

Ocean Wave

MEASUREMENTS

APL is involved in research to learn more about radar reflectivity of the surface of the ocean. To do this it has been necessary to measure the shape of the water surface to an accuracy not possible heretofore.

This paper reviews the methods used to measure wave structure and describes a stereophotogrammetric technique recently developed to measure even the smallest ripple in the sea.

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Although physical oceanographers have long been interested in the structure of the sea surface, much of the impetus to measure wave height and slope has come from those interested in radio wave propagation. Interest in the physics of transfer of momentum between the atmosphere and the water surface leads one to study the shape of the surface under various conditions. Those concerned with reflections from the ocean surface by electromagnetic waves are interested in the shape of the surface at the time of observation. Clearly, if a one-to-one correspondence can be achieved between some characteristic of backscattering and the surface, then radar can become the instrument for measuring the surface properties.

In the process of discovering the relationship between the physical state of the sea surface and the backscattered radar signal, we must develop sea-surface measuring techniques that are appropriate to the specific problem. As yet, it is not known

what portion of the wave spectrum is most important in radar reflectivity. Without doubt there is a dependence on the radio wavelength. Qualitatively, it is also known that a slight rippling of the sea surface causes a large increase in backscattering at X-band, for example. Quantitative relationships,

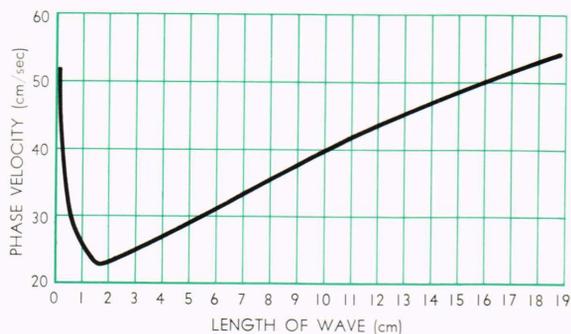


Fig. 1—Phase velocity for capillary waves and for small gravity waves.

however, await more precise measurements of the surface at the time and at the place where radar reflectivity studies are being carried out.

Ocean surface measurements have been made in various ways in the past. However, they invariably come out with two limitations: (1) most have insufficient height and length sensitivity; and (2) height versus time is measured only at one point. To obtain the space spectrum one must transform the period to a wavelength. This can be done under some conditions, but in the radar backscattering study it is deemed necessary to measure height versus distance along the surface from which a space spectrum can be obtained directly.

Experiments to obtain the space spectrum are being run, in which stereophotographs of the surface are obtained by airplane-mounted cameras flying above the ocean.¹ The height sensitivity of airborne stereophotogrammetry, however, is only about 1 ft, clearly inadequate for radar clutter studies. Despite the difficulties in analysis, we were led to the conclusion that the stereo method was the only one available to provide a space spectrum.

Discussion of Waves

Much is yet to be learned regarding ocean waves: their formation and dissolution, their structure and motion. Some things, however, are clear. When the wind just begins to blow over a smooth sea, small capillary waves with long crests and sharp troughs are formed. When the wind increases, the waves become larger in both height and length, and they form gravity waves with capillaries superimposed. The transition between capillary and small gravity waves can be seen in Fig. 1. Here we present a plot of wave-phase speed against wave length. This curve reaches a minimum at about 1.7 cm; to the left of this minimum are capillary waves and to the right are gravity waves.

As the wind increases further, the waves continue to build up until a critical height is reached; they will then break. Any further energy fed into the water by the wind will appear as an increase in wave length. Waves higher than 25 ft are rare; the highest recorded was 112 ft in the North Pacific. The interests of radio propagation specialists lie, however, in the normal seas.

If the ocean showed periodicity, that is if it contained waves described by simple harmonic motion

with the crests being infinitely long, then classical wave theory² could be used to describe the surface. But turbulence and viscosity in the air and in the sea bring in nonlinear effects, and the surface shows a confused or random appearance. Such processes are generally described in a statistical manner; in the radar-clutter problem the final need is in terms of the standard deviation of wave height and the space or wave-number spectrum of the surface.

In previous experiments, while APL was searching for solutions to limitations imposed on missile capture at low angles, ocean spectra were obtained with wave gages to be described shortly. Two sample spectra are shown in Figs. 2 and 3. In Fig. 2 is a single-peaked spectrum with the peak at about 0.09 cps. In Fig. 3 we see a spectrum in which effects of the swell and the wind waves are separated; the swell results in peaks at about 0.08 cps and the wind waves at about 0.12 cps. At this point it should be emphasized that there appears to be little energy at frequencies above 0.4 cps. The equipment used in the measurements program was insensitive to the higher frequencies, and it is just the energy in the higher frequency range with which we are concerned in the clutter problem. (It has frequently been observed that under smooth sea conditions radars "see" no clutter, and with slightly rippled surfaces the clutter increases 30 to 40 db.) The frequency of the transition region

² H. Lamb, *Hydrodynamics*, Cambridge University Press, Cambridge, England, 1932.

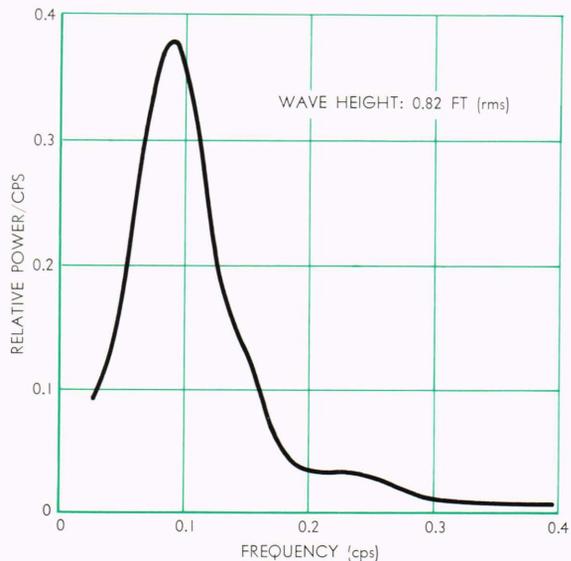


Fig. 2—Wave spectrum showing a single peak caused by ocean swell.

¹ W. Marks and F. C. Ronne, "Aerial Stereophotography and Ocean Waves," *Photogrammetric Engineering*, 21, Mar. 1955, 107-110.

between capillary and wind waves would appear at a frequency of 14 cps.

Other Methods of Measuring Waves

Various methods for measuring waves have been used. Among these the more popular are:

1. Pressure gages.
2. Step gages (resistance or relay-activated).
3. Wire gages (resistance or capacitance).
4. Altimeter.
5. Accelerometer buoy.

PRESSURE GAGE—The pressure gage is a device mounted underwater that is sensitive to the amount of water between it and the surface. As the waves move past the point directly above the gage the pressure changes; hence a recording of pressure versus time is equivalent to wave-height versus time. This device is usually connected to a recording meter on shore.

STEP GAGE—The step-resistance gage consists of a thin, vertical support which is partially immersed in the water, and on the support is a set of exposed electrodes. Each electrode is in series with a fixed resistor. As the water moves up on the gage staff, more electrodes are shorted out and the total gage resistance becomes less. Wave height is then simply a measurement of resistance versus time. A fast-response recorder, 60-cps or better, is useful in that it makes the instrument self-calibrating. With the fast-response recorder one can see the

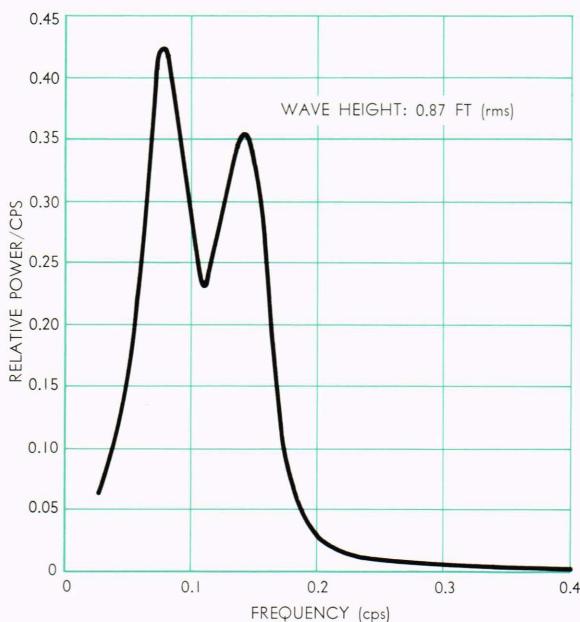


Fig. 3—Wave spectrum showing two peaks, one caused by ocean swell and one by wind waves.

discrete steps in the record as the water rises on the gage. As the water falls, on the other hand, it pours slowly off each electrode and the step function is not discernible. Since each step corresponds to a fixed increment of water height, one can check on the calibration as frequently as desired.

A modification of this gage is one in which the electrodes are replaced by small floats. The water rises and causes a float to move; in turn the float activates a relay in series with a resistor. We then have a device that does not change its calibration with time. Its use is in those applications where long-term calibration stability is required.

WIRE GAGE—The wire gage is similar in concept to the step gage except that the conducting wire is the exposed measuring device. As the water moves up and down, the total wire resistance changes. One can also use the capacitance of an insulated wire as the measuring element. In fact, if two wires are mounted vertically a short distance apart, the difference in reading between the two is a measure of water slope. Although the inherent sensitivity of the continuous wire gage is greater than that of the step gage, it, too, is limited by the surface tension of the water.

ALTIMETER GAGE—Devices using the altimeter principle have been developed to measure wave height from an airplane. If one flew over the water at a relatively low altitude and measured the transit time of a radio pulse transmitted to the surface and returned, he would have a measure of his height. The fluctuations in height versus time are dependent on the irregularities in the water height as long as the airplane motion is constant in altitude above a mean water level. Some measure of success has been achieved with this type of gage. It has the advantage that it can cover a large area in a relatively short time. However, this type of gage does not seem to be gaining in popularity.

ACCELEROMETER BUOY—A buoy floating in the water moves up and down with the waves; thus the accelerometer buoy is a device that measures wave accelerations. The accelerations are integrated twice to get displacement versus time. However, this type of gage is useful only for measuring the larger waves since the buoy, because of its size and mass, cannot respond to the capillary or small gravity waves.

All the gages just discussed (with the possible exception of the wire gage) have in common the difficulty that small waves are hard to measure. With this in mind, and with the added requirement for measurement of the spectrum, it was believed

that only the photographic technique could satisfy the need.

Stereo Method for Measuring Small Waves

Since it was clear that (1) a stereophotogrammetric method would yield information from which a space spectrum could be obtained, and (2) an airborne system would not provide the needed resolution, it was decided to attempt to develop a shipborne system. But because water is somewhat transparent to optical electromagnetic waves, we had to determine whether the actual water surface could be photographed. This had to be done accurately since a height sensitivity of one-tenth the radar wavelength was the goal; at X-band (3 cm) a height sensitivity of 0.3 cm was therefore needed. If these two problems could be solved we would have the key to our radar reflectivity program.³

A stereo wave-measurement program was therefore started under contract from the Office of Naval Research to Oceanics, Inc., with project

³ I. Katz, "Radar Reflectivity of the Earth's Surface," *APL Technical Digest*, 2, Jan.-Feb. 1963, 10-17.

supervision by APL. A pair of specially modified aircraft stereo cameras was mounted on a rigging 20 ft above the water and about the same distance forward of the bow of a ship. This structure is shown in Fig. 4. The cameras were spaced on 11.5-ft centers, facing downward in such a way as to provide a 60% overlap of the two pictures. The cameras were T-5 Fairchild cartographic cameras refocused to the 20-ft distance. Their shutters were reworked to provide a 1/1000-sec exposure. Two 6-in. selected Metregan lenses were installed.

During the 1963 tests in the Chesapeake Bay and in the Atlantic Ocean 200 miles off Cape Hatteras we found that with cloudy skies the stereophotographs were of excellent quality. When the skies were clear, however, good quality stereophotographs could be obtained only during the early-morning and late-afternoon hours when the sun was at a relatively low angle in the sky.

Under optimum lighting conditions wave-height measurements to a sensitivity of 0.8 mm were made with the equipment described above. The finest recorded resolution obtained by any method up to that time had been 13 mm, achieved with a wire gage during investigations in the Golden Gate in

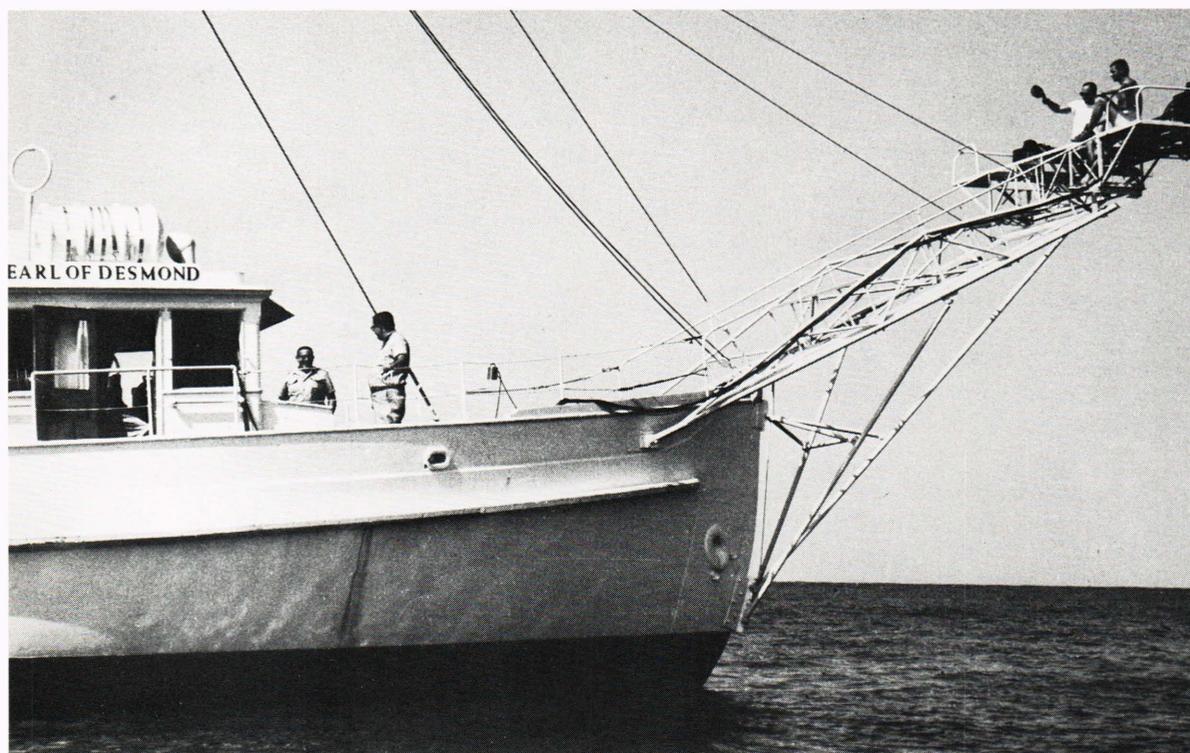


Fig. 4—Photograph of the prow of the ship *Earl of Desmond*, showing the mounting for stereophotographic equipment.

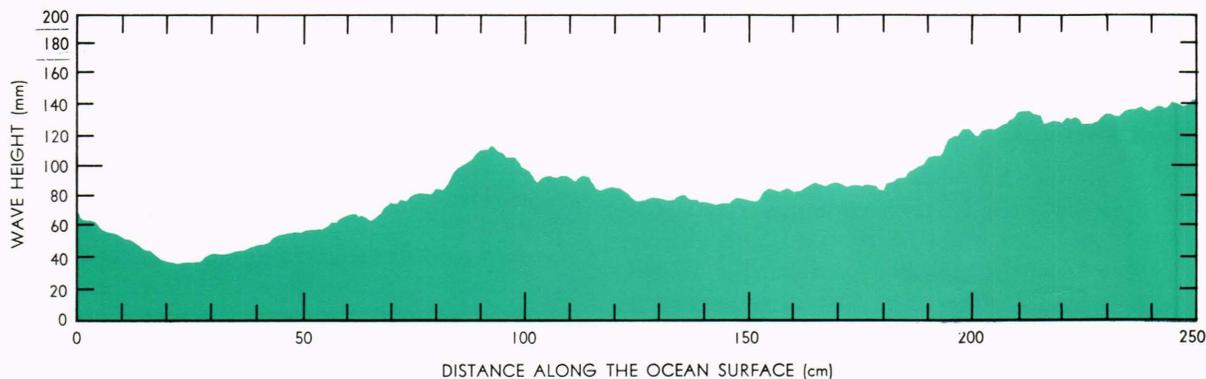


Fig. 5—Sample wave profile of a section of ocean surface, showing measurements of the small ripples.

1953;⁴ a sensitivity of 1 ft, it will be recalled, had been the best that could be obtained by airborne stereophotogrammetry. Figure 5 is a section of an ocean-wave profile plotted directly from stereophotographs made during the 1963 shipborne measurement program in the Atlantic Ocean. During the period of these particular measurements, the highest third of the waves measured an average of 1.5 ft in height. This profile represents a section of the ocean surface 250 cm long along the surface; the vertical scale of our figure is 20 cm. It can be seen, therefore, that this technique permits us to measure irregularities in wave height of less than 1 mm.

Analysis of the stereophotographs is being carried out with Kelsh Plotters at Aero Services Corporation. The wave-height information is then used in two ways. Profiles of height-versus-distance, such as shown in Fig. 5, are obtained along lines that parallel the direction of flight of the airplane making the radar backscattering measurements. For each pass of the airplane we can, for example, relate the standard deviation of the surface with the radar signal strength returned at any preselected viewing angle of the radar; the larger the roughness, the greater the returned signal.

The second use to which wave-height data can be put is in the form of spectra; here we mean space spectrum, as distinguished from frequency spectrum. In other words, we are looking for the correlative function of the surface, which is the Fourier transform of the space spectrum. There exist many theoretical treatments relating the wave-number spectrum (or correlative function) with the angular dependence of the backscattered

radar signal. If we have the radar backscatter function measured simultaneously with the sea in this more meaningful statistical manner, we will be in a position to select the most accurate theory. We hope that ultimately the radar measurement itself will give a precise description of the state of the sea.

It has been known for many years that the rippled structure of the ocean is important in the radar clutter problem. A smooth sea scatters little energy at normal incidence. However, even the slightest wind ripples the surface, and clutter levels increase two to three orders of magnitude. It should be clear, then, that these measurements of capillary and small gravity waves, i.e. the high-frequency part of the wave spectrum, will be the important link between theory and experiment.

Conclusion

We have successfully developed a system to provide wave-height measurements with a sensitivity better than required for current radar propagation programs. The system is now being used as an integral part of the continuing program to relate the radar reflectivity to the shape of the surface.

Stereophotogrammetry suffers under the handicap imposed by the difficulty and length of time needed for processing the data. But attempts are now being made to alleviate this problem by utilizing automatic data-processing equipment that is becoming available. We feel that this will increase the usefulness of the stereo system and thus the value of the data obtained.

The stereo wave-measurement program is a combined effort of Wilbur Marks of Oceanics, Inc., and William Latady of Latady Engineering, Inc.; they are supported by the Office of Naval Research, and the overall program is being directed by APL.

⁴ J. R. Gerhardt, K. H. Jehn, and I. Katz, "A Comparison of Step-, Pressure-, and Continuous-Wire-Gage Wave Recordings in the Golden Gate Channel," *Trans. Am. Geophysical Union*, **36**, Apr. 1955, 235-250.