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THE MICROWAVE MEASUREMENT OF OCEAN-WAVE DIRECTIONAL SPECTRA

Basic principles of six microwave techniques that have been used to measure ocean-wave directional spectra from aircraft are described. Three of these techniques—synthetic aperture radar, the short pulse scanning beam spectrometer, and the two-frequency resonance scanning beam spectrometer—are proposed as possible ways to measure global directional spectra from satellites.

INTRODUCTION

When we attempt to gain knowledge about the temporal and spatial variations of sea-surface displacements caused by waves, various levels of information may be specified. The most complete knowledge of sea-surface displacements would be obtained from two-dimensional images taken successively in time. Resolutions and sampling intervals in both space and time could be adjusted to control the amount of data obtained. However, even with the values set to observe only waves longer than 1 meter, the amount of available information would soon overwhelm our ability to use it. Thus, the standard practice is to average the data as they are collected.

Of course, straightforward averages would produce zero mean displacements, so Fourier transforms with respect to space and time are usually taken. We discard phases before averaging by computing the modulus squared of the transforms and normalizing by the time or space interval to yield spectra. Even this procedure is long and difficult because it involves obtaining spectra in two wavenumber components and one frequency variable from the original three-dimensional space/time information. A description of sea-surface displacements that is this complete has only rarely been obtained in practice (see, for instance, Donelan et al.[1]).

The intent of this article is to describe briefly the most complete wave measurements possible using microwave radars from aircraft or spacecraft. Because such platforms do not allow repeat observations to be made rapidly enough to obtain the time series necessary to compute spectra of the type described above, only the integral of such spectra over all frequencies can be obtained. These are the directional spectra whose measurement will be discussed here.

Although such spectra represent a great condensation of the possible information that could be obtained about sea-surface displacements, their measurement is difficult and only now becoming routinely available. Many microwave and other remote-sensing techniques yield measurement of surface waves that are integrals of directional spectra over one or two wavenumber variables (i.e., spectra obtained from one spatial dimension or simply the surface-displacement variance); they will not be discussed here. Furthermore, nonmicrowave techniques for obtaining wave-directional spectra such as stereo photography or high-frequency radar will not be discussed here. Rather, we will concentrate on microwave techniques whose output spectra have been compared with those obtained by in situ measurements and found to yield acceptable agreement.

MICROWAVE REMOTE-SENSING TECHNIQUES

Because of their ability to observe large areas of the ocean surface, microwave remote-sensing techniques typically yield directional spectra with much better wavenumber and angular resolution than in situ techniques such as arrays of probes or directional buoys. The improvement in wavenumber resolution is frequently greater than necessary, so several wavenumber bins are commonly averaged together to provide better statistical significance than is possible with in situ methods. The improvement in angular resolution, on the other hand, is often important to the proper measurement of directional spectra, which can be highly directional. The ability of remote-sensing techniques to separate wave systems of similar wavenumber but different directions is a ma-

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jor improvement over wave buoys, whose resolution is usually on the order of 60 to 90 degrees.[2,3]

The three basic methods by which directional wave spectra may be obtained using microwave techniques are listed in Table 1 along with the names of systems using those methods. The most straightforward method is simply to form an image and transform it; three systems that will be discussed use this method. The three other techniques to be discussed all operate in the manner of a linear wave-gauge array; that is, they all illuminate a large distance perpendicular to their observation direction, thus discriminating against waves not traveling along that direction. Scanning the antenna or turning the plane varies the direction in which the system responds to waves, thereby producing complete directional information without forming an image. Two of the techniques to be discussed perform Fourier transforms in the observation direction after the data have been collected by a computer. In the final technique, the transform is performed automatically by the radar itself. In order to discuss the techniques, we separate them into those without obvious spaceborne application and those that can probably be adapted to operation in space.

Systems without Spaceborne Application

Real-Aperture Imaging Radar. Real-aperture radars (RARs) (also called SLARs for side-looking airborne radars) map the power backscattered from the ocean surface to fixed side-looking antennas with fine resolution, as illustrated in Fig. 1. Resolution is obtained in range using short pulses, while azimuthal resolution is obtained from narrow antenna beams. Thus, the optimum RAR configuration is that of a high-frequency radar carried on a low-flying aircraft. In order to obtain wave height from RAR maps, received power must be related to ocean-wave height for all angles of wave travel. Knowledge of the appropriate "transfer function," especially its angular dependence, is marginal at present. The technique is not suitable for spaceborne application since azimuthal resolution degrades rapidly with altitude.[4]

Table 1—Methods of obtaining directional spectra using microwave techniques.

Radar images; two-dimensional transform taken later
Real aperture imaging radar (RAR)
Surface contour radar (SCR)
Synthetic aperture radar (SAR)
Radar images in range, integrates in azimuth; one-dimensional transform taken later; antenna scanned
Radar ocean-wave spectrometer (AM ROWS)
Remote ocean-wave spectrometer (FM ROWS)
Radar transforms in range, integrates in azimuth; antenna scanned
Three-frequency airborne radar (TRIFAR)

Surface Contour Radar. This well-developed technique (see the article by Walsh et al. elsewhere in this issue) uses a narrow, downward-looking microwave beam scanned perpendicularly to the direction of aircraft travel to map the surface beneath and to either side of the aircraft. It is illustrated in Fig. 2. Horizontal resolution in both directions is obtained from the small illuminated footprint on the surface, while range (R) to the surface, and thus surface displacement, is measured to an accuracy limited by the narrow pulse width. High-quality contour maps of the surface can be obtained with this technique, and directional spectra can be obtained from the maps without the need for a "transfer function." The technique is not applicable to spacecraft applications because of the large surface footprints resulting from such altitudes.[5,6]

Systems with Spaceborne Application

FM ROWS. The FM remote ocean-wave spectrometer (ROWS) technique involves illuminating areas of the ocean surface that are small in range extent but large in azimuthal extent and measuring the mean Doppler shift from the surface using the FM part of the coherent return (Fig. 3). The large azimuthal extent of the footprint averages out effects of waves not traveling near the antenna look direction, thus producing directional discrimination. Linear wave theory allows conversion of

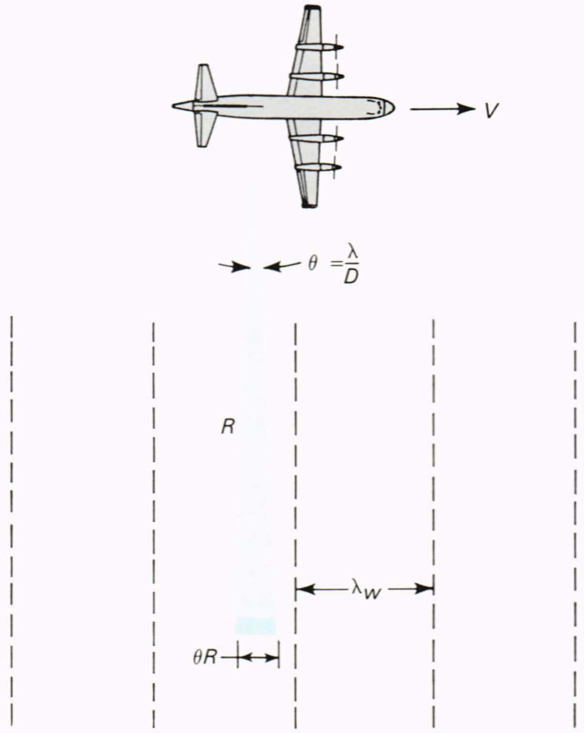


Figure 1—Real aperture or side-looking airborne radar. The image of return power is formed because of the small footprint in both directions. θ, the angular resolution, equals λ/D, where λ is the radar wavelength and D is the antenna aperture; V is the forward velocity of aircraft; R is the range to ocean; θR is the along-track ground resolution; and λ_w is the typical ocean wavelength.

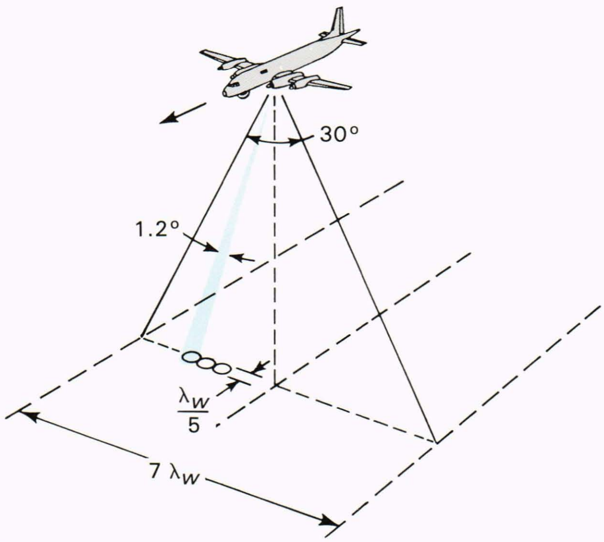


Figure 2—Surface contour radar. The image of range to surface is formed by scanning a footprint that is small in both dimensions.

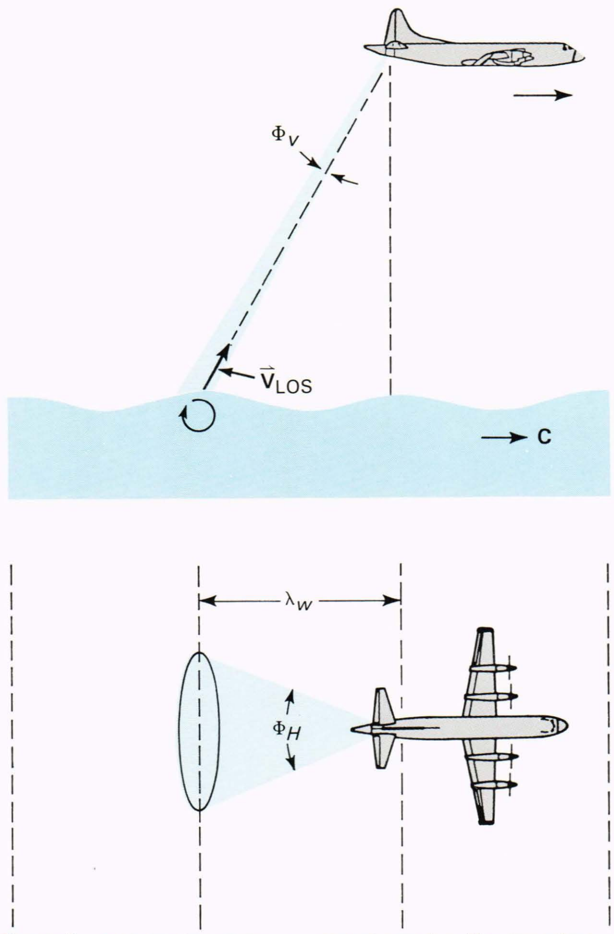
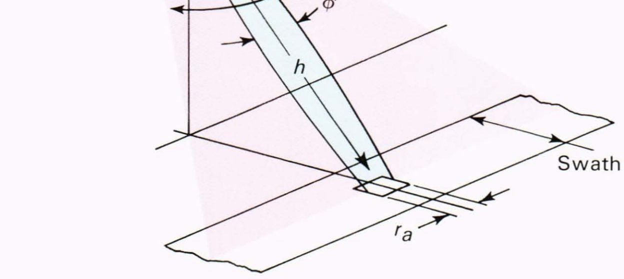


Figure 3—FM remote ocean-wave spectrometer. The transform of surface velocity along the line of sight yields one cut through the directional spectrum. No image is formed. $\mathbf{V}_{LOS}$ is the line-of-sight velocity; Φ_V is the vertical angular resolution; and Φ_H is the horizontal angular resolution.

the measured surface velocities (deduced from the Doppler shifts) into wave spectral densities without an environmentally sensitive transfer function. The technique is applicable to spacecraft altitudes but thus far has been used only from aircraft with fixed antennas looking along the direction of travel. To be useful, the technique must be used with a rotating antenna, but broadening of the Doppler spectrum when the antenna looks perpendicularly to the direction of platform motion may hinder operation.[7]

Synthetic Aperture Radar. Synthetic aperture radar (SAR) maps the ocean surface to fine resolution with a fixed, side-looking antenna using the artifice of simulating a large antenna by moving a small one. Its operation is illustrated in Fig. 4. Range resolution is achieved in the standard manner with short pulses, but azimuthal resolution relies on mapping Doppler shifts into positions on the surface. For the moving ocean surface, azimuthal resolution is a complicated combination of the surface's velocity and scattering intensity. Thus, the transfer function relating the spectrum of a SAR image to the ocean-wave directional spectrum is quite complex and for many situations remains ill defined. However, simple linear functions have produced spectra that can agree quite well with those obtained from the surface contour radar and the short pulse radar described below (see the articles by Lyzenga, Monaldo, Tilley, and Beal elsewhere in this issue).

SAR systems are the only "wave spectrometers" to have been tested in space thus far. They have flown on Seasat and on two shuttle missions (SIR-A and SIR-B). Analysis of the ocean images collected on those flights has established that SARs must be flown on low-altitude satellites (200 to 300 kilometers) in order to be viable wave spectrometers[8] because the fast azimuthal rolloff of the SAR transfer function degrades the imagery of dominant ocean waves at high altitudes. Furthermore, practical SAR wave spectrometers will require on-board



$$r_a \text{ (azimuth resolution)} = \phi' h = \frac{\lambda}{2L} h$$

Figure 4—Synthetic aperture radar. The image is formed in range using short pulses and in azimuth using Doppler mapping, which creates the synthetic aperture *L* by accumulating a continuous phase history with the real aperture *D*.

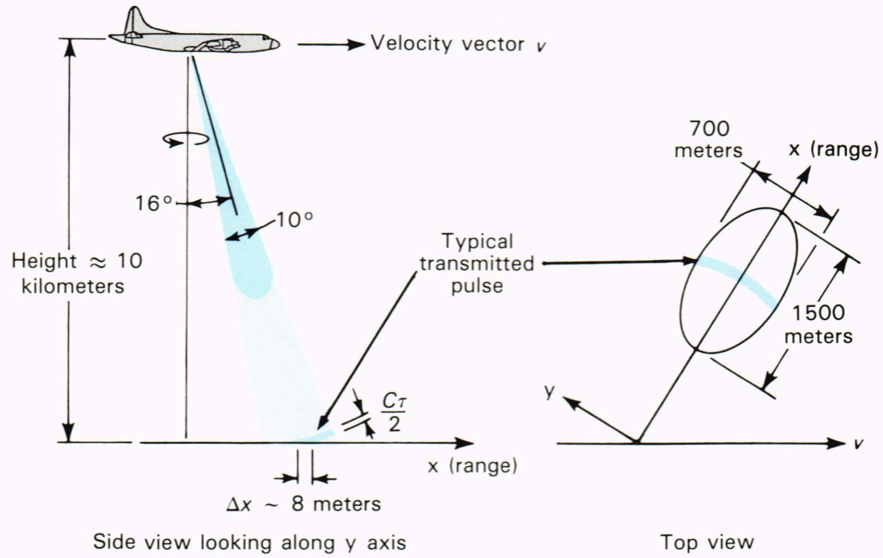


Figure 5—AM radar ocean-wave spectrometer. The short pulse scans the surface while the beam sweeps in angle. The transform of returns on individual sweeps yields the directional spectrum. No image is formed. C is the velocity of light; τ is the radar pulse width; Δx is the ground resolution; and Φ is the azimuth angle.

processors to reduce downlink data rates. The primary advantage of SAR for obtaining directional wave spectra is that they can be obtained on smaller spatial scales than are possible with other techniques.[9,10]

Scanning Beam Spectrometer. Scanning beam spectrometers are nonimaging devices that measure directional wave spectra through variations of backscattered power caused by ocean waves. The systems respond only to waves traveling in the antenna look direction, similar to the FM ROWS. Empirical modulation transfer functions that depend on environmental conditions are needed in order to relate variations in received power to ocean-wave spectra. However, the transfer functions are much simpler than those of either SAR or RAR because of the directional discrimination of the instrument and are presently quite well known. The systems have been implemented in two complementary forms: short pulse and two-frequency resonance.

The short-pulse form, also known as the AM radar ocean-wave spectrometer (ROWS), is the easiest to describe since it obtains high range resolution with a short pulse and records power returned from the different range cells across the beam (see Fig. 5). Fourier transforming these one-dimensional spatial series and applying the transfer function produce the directional wave spectrum in that direction. Rotating the antenna produces the complete spectrum. This system is best implemented at small incidence angles in order to increase the return power and improve spatial scales on which spectra can be obtained. It has been extensively tested on aircraft. Full two-dimensional spectra obtained by this method are published in the literature (see also the articles by Jackson elsewhere in this issue). The method has the advantage of using standard altimeter hardware that has been used previously on both Seasat and GEOSAT.[11,12]

The two-frequency resonance form of the scanning-beam spectrometer measures the same power variations as the short-pulse form. By transmitting two frequencies, however, it illuminates the surface with a beat pattern that resonantly produces backscatter only from ocean waves with lengths matching the beat wavelength (Fig. 6). Thus, the technique does not require the Fourier-transform processing needed in the short-pulse technique but instead requires that the separation between the two transmitted frequencies be varied to produce directional spectra. The same transfer function is needed in this technique as in the short-pulse technique. Although cuts through directional spectra in fixed directions have been produced using this technique in aircraft, a system capable of producing complete directional spectra has only recently been tested. The system actually implements the technique by transmitting three equally spaced frequencies (two per pulse) whose separations are

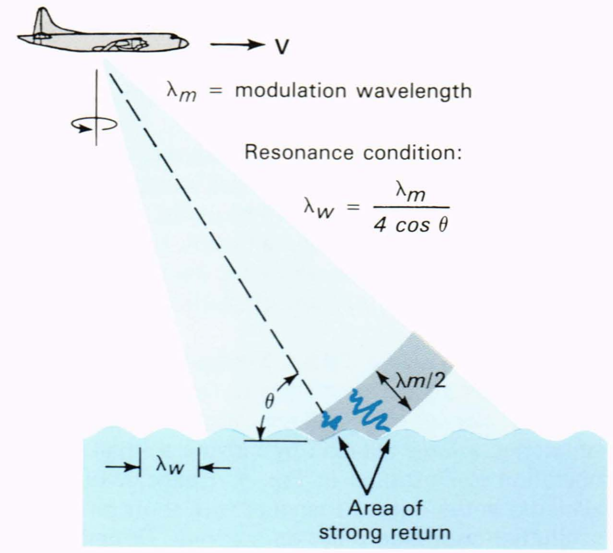


Figure 6—Three-frequency airborne radar. The resonance of the beat between two transmitted frequencies with the ocean surface pattern yields a cut through the directional spectrum at one wavenumber. The frequency spacing is varied, and the beam is scanned to complete the spectrum. No image is formed.

Table 2—Satellite techniques for the measurement of ocean-wave spectra.

Instrument	*Principle of Operation*	*Image Formed?*	*Small Spatial Scale?*	*Satellite Altitude (kilometers)*	*Present Status*
SAR	Maps surface using Doppler frequencies and short pulses	Yes	Yes	<300	Tested in space; needs better algorithm
Short pulse	Uses scanning beam, short pulses, wave-induced power fluctuations	No	No	<1000	Tested in aircraft; uses some existing hardware
Two frequency	Uses scanning beam, long pulses, wave-induced power resonances	No	No	<1000	Needs aircraft testing; simple algorithm

varied. Called TRIFAR, for three-frequency airborne radar, it receives more power than the short-pulse form because the full antenna footprint is illuminated. It is thus potentially able to operate at larger incidence angles and higher altitudes.[13-18]

CONCLUSION

This article has briefly summarized the microwave techniques available for the measurement of directional ocean-wave spectra. Several remote-sensing techniques have been identified that are potentially capable of making the measurement on a global basis by means of satellites. The three techniques that seem most suitable for satellite application in the near future are listed, along with their salient characteristics, in Table 2. Those systems, and other techniques that can be used from aircraft, are only beginning to supply information about the large ocean waves that critically affect all operations at sea. In the future, microwave remote-sensing techniques promise to play a major role in such operations as well as in ocean-wave modeling and prediction.

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