Ocean-Wave Measurement by Sonar[1]

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ABSTRACT

A bottom-mounted, narrow-beam active sonar has been designed, built, and operated to measure wave height in the open ocean. Experiments were carried out at a depth of 44 m. The apparatus is capable of measuring wave height at depths ranging from 6 to 67 m without modification, and to 150 m with a minimum of development. The amplitude resolution of the wave measurements was about 1 cm, and the spatial resolution on the surface of the ocean was approximately 60 cm. The wave data have been processed by digital methods, and the autocorrelation functions and power spectra of the ocean waves have been computed.

Introduction. The distribution of energy and frequency in ocean waves has been investigated by Neumann (5, 6), and the result is usually expressed as a power spectrum. Neumann's work is largely theoretical and is concerned with a "fully developed sea," that is, the surface disturbance of a body of water, infinite in both surface dimensions and depth, on which a wind, constant in speed and direction, has been blowing for an infinite period of time.

No serious attempt has been made to verify Neumann's predictions in water deeper than about 15 m (1, 7). Conventional types of wave-height recorders are not suitable for such an investigation, because they lack resolution—particularly horizontal resolution. In addition, most recorders are operable only in shallow water, where the Neumann distribution would not be expected to hold. The present work is concerned with development and use of an acoustic apparatus that has sufficient resolution to permit a comparison of the real ocean wave structure with Neumann's predictions.

Apparatus. Wave-height measuring apparatus used in the past has been of two basic types—either that which measures pressure at a point below the surface or that which observes a surface-piercing wave staff. Neither type is suitable for obtaining continuous records in the open ocean with the required resolution. In seeking a more suitable method, it was determined that an upward-looking, narrow-beam echo-sounder was the most promising.

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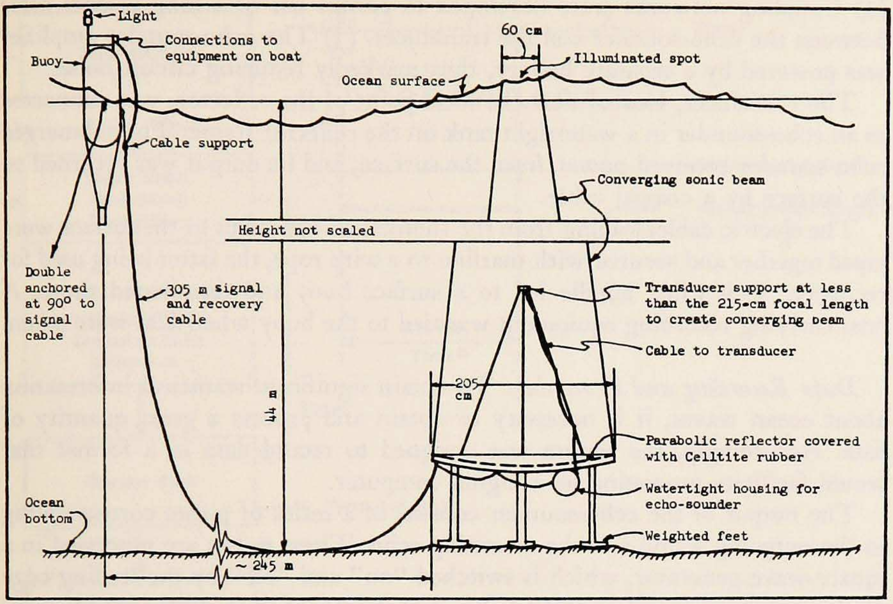

Figure 1. Geometry of experiment.

In specifying the horizontal and vertical resolution required, it is noted that the Neumann spectra show negligible energy at frequencies higher than 0.6 cps. This corresponds to a wave length of less than 6 m and to a crest-to-trough height of less than 30 cm. This leads to a specification of vertical resolution of a few millimeters, and horizontal resolution of about 60 cm. These two requirements are not directly interrelated. Horizontal resolution is obtained by focusing, while vertical resolution depends on a degree of electronic sophistication.

The apparatus is basically a reflector and an echo-sounder arranged to focus the sonic beam to finitude, with an image of the transducer formed at the surface of the ocean (Fig. 1). Ideally, the reflector should be spherical and of long focal length. However, readily available reflectors were all parabolic, and parabolic reflecting systems do not form conjugate foci. Despite this, a parabolic reflector of 205-cm diameter and 215-cm focal length was used satisfactorily. This reflector was made of Fiberglas laminate, covered with 3-mm thick "Celltite" cellular rubber.

The echo-sounder was of the type sold for use by yachtsmen. It operates at approximately 200 kc, is completely transistorized, has a scale depth of 73 m (240 feet), and makes 10 measurements per second. It was modified in the following manner: (1) The aperture of the transducer was reduced to $3/2\,\lambda$; thus it generated a wide beam capable of illuminating the whole reflector.

(2) Coupling networks were developed to permit use of a long coaxial cable between the echo-sounder and the transducer. (3) The echo-sounder amplifier was powered by a separate battery, thus markedly reducing circuit noise.

The transducer, located near the focal point of the reflector, was connected to an echo-sounder in a watertight tank on the reflector frame. The submerged echo-sounder received power from the surface, and its output was returned to the surface by a coaxial cable.

The electric cables leading from the submerged apparatus to the surface were taped together and secured with marline to a wire rope, the latter being used for recovery. This cable bundle led to a surface buoy and terminated there. A boat carrying recording equipment was tied to the buoy when data were taken.

Data Recording and Processing. To obtain significant statistical information about ocean waves, it is necessary to obtain and process a great quantity of data. Accordingly, the system was designed to record data in a format that would facilitate processing by a digital computer.

The output of the echo-sounder consists of a series of pulses corresponding to the outgoing sound and the returning echo. These pulses are processed in a square-wave generator, which is switched "on" and "off" by the leading edge of the outgoing sound and the echo, respectively. Gates with variable time delay permit switching only at times when a signal is expected; thus actuation is prevented by spurious echoes or noises. This is similar to leading-edge

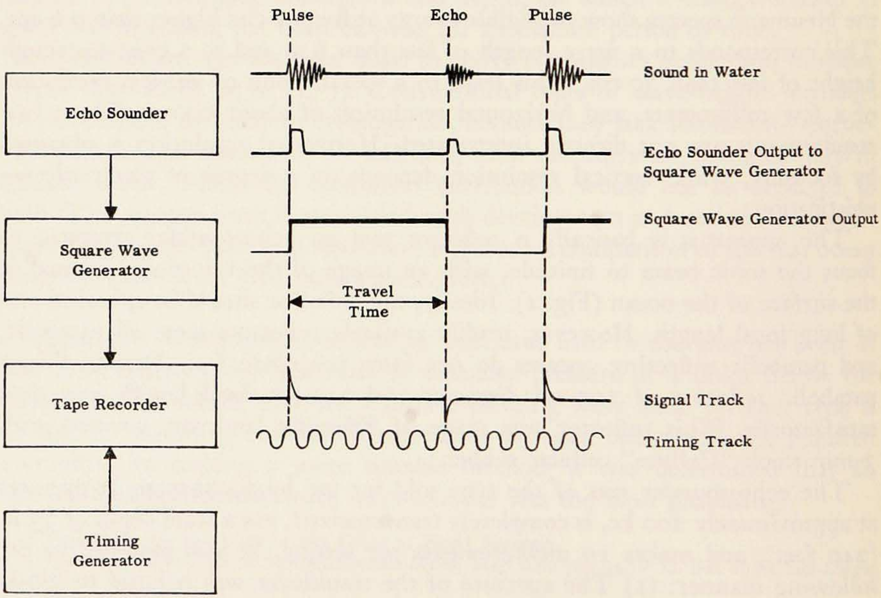

Figure 2. Data recording system.

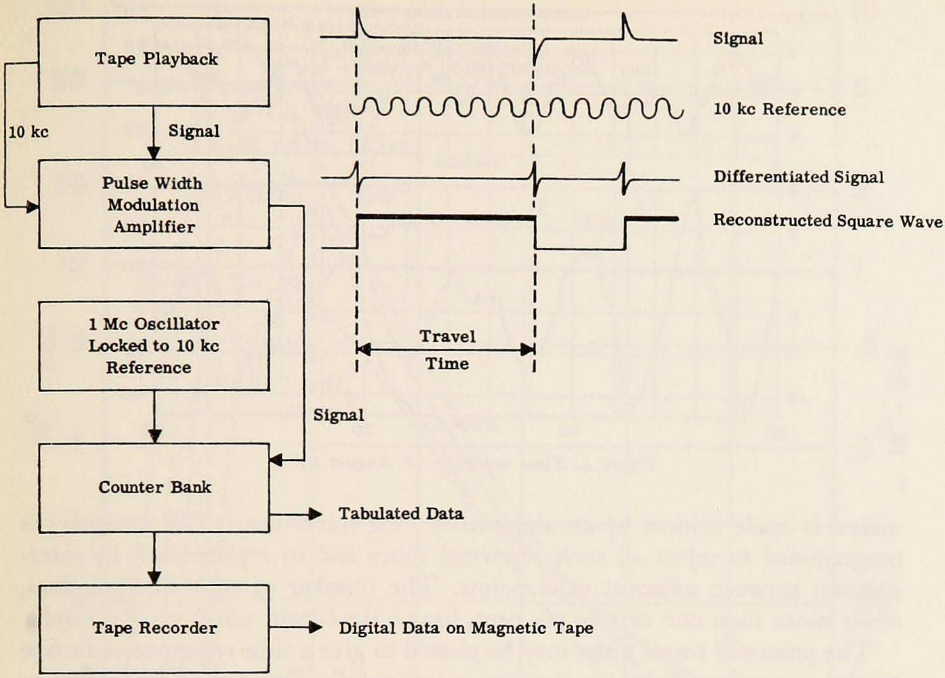

Figure 3. Data processing system.

tracking used in precision radar. By this process, the acoustic signal, with its varying amplitude and envelope shape, is converted to a constant-amplitude square wave having a switching time of less than 10^{-7} seconds. These two characteristics are essential for the accuracy of the succeeding data processing. The square-wave generator falls out of step if an echo is of too small amplitude to effect switching. However, the adjustable timing of the "on" and "off" gates forces the generator back into step.

A portable two-channel magnetic tape recorder takes the output of the square-wave generator, differentiates it, and records it as a series of plus and minus spikes. The second track records a precise 10-kc timing signal. This process, which takes place in the boat, is illustrated in Fig. 2.

The tapes are processed on shore, as shown in Fig. 3. The recorded signals are differentiated once more, and then the square wave is reconstructed in a Pulse Width Modulation amplifier. At the same time, the 10-kc timing signal is multiplied to 1 Mc. The number of cycles between the "on" and "off" of the square wave is counted, thus giving the travel time from the transducer to the surface and back, with a precision of $\pm 2\,\mu$ sec. The travel times thus measured are recorded in digital form on magnetic tape, on IBM cards, and as a print out. When the data are processed, the fact that an echo has been

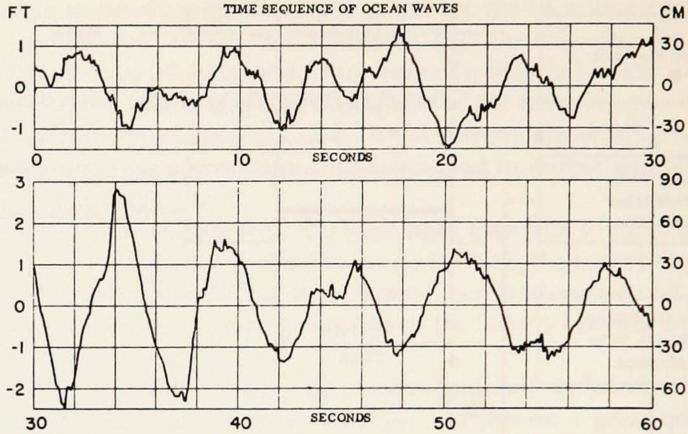

Figure 4. Time sequence—8 August 1961.

missed is made evident by an abnormally long travel time. The computer is programmed to reject all such abnormal times and to replace each by interpolation between adjacent valid points. The number of such interpolations, never more than one or two per cent, has no significant effect on the results.

The processed travel times may be plotted to give a time sequence of surface heights at a point. However, they are more usefully displayed as an autocorrelation function and power spectrum. Programs for generating these functions are available; the one used in this instance was a Tukey program (3) modified for use on an IBM 7090 computer.

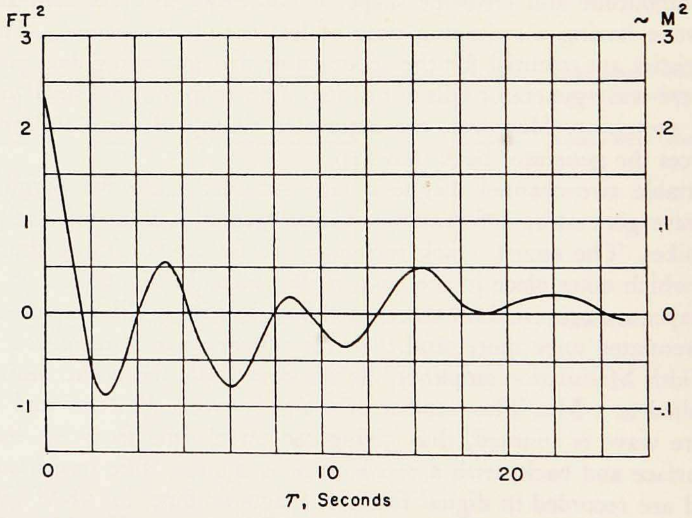

Figure 5. Autocorrelation function of a 22-minute sample of ocean wave data—8 August 1961.

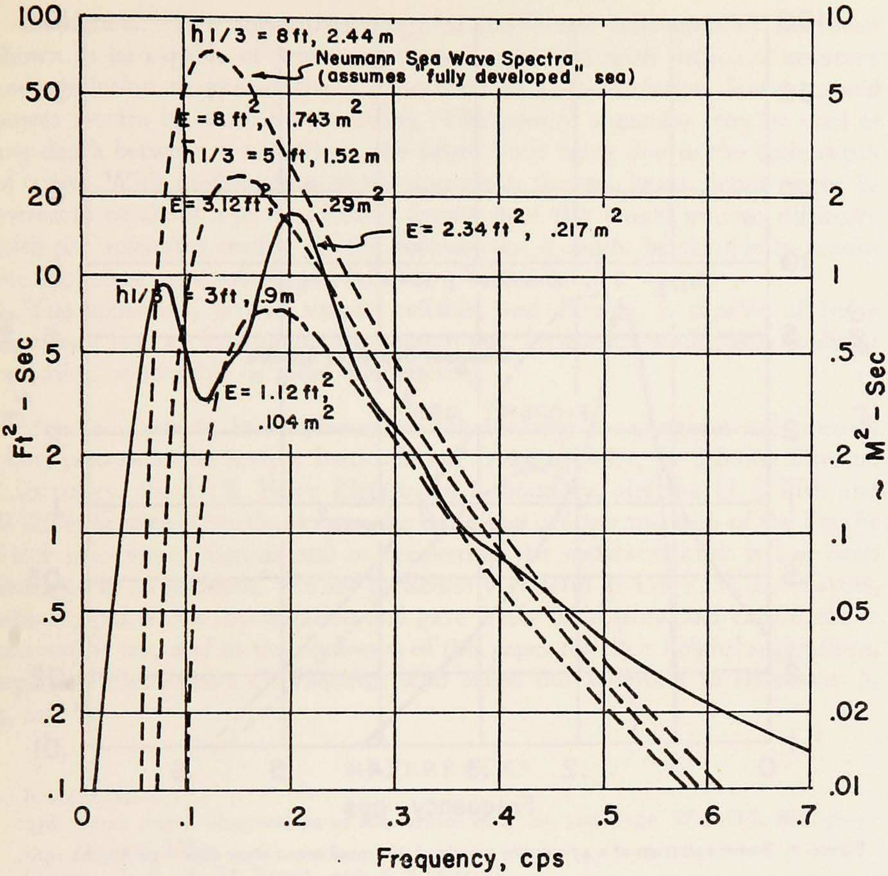

Figure 6. Power spectrum of a 22-minute sample of measured ocean wave data—8 August 1961.

Operations. The apparatus was first tested in shallow water. The transducer was focused for the approximate depth, and intensity contours of the sound pattern at the surface were observed. These contours, which agreed very well with predictions derived from depth and focus, led to the conclusion that at 44 m depth the illuminated spot at the reflector surface is about 60 cm in diameter. The apparatus was then planted at a water depth of 44 m at about 1.5 km west of the Scripps Institution of Oceanography pier, La Jolla, California. The apparatus was operated at intervals for more than a month in August and September 1961. No operating difficulties were encountered except to provide a sufficiently stable 60-cps source to drive the tape recorder.

Results. A time sequence taken on 8 August 1961 is shown in Fig. 4 and the corresponding autocorrelation function and power spectrum in Figs. 5 and 6.

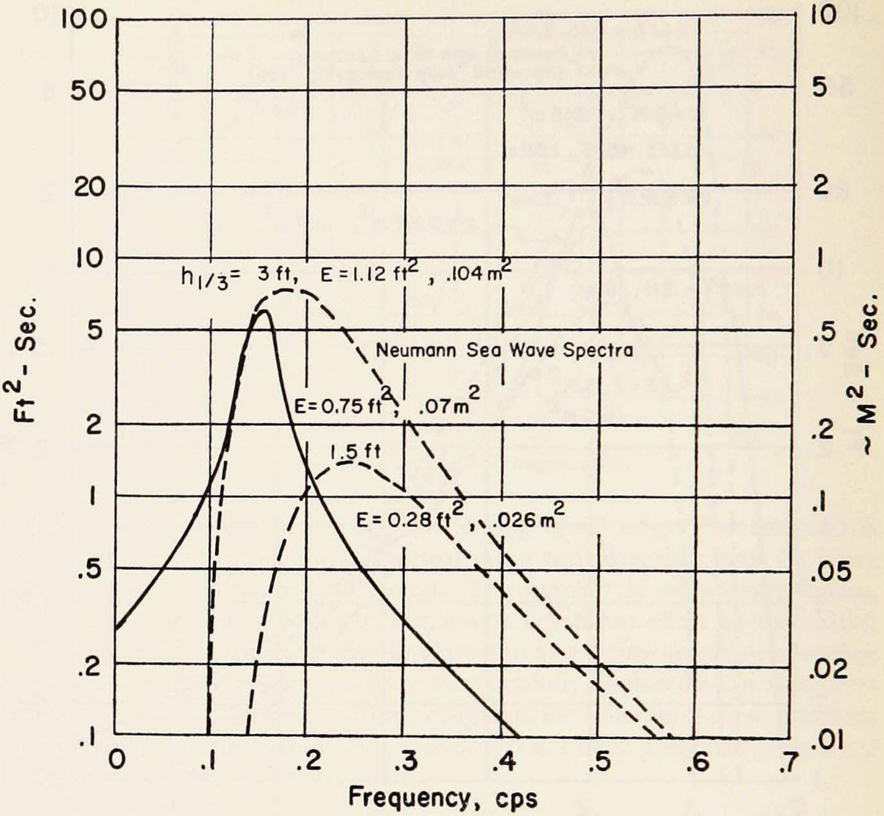

Figure 7. Power spectrum of a 47-minute sample of measured ocean wave data—30 August 1961.

A second power spectrum taken on 30 August 1961 is shown in Fig. 7. Neither of these spectra corresponds to the Neumann spectrum, but both are thought to be typical of the locality. In Fig. 5 the component at 0.2 cps is believed to be due to local winds, while the 0.07-cps component is attributed to the decaying wave system of a distant storm. The spectrum in Fig. 7 was taken on a day when there was no local wind, but a strong swell was running. This spectrum was generated by taking the machine-computed autocorrelation function, fitting an analytic curve to it by trial and error, and then making the Fourier transformation. This was a feasibility test of the procedure, since computation of the autocorrelation function is rapid, whereas transformation to a power spectrum takes considerable machine time and is quite costly. The results are considered satisfactory, although the extension of the curve below 0.1 cps is probably an artifact.

Conclusions. The upward-looking, narrow-beam echo-sounder has been shown to be capable of producing wave-height data with sufficient accuracy and resolution to permit the procurement of autocorrelation functions and power spectra by machine processing. The present apparatus may be used at any depth between 6 and 67 m, the upper limit being due to the scale depth of 73 m. With modification of the apparatus, the maximum depth might be increased to about 150 m. Greater depths than this would provide difficulty with the apparatus resting on the bottom, but it might be feasible to mount the apparatus on a submerged buoy or a submarine.

The apparatus, proved simple, reliable, and durable, is capable of being developed into an instrument for routine use. Its output is adaptable to direct recording or to cable or radio telemetering.

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