RADAR MEASUREMENTS OF WIND AND WAVES

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1. Introduction

Radio signals scattered from the sea surface are used to measure many things such as wind speed and direction, currents, current boundaries, and the directional ocean-wave spectrum. Yet the scatter itself really only senses ocean waves. In the case of HF signals, these waves have decameter wavelengths, but microwaves sense only shorter wavelets. All other processes must be inferred indirectly through their influence on these waves. Thus, it is critical to understand the nature of these influences and modulations if radio techniques are to fulfill their promise. Here we assess the modulation of wavelets by long waves, their relationship to wind, and finally, radio techniques useful at HF frequencies.

2. Microwave Measurements of Long Waves

Application of microwave techniques to oceanography offers a promise and a challenge. The promise is the potential of providing all-weather global measurements of waves, surface winds, current and temperature. The challenge is to gain needed insight to validate their use in solving important oceanographic problems.

The utility of microwave sensors in ocean studies stems from their response to specific ocean-surface structures, which are composed primarily of capillary and short gravity waves. The modulation of these wavelets or microstructure by relatively long ocean waves allows the observation of the directional wave spectrum by microwave techniques. Similarly, the dependence of the microstructure on wind, currents, surface contaminants and other processes allows also these to be observed. But the collective presence of these different phenomena makes it difficult to produce a unique relationship between scattered microwaves and any one of the oceanic variables. This is where the need arises for simultaneous surface measurements for comparison with those from microwave sensors.

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2.1. Instruments

It is pointed out in several papers in this issue that microwave radars sense ocean waves and other large-scale phenomena as a result of the modification of the small-scale structure of the ocean surface. Existing radar systems which can potentially provide quantitative measurements of one or more large-scale ocean-surface phenomena include: two-frequency radars; incoherent, pulsed radars, particularly when used in an imaging or map-making mode (e.g., the Side-Looking Airborne Radar, SLAR); and the imaging Synthetic Aperture Radar (SAR). Simple Continuous Wave (CW) Doppler radars are useful for measuring modulations of scattering cross-section in research applications; and shore-based radars are being tested for determining wave direction in coastal zones up to 2 km offshore.

(A) The two-frequency radar is not an imaging radar, but it is potentially capable of obtaining ocean-wave spectra from satellites for waves travelling along the direction of radar look. An airborne version of a coherent, pulsed, L-band, two-frequency scatterometer has been built and is being evaluated in flights over the North Sea. It is specifically designed for wave sensing.

(B) The side-looking airborne radar (SLAR) has the advantage of being less complex than the SAR. It has demonstrated that it can detect waves and wave-like patterns produced by the amplitude modulation of ocean-surface microstructure, although it does not detect phase modulation of the microstructure as does the SAR. The sensor is suitable for use in aircraft and has detected slicks, ships, continental-shelf bottom sand waves, and internal waves, in addition to surface waves. The system is not particularly suitable for use with satellites; but, because the data processing and system transfer function of the SLAR are relatively well understood, further developments of the SLAR for oceanographic studies require only a basic understanding of the hydrodynamic modulation of short waves by long waves.

(C) The imaging Synthetic Aperture Radar possesses azimuthal resolution which depends on the ratio of along-track velocity to range, and is about the same for satellite and airborne radars. SAR offers the potential of obtaining resolutions of the order of 25 m from space. An airborne version of this radar has now demonstrated that it can provide information about wave length and direction and the general shape of the wave-height spectrum; and wave measurements with SAR are now available under moderate and extreme (hurricane) conditions. The sensor is uniquely suitable for use from a spacecraft; and an L-band system is now planned for SEASAT-A which is to be launched in 1978.

The SAR has also demonstrated it can detect ships, icebergs, current boundaries, slicks and internal waves. Processing of SAR imagery is complicated by the effect of scatterer motion; and the system transfer functions relating the SAR image to modulation in cross-section and to wave velocity fields are lacking. In addition, further understanding and development of SAR as an oceanographic instrument requires a basic understanding of the nature of the hydrodynamic modulation of short waves by long waves. In this respect, the SAR and SLAR have an essentially common need.

(D) The CW Doppler radar has been useful for measuring modulations of scattering cross-section in research applications; and it may find a use as a wave probe from a fixed platform by measuring the line-of-sight velocity. Shore-based, mechanically-scanned, incoherent, pulsed radars are useful for wave refraction studies, and frequency-modulated Doppler radars may find application for measuring surface velocity and wave fields in the coastal zone.

2.2. Recommendations for future research

Past research and development efforts in remote sensing have been primarily in the area of radar system development and demonstration of their capability to detect ocean phenomena. What is now needed are theoretical models and analytic techniques to interpret the radar measurements in oceanographic terms. This will enable these radar sensors to evolve into oceanographic tools capable of measuring variables such as waves, winds, and currents with sufficient accuracy to render them useful in solving oceanographic problems. Quantification of radar information can only take place by controlled experiments, including adequate sea-truth measurements.

The most promising avenues of research can be presently accomplished through collaborative efforts involving radio scientists and engineers on the one hand and oceanographers, geophysicists, and hydrodynamicists on the other. There is a great need for experiments involving aircraft equipped with SAR, SLAR, and two-frequency scatterometers flown in coordination with carefully planned surface-truth measurements. The latter has been overlooked in the past and merits much attention in the future.

It is strongly recommended that wave tank and tower experiments be conducted to develop and test models of hydrodynamic and electro-magnetic modulation of the ocean surface microstructure by long waves. Measurements of the dependence of these modulations on the windspeed and wavelength of the microwaves are needed to determine optimum radar-system wavelengths. Tower experiments can be coordinated with remote measurements using simultaneously-operating microwave systems to define the interaction of short waves and long waves and their interaction with electromagnetic waves.

Research on radar ocean interaction should have priority over the search for the applications of these radar systems to new oceanographic features with wave or wave-like patterns.

Tower and aircraft measurements should also be coordinated with future spacecraft measurements to define the capability of these systems to detect waves from space on a global scale. The latter is essential to the development of the global ocean-wave climate.

We recommend efforts to develop a theory of SAR systems yielding the SAR image and wave directional spectra from the modulated cross-section and wave velocity fields.

We also recommend that a multinational scientific group be convened to plan, organize and coordinate the above outlined program of tower and ground-truth experiments.

3. The Average Microwave Cross-Section of the Sea

The goal of world-wide determination of surface windspeed from satellites is considered to be critically important for the development of improved long-range weather and wave forecasts. It is highly probable that measurements of the microwave cross-section (σ_0) of the sea can be used to infer surface wind conditions to a useful degree of accuracy.

3.1. Assessment of present capability

The radar cross-section of the sea has been observed for many years, from aircraft and from space, and for various wind conditions. These studies have demonstrated that σ_0 is dependent on ocean roughness elements highly correlated with surface wind velocity. Yet the uniqueness of the dependence has not been established in that the data are not always consistent, and other variables may contribute to σ_0 through their influence on the small waves. Thus, the full potential of the technique will not be reached until a universal, non-dimensional relationship is found which properly accounts for these additional variables.

3.2. Recommendations for further research

To realize the full potential of the technique, future research must be directed toward developing a better understanding of the physics of the processes which modulate the mean amplitude of the small waves responsible for radio scatter. The work should aim at establishing a universal non-dimensional relation between wind speed, radar cross-section, and other variables such as average wave height or frequency, surface tension, or fetch.

Both tower and aircraft studies are seen to be required to achieve this objective. Where possible, they should be coordinated with planned satelite programs such as SEASAT. Specifically, these field programs should include both long-term studies to establish a statistical basis for the analysis, and detailed studies of the interaction of radar with wind waves to clarify the hydrodynamic processes involved in the scattering problem.

As was stated in the section on measurements of long waves, the quantification of the radar information can come only from controlled experiments, with particular care taken to obtain adequate surface observations. This can best be accomplished through collaborative work by interdisciplinary teams with expertise from various areas of research.

4. HF Radio Oceanography

4.1. Potentiality

Radio waves with decameter wavelengths, i.e., in the HF radio band, are Bragg scattered by waves which lie in the typical ocean gravity wave range. By analysing the Doppler (frequency) spectrum of the scattered radio signals, it is possible to measure the properties of the scattering ocean wave, and to infer wind and currents in the scattering area. Scatter may come from line-of-sight distances, which can extend out to several hundred kilometers, or via an ionospheric path to distances of 4000 km.

The Doppler spectrum yields a measure of the wavelength, frequency, and direction of travel of the resonant ocean wave. Radio scatter can therefore be used to measure directly and precisely the directional distribution of ocean waves and their phase velocity. It can also be used to infer indirectly the surface currents which influence the propagation of ocean waves, and the winds which generate them.

By observing the sidebands to the resonant scatter in the Doppler spectrum, it is possible to observe the ocean-wave directional spectrum using a single radio frequency, and to infer the local wind speed and direction in the scattering area.

If an ionospheric path is used, the resonant scatter and its sidebands can be used to study 0.3–0.4 Hz ocean waves. These are usually in equilibrium with the local wind, so the radar can be used to map the surface wind circulation over large oceanic areas, particularly around storms.

4.2. Present capabilities

Because of the long wavelengths of HF signals, antennas place severe limitations on the types of experiments that can be performed within a limited budget. Based upon the size of the antennas, HF facilities can be divided into those which (i) consist of long arrays (from 100 to 3000 m) which can (electronically) form and steer narrow beams, and (ii) smaller, transportable antenna structures (less than 10 m in dimensions) which either obtain no directional information, or derive directional data via other novel techniques. The former arrays, because of their size, are typically permanent expensive facilities and are frequently used for sky-wave (reflection from the ionosphere) and sometimes for surface wave (line-of-sight) operations at mid and upper HF (above 6 MHz).

Smaller antennas are more common. The following novel techniques have been used to obtain directional information from these small antennas: (i) bistatic configurations in which the transmitter is separated 100–300 km from the receiver, and (ii) synthetic-aperture experiments where the motion of the receiver is used to synthesize a large antenna. Four variations of this technique have been used: (i) the receiver has been driven along a straight path in an automobile, (ii) the entire radar has been carried by a moving ship, (iii) the receiver has been used in a bistatic experiment aboard a moving aircraft while the transmitter sits stationary on the surface, and (iv) the entire scattering area has been transported at constant velocity relative to the radar by known ocean currents.

Other novel concepts employing small, transportable antennas have been used to derive wave and current information from resonant scatter. These include: (i) two or three element stationary receiving antennas (less than 10 m in total extent) and a computer which processes the complex signals from each element to derive directional information; and (ii) scanning a broad beam, either electronically or mechanically, such as that from a small loop antenna. Both techniques, in certain situations, gather directional information otherwise obtainable only with large, permanent, shore-based facilities.

The following concepts, based upon first-order scatter at MF and low HF, have been successfully employed in various experiments. Because the scatter process is described by simple, generally accepted mathematical models, and because experiments performed thus far have been supported by independent oceanographic observations, these techniques can be recommended for use in physical oceanographic experiments and/or short-range (~ 200 km) ocean monitoring. Bistatic radars at 1.9 MHz, in which available LORAN-A navigation transmissions were used in conjunction with a simple, portable omnidirectional receiving system, have been employed to obtain ocean-wave directional spectra. Synthetic-aperture radars, in which LORAN-A transmissions were received by an automobile-driven receiver, have been used to study the directional distribution of 7-s waves and their growth as a function of time. The directional distributions of several ocean wavelengths have been observed from radars on moving ships. Directional wave spectra have also been gathered by employing a transmitter on a tower in conjunction with an airborne receiver in a bistatic configuration. In all of these techniques, one must generally employ several radar frequencies to obtain wave directional information at several ocean wavelengths.

Surface-wave experiments with shore-based antenna arrays have demonstrated the feasibility and desirability of using the sidebands of the Doppler spectrum to extract wave spectral data. In particular, this concept, supported by independent wave observations, has shown that sea and swell wave heights and wave periods can be measured with acceptable accuracies. Theoretical analyses and simulations hold considerable promise for obtaining estimations of the complete directional spectrum. Nondirectional wave-height spectra have thus far been extracted from the sidebands, although accuracies have not yet been established.

Limitations on ionospheric propagation and its distortion of the scattered radio signal make it unclear at present whether fine wave-height spectral details can be observed in the Doppler spectrum, similar to those obtainable via a line-of-sight system, for data gathered over wide ocean expanses. However, empirical correlations have demonstrated the feasibility of measuring surface wind directions with skywave systems. Storms and hurricanes have been quite accurately tracked, and their surface circulation patterns mapped.

Small, transportable, coastal-based surface-wave radars operating at upper HF and using the resonant scatter are presently being demonstrated for mapping near-surface Eulerian current vectors. Coverage areas extend from the coast to ~ 80 km, with some 1000 complete vectors obtainable every 5 min at a 3×3 km grid of points. While the current-vector accuracy is still being assessed, preliminary indications are that it could exceed 10 cm s^{-1}. Current shear with depth in the upper 6 m has been measured by varying the radar operating frequency.

4.3. Recommendations

The soundness of the second-order theory for predicting the sidebands in the Doppler spectrum has been validated. HF systems using this portion of the spectrum may have a wide variety of remote-sensing applications because much more sea-surface information is available from the continuum in the sideband than from many separate measurements employing the resonant scatter. Therefore, both theoretical as well as careful experimental studies should continue on the inverse problem of calculating wave information from the observed Doppler spectrum, with the ultimate goal of estimating as much of the ocean-wave directional spectrum as possible. Third-order contributions to the Doppler spectrum should be theoretically estimated in order to determine how these higher-order effects will limit inversion of the second-order sidebands. Finally, the relationship between the shape and width of the resonant-scatter Doppler peak (due to third-order wave-wave interactions) should be established theoretically in order to: (1) determine whether this observable can be used to estimate the non-directional spectrum; and (ii) assess the limitations this mechanism places on the accuracy of current measurement.

Resonant scatter techniques should be employed experimentally to establish more complete models for the directional wave spectrum and its dependence upon wind speed, duration and fetch. Such experiments should also address the small remaining differences between radar-measured scatter and that predicted by theory using buoy-measured wave-height spectra.

Further skywave radar investigations should establish the ionospheric limitations on the measurement of sea-state, and concentrate on methods for circumventing ionospherically-imposed distortions in the scatter. Where skywave radar has proven to be successful in measuring surface wind direction, research should continue to develop and refine empirical techniques for estimating surface wind speeds, directions, and even surface currents where possible.

Because HF radar systems which form narrow beams are large expensive installations, the search should continue for novel concepts to obtain directional data. Candidates include three or four element antenna systems, as successfully used with the current-mapping radar, and large-beam goniometers, in which the beam is steered to improve directional resolution. This is especially important for measuring swell direction, where alternative HF techniques have poor directional capabilities.

Research should concentrate on relating radar measurements of currents to actual surface water drift, correlating the radar observable with tides, geostrophic currents, wave interactions, wind stress, and storm surges. Special thought and analysis should be devoted to relating *all* radar measurements (waves *and* currents) made over areas to *in situ* oceanographic point measurements, both Eulerian and Lagrangian, as for example measured by wave buoys, moored current meters, and drifting buoys. The potential of estimating upwelling from radar maps of horizontal current vectors should be explored. Modelling of complete water circulation in coastal areas should be investigated, where radar-deduced surface currents are used as initial conditions for such models. Finally, the prospect of 'hindcasting' surface wind fields (vs space and time) from wave height directional spectra and surface currents (radar-measured vs space and time) should be analyzed.