longer deployment time. The buoy was tested in sea states corresponding to winds of 15 m/sec (34 mph) without capsizing. This buoy is extensively engineered, building on experiences of the British Institute of Oceanography and Hudson Labs. Honeywell, Inc. provided both the vertical gyro/accelerometer assembly and the buoy hull assembly.

(d) NOAA Data Buoy Office

The NOAA Data Buoy Office (NDBO) has been developing techniques for providing directional capability on their discus buoys by installation of pitch-roll sensors and directional sensors (Steele et al. 1978).

(e) Other developments in pitch-roll studies

Datawell, b.v. of the Netherlands plans to market pitch-roll buoys in 1980 (Datawell 1978). The hull is to be nearly hemispherical.

Duncan Ross of NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML), Miami, Fla., has obtained a newly manufactured pitch-roll buoy from the British Institute of Oceanographic Sciences.

W. E. Baker (1970) describes a design by the British Admiralty Underwater Weapons Establishment where a toroidal buoy with pitch-roll capability, similar to that described by Cartwright and Smith (1964), was modified for additional higher-frequency measurements. Modification consisted of mounting eight resistive wave staff probes in a circular pattern around the float. A modified version of this design was commercially available from Marconi Space and Defence Systems, Ltd., Great Britain (as of 1972).

Environmental Devices Corp. has developed a pitch-roll buoy with external configuration nearly identical to their nondirectional wave buoy.

2. Cloverleaf Buoy

The British National Institute of Oceanography's cloverleaf buoy (Cartwright and Smith 1964) is an approach to improving directional resolution over that of pitch-roll designs. In addition to the compass and gimballed gyro, the cloverleaf buoy uses three disc-shaped floats which form vertices of an equilateral triangle. The floats are attached to the buoy frame by universal joints, each having two-axis, linear potentiometers to provide two components of tilt for each float (pad) relative to the frame. The sensors provide measurements of wave curvatures and an additional four coefficients of the directional energy distribution equation at each representative wave frequency. Power and a data link to the buoy are provided by a 26-conductor cable buoyed with small floats. Tests and studies of the cloverleaf are provided by Cartwright and Smith. Mitsuyasu et al. (1975) report further use of a cloverleaf buoy.

Although ocean waves are considered to be generally short crested, random, and chaotic, no study was encountered where estimates were made of the effect of the random nature of waves on uncertainties in directional measurements via measurement of slopes and curvatures. However, there are reports of analysis of slope distributions of waves usually directed toward analysis by radiation scattering, for example, Krishnan and Peppers (1973), Saenger (1972), and Pierson and Stacy (1972), which might be used as a basis for such studies.

3. Spar-on-its-side Buoy

The pitch-roll buoy is the simplest, most widely accepted directional buoy, but it lacks good resolution and is too complex for some purposes. The cloverleaf buoy is considerably more complex and has been restricted in use principally to the British Institute of Oceanographic Sciences. However, both the pitch-roll and cloverleaf buoys can capsize. There is a definite need for a simpler design of directional buoy, and the spar-on-its-side buoy is a design intended to fill this need.

The prototype, Model 864, developed by Environmental Devices Corp., of Marion, Mass. (1977) is a cylinder of 9 in (0.23 m) diameter and 19 ft (5.8 m) length balanced to lie on its side with a preferred cylinder ray along the top. This cylinder tends to aline parallel to the wave crests. In deep water, the cylinder is tethered to a subsurface buoy via a line from the midpoint. The cylinder contains a potentiometric compass and a potentiometric roll sensor which provide information on wave-induced buoy roll and directional orientation of the cylinder as measures of wave direction. The roll sensor removes 180° ambiguity. Oscillations of direction measurement are a measure of the directional dispersion of the wave energy. The concept is empirical in nature. If the technique shows favorable characteristics, an accelerometer to sense wave height will be added. Preliminary tests indicate that the design senses direction for specific wave periods but is insensitive to others.

4. Force Vector of an Elastic Tethered Buoy

Studies at the University of New Hampshire have determined characteristics of a toroidal buoy moored via a highly elastic tether under tension at all times (Winn et al. 1975 and Stotz et al. 1975). The sensor consisted of a tether-force-magnitude tensiometer and two inclinometers to measure direction components of the tension. A pressure transducer measured water height for calibration purposes. These were all mounted at the anchor/tether-cord junction. Power source and information transmitted were via hard-wire link along the ocean bottom to a remote shore station.

5. Spar Buoy With Staff Array

Spar buoys using staff arrays for wave direction measurement, that were located in the literature survey, were the "Triset" by Interstate Electronics Corp. (Ford 1967 and Ford, Timme, and Trampus 1967), the TRITON buoy used in the 1968 Barbados area studies (Warsh et al. 1972), and the research platform FLIP, also used in these Barbados BOMEX studies (Regier and Davis 1977 and Davis and Regier 1977).

The Triset spar buoy was developed initially for use by the Naval Undersea Weapons Center, China Lake, Calif., in 1967. It had three resistance wave staffs located at the corners of a right triangle. Staffs were 6 m long. Wave direction was related to a buoy-heading sensor. A buoy response period of 20 s allowed some buoy motion to enter the record. The buoy was said to provide satisfactory radio telemetry of wave data to a shore station. The buoy could be tethered to a deep-water, subsurface buoy.

Warsh et al. (1972) describe tests with the TRITON meteorological and wave-measurement buoy. The TRITON, one of the larger spar buoys, was used in the BOMEX large-scale meteorological experiment. It had a triangular array of resistance wave staffs, the triangle having sides of 1.6-by-1.6-by-2 m and staffs of 3.7 m length. Vanes allowed orienting the staff array into the wind. Two accelerometers and a pressure transducer allowed compensation for buoy vertical motions, but, usually, a digital, high-pass filter with 0.06 Hz cutoff instead of buoy-motion compensation was applied to the wave data.

The FLIP research platform had six resistance wave staffs of five meters length. The staffs were of Nichrome wire helically wound on PVC pipe. They were mounted on booms in an array such that calculation of the wave directional spectrum, using all the combinations of pairs of staffs, would provide spectra over a wide range of wave frequencies. Regier and Davis (1977) describe some of the data analysis techniques and analyze some of the test results. Davis and Regier (1977) provide extensive analysis of array design and data analysis techniques.

D. Current (Velocity) Meters

Certain fast-response, current meters having 360° directional capability and positive negative sense can be used to measure wave height and direction. Some orthogonally ducted impellers (Ribe 1975 and Wood 1970), orthogonal propellers, and a number of solid-state (no-moving-parts) current meters (Appell and Woodward 1973) can also provide this measurement. Two orthogonal components of horizontal velocity would be measured. These current meters, along with pressure transducer or staff measurements, could be used to obtain both height and direction. Panicker (1974) indicates that these measurements could be used to calculate coefficients in the Fourier-series representation of the directional spectrum analogous to the method used in pitch-roll buoy calculations.

Reports on measurements are given by Bowden and White (1966) and Nagata (1964). There are many reports on studies of wave-induced velocities (Krapohl 1972).

E. Devices to Measure Force Vectors from Wave-Induced Currents

There have been a variety of instrument designs for measurement of wave direction from wave-induced forces. Yet, there are no commercially available instruments using this principle. Panicker and Borgman (1974) provide general transfer functions for this mode of measurement.

A simple sensor for this type of measurement would be a cantilevered circular cylinder, mounted vertically from the top, with a thin wall to provide high strains at the surface (for increased sensitivity) and strain gauges mounted at 90° angles around the periphery near the base (top). Measurements of drag force would be used to calculate wave-generated velocities which could then be used to measure wave heights and directions. Such a configuration has a drag coefficient dependent on Reynolds number via velocity and viscosity coefficient, and drag coefficient will vary with roughness and with water temperature. Even so, attenuation of wave-induced velocity with depth is not an easy function to manipulate, and drag is proportional to square of velocity. Steady-state currents can bias results. In effect, it is complicated to relate such measurements to a surface wave condition. It could be more practical to use a separate sensor for water elevation vs. time and use the subsurface force-vector direction to correlate waves with direction.

Raman et al. (1974) use a variation having a cantilevered steel strip (with strain gauges) inside a horizontal duct. Gauge output varies as square of the velocity component along the axis of the duct as would be expected. This instrument was used in a laboratory wave flume.

Smith and Harrison (1970) investigated a number of designs of spheres, approximately 9.4 cm in diameter and used various patterns of systematic surface roughness to decrease Reynolds - number variation effects. A two-component drag balance, based on foil strain gauges, was mounted inside the sphere as interface between the sphere and mounting rod (sting). Tests and theory are provided. N.B.A. (Controls) Ltd. of Farnborough, Hants, England, sells a similar instrument.

Lowe, Inman, and Winant (1974) describe an instrument developed at Scripps Institute of Oceanography for nearshore studies. The sensor consists of an 8.9-cm-diameter, air-filled, filament-wound pipe, attached via a universal joint to an anchor plate. The pipe extends above the water and is capped with a telemeter antenna. The top of the pipe contains orthogonal accelerometers and a radio transmitter. The authors have developed relationships between pipe tilt and wave-induced velocities and have conducted tests to confirm the relationships.

Retief and Vonke (1974) of South Africa have developed a low-cost, wave-generated force indicator to measure the direction of swell in the nearshore zone. A cylindrical bristle brush attached to the top of a shaft extends downward through the top of a sealed, oil-filled cylinder that rests on the bottom. Because the shaft is free to pivot where it enters the cylinder, the lower end of the shaft, when deflected by swell-induced forces, contacts a ring consisting of a linearly wound electrical resistance. Thus, resistance, converted to an appropriate signal, is a measure of direction of deflection of the shaft-brush. A variety of techniques and instrumentation have been developed for this sensor.

F. Remote Sensing

Remote sensing can, at times, increase the area of ocean surface studied. Some remote sensors can also measure wave direction, possibly with good accuracy. The useful life of the remote sensors is much greater than those exposed to the marine environment.

1. Radar

A variety of techniques, using different types of radar sensors, are being developed. This is an active and expanding field with some techniques simply consisting of downward-directed sensors mounted on a platform while others will measure sea state for large areas of ocean quite rapidly. The NOAA Wave Propagation Laboratory, Boulder, Colo., is in the forefront of radar studies. Recent publications by Barrick and Lipa, J. W. Maresca, Jr., and C. C. Teague are compiled and edited by Earle and Malahoff (1978).

2. Photography

(a) General Photography

Photographs of the ocean surface, when directional orientation is established, can provide sea state and direction to the trained interpreter. Pierson (1976) describes conditions and techniques for improving efficiency. McClenan and Harris (1975) provide extensive study and analysis of a variety of aerial photographs of ocean wave conditions.

Stilwell and Pilon (1974) have established a technique for systematic analysis of photographs of the waves. A holograph is made of the photographic negative which is then digitized by means of a densitometer. Pierson (1976) indicates that the system is infrequently used; it requires high precision of technique and analysis. Klemas et al. (1974) describe modifications of apparatus and techniques of the Stilwell method to adapt it to shallow water where the wave field is inhomogeneous (spectra changing with depth). King and Lizzi (1973) have modified the Stilwell technique to use television equipment. Krishnan and Peppers (1974) summarize photographic analysis techniques as of 1974 and also discuss some other optical techniques based on the characteristics of illumination reflected from the ocean surface.

(b) Stereo Photographs

The original major contribution in this technique was provided by Cote et al. (1960) and Chase et al. (1957). The concept is to obtain and interpret simultaneous, stereo photographic pairs from two cameras of known, optimum spacing and height above the water (usually mounted on airplanes in formation) and with some sort of scale distance on the photographs. Special apparatus is used to make measurements from the photographs. Kinsman (1965) provides a convenient summary of the situation. Holthuijsen et al. (1974) describe planning techniques and results based on this concept for developments in the Netherlands to 1974.

Pierson (1976), who participated in the original Stereo Wave Observation Project (SWOP), provides a summary with up-to-date commentary. He believes that a renewal of the project, using modern techniques, would be of great value and considerably less tedious in data reduction and analysis.

There have been other references related to the SWOP project and techniques. Some provide suggestions for improvement. Nearly all include some comment on the difficulty of the technique and admiration for the tenacity of the participants.

The U. S. Naval Oceanographic Office, using the same photograph processing procedures as SWOP, took a series of photographs in 1964 (Simpson 1967) with an improved stereo technique. Test conditions caused some difficulty in getting good results.

(c) Satellite Photographs

There have been other approaches to photographic studies and they are dispersed throughout the literature.

Libby et al. (1969) discuss satellite photographs from the manned Apollo 6 satellite and remark on the great clarity of enlargements of ocean wave images taken from a satellite altitude of 115 miles. They suggest using a polar orbiting satellite with television camera as a primary standard of worldwide wave measurement.

Since the Libby paper, there have been considerable advances in unmanned satellite photographic monitoring, e.g. the GOES satellite, but a survey of the literature in this field was not implemented.

G. Crest-wave-on-pile Gauge

Hallermeier and James (1974) have made extensive studies of wave crest runup and drawdown around a pile with the purpose of using the characteristics to design a gauge measuring heights and directions. The program is continuing.

H. Shipborne Wave Recorder (SWR)

The usually nondirectional shipboard wave recorder can be used as a measure of wave direction. It is necessary to determine the SWR transfer function versus direction by, for example, comparison with a pitch-roll buoy (Cartwright 1961). Routine wave direction measurement would then require measuring waves while steering a controlled sequence of courses through 360 degrees. No indication of frequent use of this technique was encountered.

DISCUSSION

Probably for good reason, there is occasional comment on the necessity to standardize ocean wave measurement instrumentation and techniques. It became very obvious as this study progressed that there has been little progress toward standardization. There are no sensors that are suitable for all the wide variety of measurement applications.

Wave direction measurement is required for many purposes, but routine measurement is restricted to shallow water and to a few offshore towers for staff or pressure-transducer arrays. Data reduction and analysis techniques have their own accuracy and error contributions which can be substantial. Recently, major oceanographic organizations have devoted more effort and funds to wave direction studies. This is an area of great activity.

Many of the sensors or wave instruments encountered in the literature survey represented considerable development effort yet never received wide acceptance.

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