HF RADIO OCEANOGRAPHY—A REVIEW

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Abstract. The understanding and utilization of HF radar sea-echo have enjoyed steady progress since the experimental discovery of the underlying radar/sea interaction process over two decades ago. The agreement of theory with measured data confirms the correctness of currently accepted explanations for both the first-order and second-order portions of the sea-echo Doppler spectrum in terms of the wave-height directional spectrum. Furthermore, experiments have shown that any currents present near the surface produce a readily distinguishable Doppler shift on the wave-scattered echo which is directly related to the current velocity.

Present research activities in HF radio oceanography are of two types. The first involves efforts to extract ocean surface descriptors from the sea echo and thus establish the soundness of a sea-surface remote-sensing concept. The ultimate outcome of successful endeavors of this type, for example, could be the implementation of operational systems for routinely monitoring sea state, ocean surface winds, or surface currents over large areas. The second type of research activity involves the use of radio-oceanographic techniques to advance knowledge in physical oceanography.

Progress on three classes of sea-scatter research programs is reviewed; these three are differentiated by the oceanic variable sought from the echo. The first and most extensive class seeks information about the wave height directional spectral properties; both surface-wave and sky-wave radars are being used for such research. In the second class involving sky-wave radars, surface winds are being related empirically to sea-echo. The third class is concerned with extraction and mapping of near-surface currents from the sea-scattered signal spectrum. Potential future directions in these areas are discussed.

1. Introduction

Radar echo from the sea at high-frequency (HF)* was reportedly first observed in Britain during World War II on air-defense nets around the English Channel. Because it imposed a limitation at times on the detection of aircraft, it was dubbed 'clutter'. The simple processing and display of target echo intensity, however, did not lend itself to an understanding of the physical mechanism of the scatter process. It was not until Crombie (1955) examined the received (temporal) power spectrum of the back-scattered sea echo from shore that the simple physical interaction mechanism was correctly identified. He observed that the echo Doppler spectrum consisted primarily of two well-defined spikes symmetrically placed about the radar carrier frequency (see Figure 1), but not necessarily of equal amplitude. The displacement of these peaks from the carrier appeared to vary with the *square-root* of the carrier frequency, rather than in direct proportion, as the Doppler echo from a discrete target such as an aircraft. Yet the 'spiky' nature of these peaks suggested

* The term HF specifically designates frequencies between 3 and 30 MHz (wavelengths between 10 and 100 m). We will use the term here loosely to include frequencies between 500 kHz and 50 MHz (wavelengths between 6 and 600 m), which spans the MF, HF, and VHF bands. Note that 'high frequency' may appear somewhat misleading to one who pictures a microwave radar with its familiar parabolic dish antenna; the latter system operates some three orders of magnitude higher in frequency than a 'high-frequency' radar.

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that the echo was originating from two discrete, identifiable targets, rather than from the randomly moving surface that one observes visually when looking at the sea.

Crombie deduced the scatter mechanism from these peculiar sea-echo Doppler characteristics as follows: since the Doppler echoes consist of two discrete spikes, scatter must be originating from two targets moving at constant velocity. Ocean wave-trains of given wavelength are known to move at given velocity. Therefore, the velocity component of these 'target' wave-trains in the direction of the radar is calculated from the familiar 'Doppler shift' (Δf) formula to be $v_r = \lambda\ \Delta f/2$, where λ is the radar wavelength. From this result he then deduced the wavelength of the ocean wavetrain, L, as seen by the radar from the gravity-wave dispersion relation as $v = \sqrt{gL/2\pi}$, where g is the acceleration of gravity. Equating these two, he found that the wavelength of the backscattering ocean wave-train, L, was precisely one-half the radar wavelength, λ. The 'resonant' effect revealed by this phenomenon is therefore Bragg scatter, or the diffraction-grating mechanism. In other words, all of the ocean wave-trains present on the sea interact with the radar wave, but the only two which can backscatter energy toward the radar are those that have wavelengths precisely one-half the radar wavelength, and moving toward (positive Doppler frequency) and away from (negative Doppler frequency) the radar. That this is the correct explanation of HF sea echo is confirmed by the correspondence of the unique observed square-root relation between the carrier and Doppler frequencies and the square-root gravity-wave dispersion equation. The fact that one always observes discrete Doppler spikes in the echo (even though he may not be able to discern the half-wave backscattering train) arises because any Fourier decomposition of a random but finite patch of sea always contains wave spectral energy at and near the required wavelength and directions. Crombie recognized in his original article that this discovery should lead to the development of sea-state radar remote-sensing techniques. Indeed his finding forms the underlying basis of *all* HF (i.e., MF through VHF) radar sea-surface remote sensing, as well as a large portion of microwave radar sea-surface sensing techniques.

About a decade later, theoretical studies began to appear which confirmed Crombie's experimental discovery, and in addition quantitatively related the sea-echo Doppler spectral strength to the ocean wave-height spectral strength. Looking at a single, sinusoidal wave-train, Wait (1966) showed that one could relate the strength of the signal voltage at the Doppler-echo peak to the height of the Bragg-resonant wave-train. Wetzel (1966) – using a physical-optics approach (which is not entirely appropriate for the sea-surface boundary at HF) – obtained a result for a random sea echo relating the average Doppler spectral peak strength to the sea-surface spatial height spectrum evaluated at the Bragg wave-number. Barrick and Peake (1967, 1968) and Barrick (1972a) employed a boundary perturbation approach put forward by Rice (1951) which quantitatively explained first-order HF sea echo from a random sea surface, including the observed polarization dependence lost in physical optics solutions to the problem. This solution shows that – in the absence of propagation effects which increase the signal bandwidth – the average echo power spectrum consists of two impulse functions (in the frequency domain), located at Doppler frequency shifts $\pm\sqrt{gf_0/\pi c}$ Hz from the carrier frequency, f_0 (c is the free-space radio-wave propagation velocity). The amplitude factor multiplying these impulse functions is precisely the ocean wave-height directional spectrum evaluated at the Bragg wavenumbers $k_{rx} = 2k_0 \cos\phi$, $k_{ry} = 2k_0 \sin\phi$; here $k_0 = 2\pi f_0/c = 2\pi/\lambda$ is the radar wave-number and ϕ is the angle between the (backscatter) radar direction and the x-axis of the coordinate system. Barrick (1972a) also obtained general results valid for arbitrary bistatic incidence/scattering angles, as well as all polarization state combinations. Again, these solutions clearly obey the Bragg or diffraction-grating scatter mechanism. The sea surface is effectively decomposed (over the scattering patch) into series of wave-trains; to first order, each of these scatters the incident energy in a unique direction determined by the wave-train wavelength and orientation. The Doppler shift in turn is precisely the wave frequency of this ocean wave-train. This simple mechanism underlies many of the experiments to be described in subsequent sections.

Sea-echo Doppler spectra measured with modern radar systems clearly show these 'first-order' spikes resembling impulse functions. Figure 1 is an example. This plot was taken at San Clemente Island looking westward at 13.4 MHz. The basic Fourier transform was taken over 200 s, providing a Doppler resolution (or system band-width) of ~0.005 Hz. Nine consecutive 200-s spectra were added together (incoherently averaged) to produce Figure 1. The scattering patch was located 30 km from the radar, and was approximately 3 km in radial extent by 5 km in azimuthal extent.

Also in evidence in nearly all records such as Figure 1 is a broad echo continuum surrounding the first-order spikes. This continuum has been proven experimentally to be sea echo (rather than system noise), and has been observed to vary both in amplitude and shape with sea state and radar frequency. Since 'first-order' theories predict zero echo in these regions of Doppler space, it was concluded that this continuum is of 'higher order'; hence investigators began extending the theories to second order. Barrick (1971, 1972b) derived a result which related the second-order Doppler spectrum to an integral involving the wave-height directional spectrum, the latter quantity appearing as a factor twice and evaluated at two sets of ocean wave-vectors. The result was obtained from second-order terms in the perturbation expansion of the nonlinear equations for both (i) the electromagnetic boundary conditions at the ocean surface, and (ii) the hydrodynamic boundary conditions at the free air-water interface under the influence of gravity. The interpretation of the mathematical expressions for second-order sea echo indicates that a double interaction is responsible for the scatter. Formally, one can express the Bragg-scatter relationships for the first-order Doppler spectrum as

$$\bar{k}_s - \bar{k}_i \equiv \bar{k}_r = \bar{\kappa} \quad \text{and} \quad \omega_s - \omega_i \equiv \omega_r = \omega_0\,, \tag{1}$$

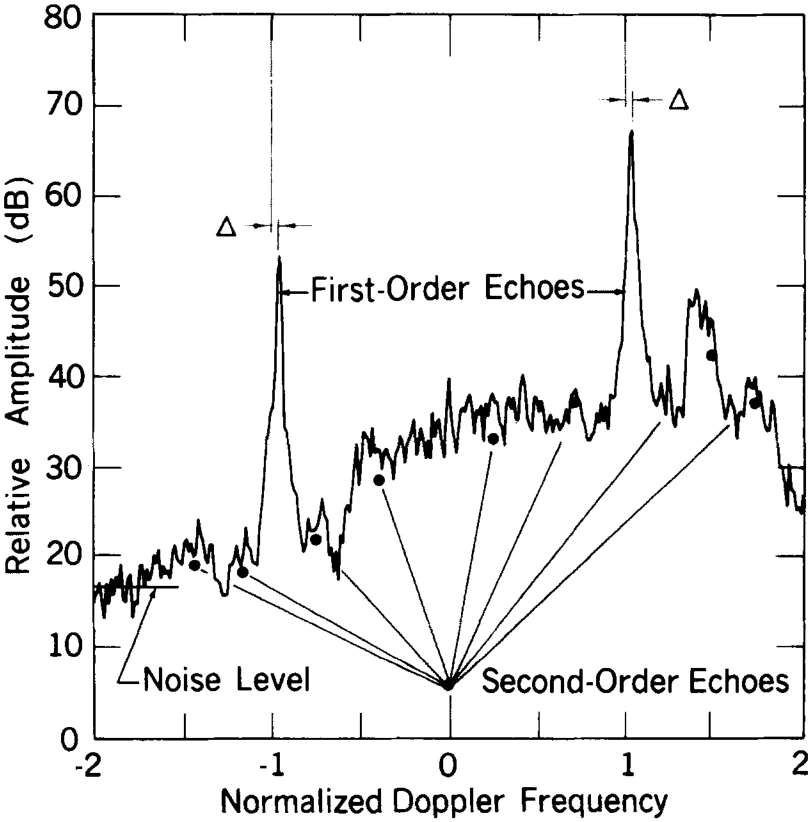

Fig. 1. Measured surface-wave sea-echo Doppler spectrum at 13.4 MHz from San Clemente Island on 4 December 1972. Nine consecutive 200-s power spectra were incoherently averaged to obtain the above record. The Doppler frequency axis is normalized, with 0 corresponding to the transmitted carrier frequency position, and ±1 being the first-order Bragg frequency ($\pm\sqrt{gf_0/\pi c} = \pm 0.3734$ Hz).

(where $\bar{k}_s$, $\bar{k}_i$ are the horizontal projections of the scattering and incident wavevectors, $\bar{\kappa}$ is the wavevector of the Bragg-interacting ocean wave, ω_s and ω_i are the scattered and incident (radian) frequencies of the radar signal, with ω_0, the frequency of the Bragg-scattering oceanwave satisfying the lowest-order dispersion equation $\omega_0 = \pm\sqrt{g\kappa}$). Thus theory shows the Doppler shift, $\omega_s - \omega_i$, of the first-order scatter process is identically $\omega_r = \sqrt{2gk_0}$ ($=\omega_B$), the value discovered experimentally by Crombie. In the same manner, the second-order theory illustrates the double-interaction Bragg process:

$$\bar{k}_s - \bar{k}_i \equiv \bar{k}_r = \bar{\kappa}_1 + \bar{\kappa}_2 \quad \text{and} \quad \omega_s - \omega_i \equiv \omega_r = \omega_{01} + \omega_{02} \tag{2}$$

where $\bar{\kappa}_1$ and $\bar{\kappa}_2$ are now the wave-vectors of the two ocean waves interacting simultaneously to produce the scatter, and the lowest-order dispersion equation again relates the temporal to the spatial wavenumbers, $\omega_{01} = \pm\sqrt{g\kappa_1}$ and $\omega_{02} = \pm\sqrt{g\kappa_2}$. Without repeating the cumbersome expressions for the Doppler spectrum found in Barrick (1971, 1972b) and Barrick and Weber (1977), Equation (2a) shows that there are whole series of ocean waves whose wave-vectors form two sides of a triangle which participate in the scattering process. Equation (2b) reduces the degrees of freedom of the vector sets satisfying this triad relationship from two to one, thereby evidencing itself as an integral over a single variable for the second-order sea-echo Doppler spectrum.

That these first- and second-order scatter theories correctly explain HF sea echo has been demonstrated experimentally. Figure 2 is a comparison of theory and experiment, using the same data as shown in Figure 1. Here, however, the measured spectrum of Figure 1 was 'filtered' to remove much of the noise-like structure due to the finite sample size. Likewise the theoretical data – computed for the sea conditions modeled by a Phillips spectrum with a $\cos^4(\theta/2)$ azimuthal wave pattern – have been 'filtered' by the same amount to permit comparison. That the Phillips model was applicable for use in calculating the predicted Doppler spectrum was verified by both buoy measurements and hindcasts made for the scattering area. Many comparisons such as this suggest that first- and second-order models available today correctly explain scatter. Hence, the models can be safely used to develop and test inversion techniques.

One final feature shown in Figure 1 illustrates the remaining remote-sensing application to be reviewed in this paper: the measurement of near-surface ocean

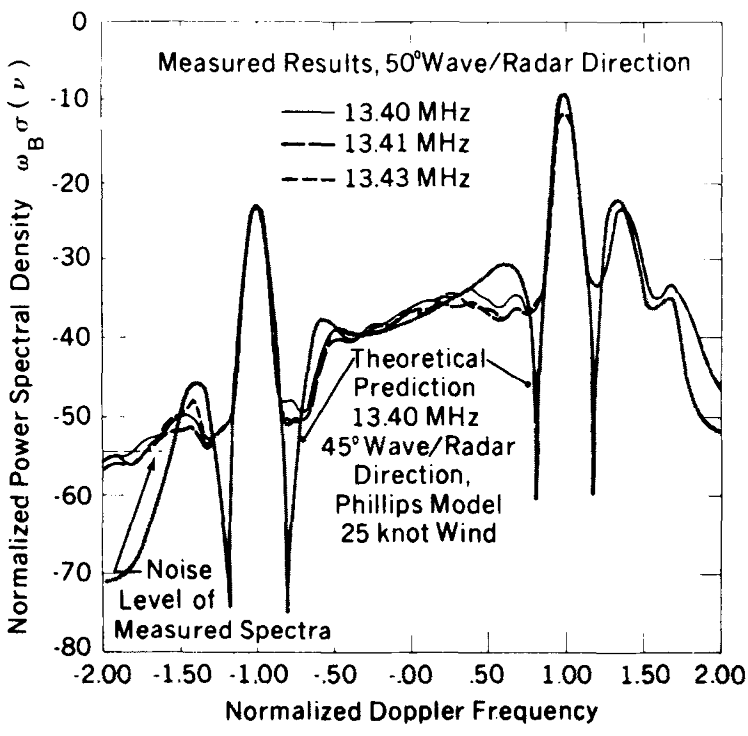

Fig. 2. Comparison of smoothed versions of theoretical Doppler spectrum and measured results shown in Figure 1.

currents. One observes a small overall displacement of the entire spectrum (by a normalized amount, Δ) as seen from the shifts of the sharp first-order peaks from their expected positions at $\pm\omega_B/2\pi$. This displacement arises from the fact that the scattering wave-trains are being transported by underlying currents. Using the same data set from which Figure 1 was made – along with drogue buoys in the scattering area – Stewart and Joy (1974) showed that this explanation in fact accounts for the displacement, while conversely, the current velocity can be calculated from the displacement. Furthermore, both Stewart and Joy (1974) as well as Barrick *et al.* (1974) examined the meaning of this shift when a current 'shear' vs depth is present.

2. Nature of HF Remote Sensing and Research Programs

The nature of HF radars for oceanic remote sensing differs considerably from the more familiar microwave radars characterized by parabolic dish antennas. As a result, the types of experiments to be discussed can only be appreciated if one understands these differences. Because the HF wavelength is three orders of magnitude greater (typically 30 m), the most obvious hardware difference involves the antenna. The type of narrow beam used in any scanning radar requires an antenna aperture many wavelengths in extent.* Thus it is obvious that it is not possible to scan a 2° beam by mechanically rotating an HF antenna as with microwave radars. If one wishes to scan a narrow beam at HF, he is forced to do so by electronically controlling the signal phase at each element of a linear antenna array several hundred meters in length. Therefore, HF experimental facilities either involve long, fairly expensive phased arrays requiring a considerable amount of real estate; or experiments must be designed around either omni-directional or broad-beamed shorter antenna elements and – if direction of arrival is important – by resorting to alternate techniques.

A second very important difference has to do with the propagation of HF radio waves. All electromagnetic waves propagate along straight lines in free space. Thus microwave and optical rays leaving a point near or on the surface of the earth cannot generally propagate to other surface points below the horizon. HF radio waves, however, have two alternate modes by which they can reach surface points beyond the horizon. The first has to do with diffraction by the curved earth; at HF, a vertically polarized wave can be diffracted a considerable distance beyond the horizon due to the much longer wavelength and the highly conductive properties of sea water at these frequencies. With typical powers available today, such radars located at ocean level can observe sea echo as far away as 200 km. The theory behind this mode of radio propagation began with Sommerfeld (1909) over 75 years ago, and today is referred to as the 'ground-wave' or 'surface-wave' mode. We will use the term surface wave here to avoid the confusion which could result from referring to 'ground' waves above the 'sea'.

* More precisely, the beamwidth in the plane of an aperture having length L is λ/L radians.

The second 'different' mode of HF propagation – referred to as 'skywave' – results from the presence of the ionosphere above the Earth. The charged particles comprising this layer cause a departure of the effective refractive index within this region from unity, and this departure varies inversely with the square of the radio frequency. Hence, while the ionosphere is virtually invisible to microwaves, it can appear at HF (below 30 MHz) as a concentric mirror at 100–400 km above the Earth. As one goes lower in frequency, however (i.e., less than 3 MHz typically), the effect of lower-altitude charged particles is felt in the form of increased attenuation to the propagating signal. Thus there is a fairly narrow window of frequencies, usually in the mid and upper HF region, within which HF radar operation is practicable. Even within this window, however, moving ionospheric inhomogeneities and multiple layers often distort a skywave signal to the point where it is unusable. Skywave propagation distances – based on a single reflection from the ionosphere – can reach a maximum of 4000 km.

As a consequence of the wavelengths, antenna sizes, and propagation modes at HF, one is faced with several constraints on ocean remote sensing experiments. To observe the important lower end of the gravity-wave spectrum using first-order scatter (where the ocean wavelength observed is one-half the radar wavelength), one must use frequencies typically between 500 kHz and 2 MHz. Besides the presence of the universally used AM band (550 kHz to 1.6 MHz) which would interfere with radar operation in this region, huge antennas would be required to form a fairly narrow beam. Furthermore, observations of a given patch of ocean from two or more directions would be necessary to infer any directional information about the longer ocean waves. Finally, the ionospheric attenuation at these lower frequencies is such as to preclude skywave propagation to greater distances, restricting one to shorter-range surface-wave observations. Even with these constraints, however, several promising techniques have been tested as low as 2 MHz, which give important information about the lower end of the wave-height directional spectrum; these will be discussed subsequently.

On the other hand, use of the upper HF band – more ideally suited to long-range skywave propagation – implies that to first order, the less interesting shorter ocean waves (5–15 m in length), are being observed, which on the open oceans are nearly always developed to their maximum possible height. Because of this and because of unknown ionospheric path losses, it is not possible to use the first-order skywave sea echo to obtain information about the lower end of the gravity-wave spectrum. Such information is therefore obtained by employing the second-order sea echo, normalized against the 'fully-developed' first-order echo.

Two other factors are peculiar to HF systems. All sensing systems are plagued with additive noise; in the microwave band, the prevailing noise is 'internal', due to random electron motion. At HF, however, the dominant noise is external, generated by (i) atmospheric sources, such as thunderstorms, (ii) extraterrestrial or galactic sources, and (iii) man-made sources, such as automobile ignition systems. At 10 MHz, for example, total external noise typically exceeds internal noise by

4–5 orders of magnitude. This dominance of external over internal noise influences choice of antennas and also can cause a diurnal or geographical variation of system sensitivity. A final factor which facilitates implementation of HF systems is the low data rates attendant with the lower operating frequencies (compared with microwaves). The state of the art today is such that all HF receiver signal processing can be done with reliable, inexpensive digital minicomputers or microprocessors. Microwave radars are still forced to rely on analog devices for most of their signal processing.

Research and experiments in HF radio oceanography can be divided into two categories. In the first, the research is focussed upon the development, interpretation, and application of the radar sensor to a particular problem; the emphasis here can be thought of as research and development of a remote sensing technique. The second type of research has to do with the application of a proven HF remote sensing technique to a particular research task in physical oceanography. Traditionally, the radar specialist has emphasized research of the former category, whereas the oceanographer has been more interested in the latter. By promoting interdisciplinary meetings, it is hoped the 'radio oceanographer' of the future will be able to produce contributions more effectively and proficiently in both categories, rather than being bound strictly to the area of his academic training.

The remainder of this paper will review research, experiments, and potential future HF radio oceanographic techniques which fall into one of three classes, based upon the oceanographic observable desired: (i) the wave-height directional spectrum or properties thereof; (ii) the wind field near the sea surface; (iii) ocean currents near the surface.

3. The Wave-Height Directional Spectrum

Crombie (1955) suggested over two decades ago that HF radars could be used to measure sea state. Very little was done in the next decade to further this suggestion, either experimentally or theoretically. Beginning in about 1966, a series of theoretical discoveries (discussed earlier) showed the quantitative relationships – to first and second order – between the wave-height directional spectrum and the sea-echo Doppler spectrum. These theoretical advances spurred further experimental investigations, employing a variety of novel concepts with both bistatic as well as backscatter geometries, and by moving the receiver as well as keeping it fixed.

A. Surface-wave experiments

Having the theories for first-order sea scatter put forward and extended by a number of investigators (Barrick and Peake, 1967, 1968; Munk and Nierenberg, 1969; Barrick, 1970; Barrick and Grimes, 1970), a number of organizations initiated various scatter experiments. Joint efforts between Scripps and Stanford University were first directed at examining the nature of surface-wave bistatic scatter. Using LORAN-A signals ($\sim$1.85 MHz) transmitted from various points along the California coast, this group received sea-echo signals and spectrally analyzed them. Employing the mathematical models for first-order bistatic sea scatter, they derived the relationships which permitted them to 'map' the echo intensity from time-delay/Doppler-frequency space to x/y wavenumber space (see Teague, 1971a, 1971b; Peterson *et al.*, 1970; Barrick, 1972b). While this technique does not uniquely allow the determination of the wave-height directional spectrum at all wave-numbers from a single set of measurements at a given frequency and receiver location, it was shown experimentally to yield a considerable amount of wave-height directional spectral information. One must assume that these wave statistics are homogeneous over the coastal radar coverage area, typically 200×200 km. The advantage of this technique – as employed by Scripps and Stanford – is that it uses existing navigational transmissions, requiring only a receiver and processor. Barrick and Grimes (1970; see also Barrick, 1972b) examined the characteristics of bistatic scatter at mid-HF (5, 10, and 15 MHz) using a buoy transmitter. Still later mid-HF experiments of the Riverside Research Institute (1974) were aimed at mapping the average bistatic scatter intensity vs time delay and Doppler frequency.

The Scripps–Stanford team also pioneered another novel concept for measuring the azimuthal variation of the wave-height directional spectrum at a given ocean wave-number. The direction of arrival is obtained by translating the small, omni-directional receiving antenna along the surface at a constant velocity. This imparts a different Doppler shift to the sea echo arriving from each azimuth angle, the receiver-induced Doppler component varying as $\Delta f(\theta) = v \cos \theta/\lambda$, where θ is the azimuthal echo arrival angle from the receiver velocity direction. (The configuration here was essentially a backscatter geometry, with the transmissions again originating from a LORAN-A tower.) Thus the solitary first-order Doppler spikes – represented by the impulse functions – are spread into bands about their first-order positions ($\sqrt{g/\pi\lambda}$) of width $2v/\lambda$, with each Doppler shift in this band corresponding to a different direction of arrival. The ambiguity in angle, θ (due to the even nature of the cosine function) was resolved by making runs at different angles. In Teague *et al.* (1973) and Tyler *et al.* (1974), an experiment of this type is described which was conducted on Wake Island. The receiver was driven in an automobile along aircraft runways. Since the frequency being transmitted was $\sim$1.95 MHz, the portion of the ocean wave spectrum being observed had wavelengths of 77 m and periods of 7 s. Hence, models were developed from these data relating the angular pattern of the waves at a given frequency to the wind speed.

The 'synthetic aperture' technique* tested at Wake Island has already proven to be a useful tool for oceanographic research; two significant results have emerged

* The use of motion of one or both of the terminals is referred to in radar terminology as forming a synthetic antenna aperture because the antenna is being translated in time to the positions that would normally be occupied simultaneously by many elements of a phased-array antenna.

thus far. First, the angular dependencies (shown in Figure 3) for the first time reveal that significant amounts of wave energy propagate against the wind, a fact which was predicted years ago from nonlinear wave–wave interaction theories. Secondly, these measurements permitted development of an angular model of the form $\cos^s \theta/2$, in which s depends upon the wind speed (for fully developed seas) and the ocean wavelength being observed (see Tyler *et al.*, 1974). Presently, Scripps and Stanford are conducting experiments in the Gulf of Mexico off Galveston using this technique to study wave growth with distance from shore.

Other techniques have been proposed for observing the wave-height directional spectrum by exploiting motion at one or both of the transmitter/receiver terminals and using the first-order portion of the wave-height spectrum. One method employs a satellite (or aircraft) for one of the terminals and a buoy or tower-based stationary point for the other. Sea echo at a given delay after reception of the direct signal is recorded, spectrum analyzed, and normalized in intensity using the direct signal. Barrick (1972b) describes this concept. Experiments were conducted by Battelle Memorial Institute (Ruck *et al.*, 1972; Ruck, 1975) which showed that the technique can indeed provide useful information at a variety of ocean wave-numbers and wave angles. Barrick (1972b) also discusses using a ship with a back-scatter radar to measure the directional spectrum, again utilizing the known ship velocity to relate wave angle to first-order sea-echo Doppler shift. This technique has been tried experimentally by Stanford and also works satisfactorily; appreciable limitations on the angular accuracy in this case can be imposed by uncertainties in ship velocity, however.

The final type of surface-wave experiment involves shore-based back-scatter radars which can look at a given patch of sea from a single direction. The antenna beamwidths in these experiments have varied between ~7° and ~180°. The first reported experiments (following Crombie's original experiments two decades ago) were by Crombie in the mid 1960's (Crombie *et al.*, 1970; Crombie, 1971) in connection with the BOMEX program on Barbados Island. The Naval Research Laboratory conducted surface-wave experiments in the late 1960's on the Chesapeake Bay which verified the quantitative predictions of the first-order sea-echo amplitude (see Barrick, 1972a). Stanford University reported measurements at 30 MHz (Tyler *et al.*, 1972) with a nearly omnidirectional antenna system; second-order echo features were clearly in evidence on these Doppler records. Surface-wave sea-echo back-scatter Doppler data were observed within many Defense Department programs in the early 1970's, but the primary emphasis in these efforts was the elimination of this echo as unwanted 'clutter' rather than in its use as a remote sensing mechanism. A French program is presently underway (de Maistre *et al.*, 1978), which is investigating the potential of surface-wave sea-echo for measuring wave characteristics. A fairly extensive set of surface-wave measurements was made looking westward from San Clemente Island in late 1972 and early 1973 in a joint NOAA/ITS/NAVY program (Barrick *et al.*, 1974). These data taken on frequencies from 2 to 25 MHz were gathered primarily for the purpose of testing theories relating the second-order Doppler spectrum to characteristics of

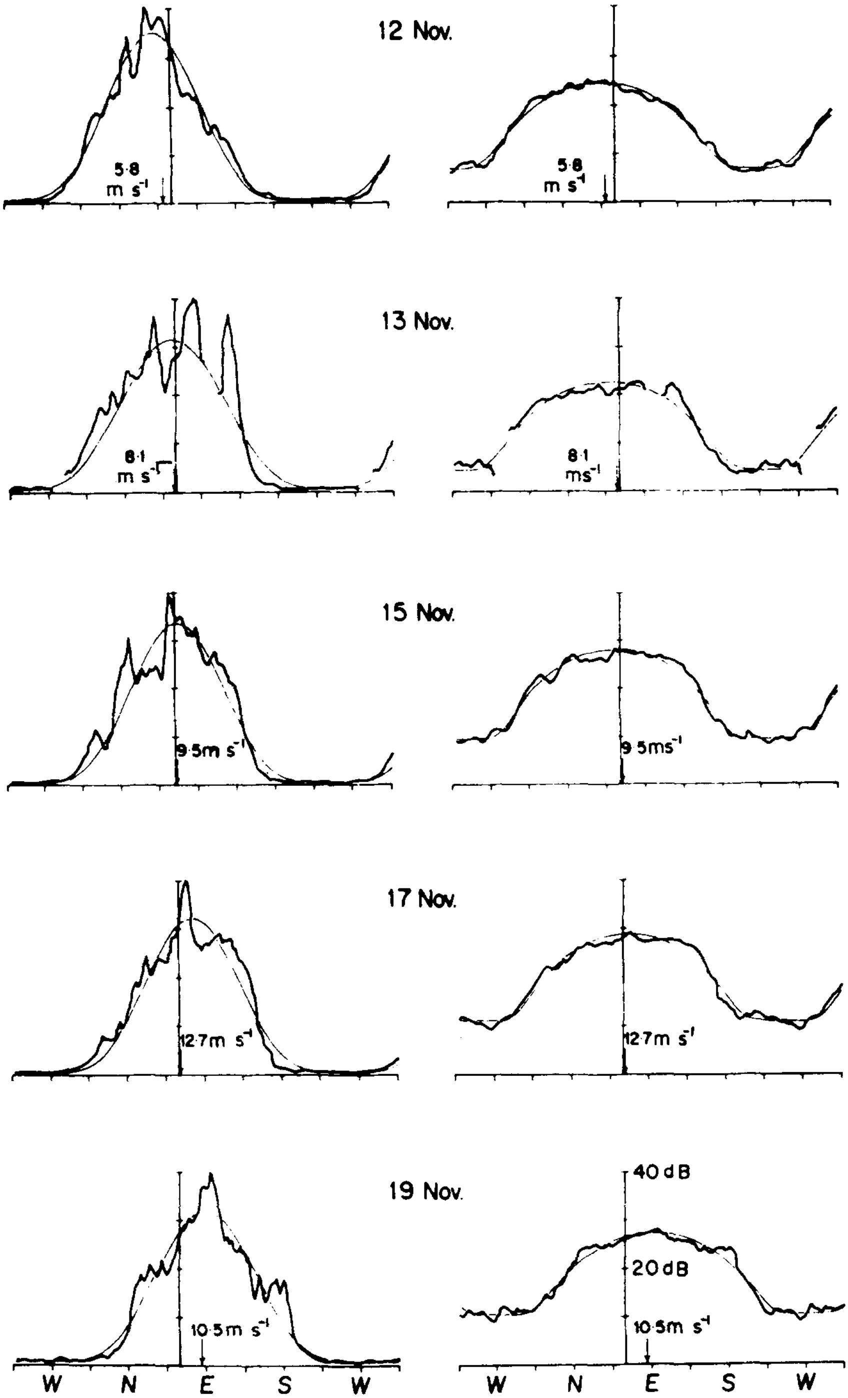

Fig. 3. Directional spectra of 0.14 Hz waves approaching Wake Island as measured by synthetic-aperture HF radar at 1.95 MHz in 1972 (from Tyler *et al.*, 1974). Plotted is energy density on a linear scale (left) and logarithmic scale (right); smooth curves are least-square fits. Wind averages over preceding eight hours are indicated.

the wave-height directional spectrum. Figures 1 and 2 were taken from these measurements. The results of these analyses are discussed in the next section.

Using data gathered at the San Clemente Island facility, Barrick and Snider (1977) showed that the sea-echo signal amplitude is for all practical purposes a Gaussian random variable; this applies to both the first- and second-order portions of the echo. Furthermore, they determined that the time between independent Doppler spectral samples at mid-HF is approximately 30–50 s. These two facts are useful for system design and analyses because they provide statistical confidence limits of spectral sample averages as a function of radar observation time.

B. Second-order echo-inversion efforts

It was mentioned previously that few features of the wave-height directional spectrum can be extracted from practicable non-moving backscatter radars using the first-order echo. Essentially, only two points in the directional spectrum are sampled by the first-order interaction; these are the two sets of ocean wave-trains half the radar wavelength moving toward and away from the radar. For radar frequencies between 3 and 30 MHz, for example, that portion of the spectrum with temporal frequencies between 0.18 and 0.56 Hz are sampled; waves at these frequencies on the open ocean are nearly always developed to their maximum 'equilibrium' heights. The dominant wave direction of the Bragg-scattering waves with respect to the radar direction can be inferred if one uses a directional model such as that put forth in Tyler *et al.* (1974). It is generally not satisfactory to attempt to extrapolate wave directional features at the more important, lower wave-numbers from a single set of such measurements at higher wave-numbers.

As soon as theoretical models for the second-order sea-echo Doppler spectrum were published (Barrick, 1971), it was obvious that from this portion of the echo one could hope to extract many more important wave-height spectral features, still employing only a single radar frequency and direction for a given patch of sea. The mathematical relationship is a nonlinear integral equation, with the desired wave-height directional spectrum appearing as a factor twice in the integrand, evaluated at the double Bragg-scattering wave-vectors $\bar{\kappa}_1$ and $\bar{\kappa}_2$ forming two sides of a triangle. Hasselmann (1971) first suggested that this integral equation could be approximated under certain circumstances to yield the wave-height nondirectional spectrum; furthermore, he pointed out that by dividing by the first-order echo as a normalization, one could remove unknown path losses and/or system gain factors. Stewart (1971) explored Hasselmann's claim, employing only the hydrodynamic second-order contribution and a restrictive directional model. Barrick (1977b), using the general second-order expression, derived and tested this suggested result. He found that much of the directional dependence of this inversion technique could be removed by dividing the Doppler spectrum by a known weighting function; upon testing this inversion method theoretically, Barrick showed that reasonable accuracy was obtainable for $k_0h > 0.2$, where k_0 is the radar wave-number and h is the rms wave-height.

The first testing of second-order inversion techniques against measured data (supported by independent wave buoy measurements) was done with the San Clemente Island data discussed above. Barrick (1977a) showed that rms wave-height and mean wave period could be deduced to acceptable accuracies. The technique – based upon the weighting-function approach described in the preceding paragraph – requires neither the assumption of a given wave directional model nor the assumption that the seas are fully developed. Figure 4 shows data points for wave-height. The ordinate represents the correction factor, relating radar-deduced wave-height, h_*, to buoy-measured wave-height, h. Some small, residual directional dependence can be expected, as seen from the theoretical curves. The experimental data show that for $k_0 h_* > 0.3$, the rms wave-height error is $\sim 22\%$.

The ultimate objective is to invert the second-order Doppler spectrum exactly, obtaining the entire wave-height directional spectrum. Because of the nonlinearity of the integral equation and the two-dimensional nature of the desired quantity, this is indeed a formidable problem. Stanford University and NOAA's Wave Propagation Laboratory are presently investigating this task. Lipa (1977) has derived and discussed a simplified but quite promising solution.

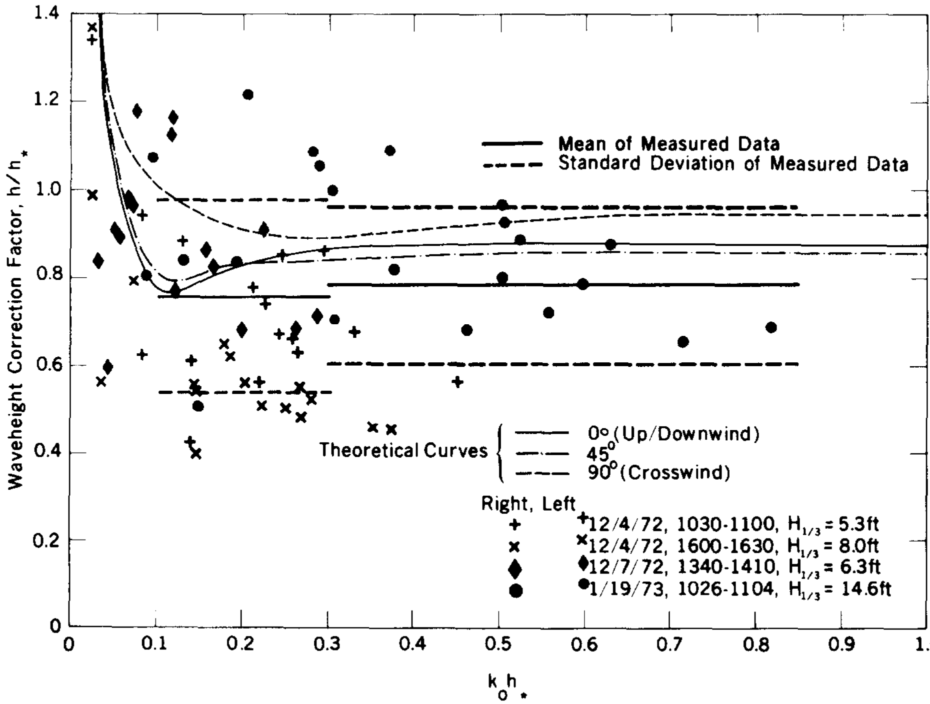

Fig. 4. Theoretical and experimental results of use of waveheight inversion model; h_* is radar-deduced rms wave-height, while $h(=H_{1/3}/4)$ is buoy-measured rms wave-height. Measured data were taken at San Clemente Island on azimuthal bearings of 240° (left) and 270° (right), and are inverted from averages of nine 200-s spectra on frequencies from 3 to 20 MHz.

C. Skywave experiments

Ever since Crombie's initial surface-wave discovery two decades ago, many have been intrigued by the concept of using skywave radars to measure 'sea state' remotely over vast ocean expanses at great distances. Tveten (1967) first published skywave Doppler records of sea echo around Florida measured from Boulder, Colorado, which exhibited the characteristic, symmetrically placed first-order Bragg peaks. Ward (1969) published similar skywave sea-echo data. Both the Stanford Research Institute and Naval Research Laboratory have often observed sea echo with skywave radars, which also clearly shows the expected second-order spectral features; these observations have thus suggested the possibility that the inversion techniques mentioned above – using the second-order echo – can be exploited to obtain important parameters of the wave-height directional spectrum.

Since the second-order sea echo must be utilized in order to recover anything more than crude wave direction estimates at the shorter ocean wavelengths, this portion of the Doppler spectrum must be clearly recognizable. Yet it is well known that a time-varying ionosphere will smear the Doppler record, sometimes to the point where one cannot recognize or utilize the second-order echo. Hence inversion techniques – for example, those discussed in the preceding section which proved so useful for obtaining wave-height and wave-period from surface-wave data – may only be useful for a small percentage of the time with skywave radars. NOAA's Wave Propagation Laboratory has embarked on a research program to determine the utility and accuracy of a skywave radar for obtaining wave-height directional spectral parameters. Located on the north end of San Clemente Island, the radar looks into the North Pacific and Gulf of Alaska. Real-time ionospheric diagnoses and use of adaptive techniques can permit the skywave radar user to recognize bad operating times and areas and, in some cases, to work around these difficulties. In addition, simulations – in which previously recorded surface-wave data are distorted to resemble ionospherically smeared skywave data – are being used to develop and test inversion techniques for dealing directly with the skywave sea echo. If the program indicates that the skywave radar can observe wave parameters a reasonable percentage of the time with adequate accuracy, this remote sensing instrument should prove to be a very useful tool both for routine monitoring of sea state over large areas and for specific oceanographic experiments.

4. Ocean Surface Winds

Inasmuch as the waves on the ocean are produced by the winds near the surface, it was recognized some time ago that the skywave radar would ultimately become a useful tool for remotely sensing oceanic winds. Since only two parameters are required to describe the wind vector (magnitude and direction), it was felt (Long and Trizna, 1973) that these quantities could be deduced from readily recognizable features of the Doppler spectrum. The emphasis was toward deriving empirical techniques for extracting wind velocity from the echo signal, since no direct link between the radar echo and wind is possible.*

As was mentioned earlier, the strengths of the positive and negative first-order Doppler peaks are proportional to the heights of advancing and receding ocean waves equal to roughly one-half the radar wavelength. At skywave radar operating frequencies, these ocean wavelengths are 5 to 15 m. Inasmuch as these shorter ocean waves respond fairly quickly to wind changes, several investigators recognized that the ratio of the two first-order peaks might be a useful indicator of wind direction. One must of course assume a directional model in order to relate this ratio to the wind vector orientation with respect to radar direction, and all such models are symmetrically ambiguous about the radar direction.

The first group to map ocean surface winds with a skywave radar system was the Naval Research Laboratory (NRL). Looking into the North Atlantic from their Chesapeake Bay facility, they plotted wind directional arrows which clearly exhibited the features of both cyclonic storm patterns and frontal systems (Long and Trizna, 1973; Ahearn *et al.*, 1974). Radar-deduced arrows were compared with weather maps based on ship reports. Most of these efforts attempted to deduce only wind directions from the first-order echo ratios; features of the sea-echo Doppler spectrum which could be used to deduce wind speed were less obvious. NRL investigated the comparison of the first-order echo peaks with the (second-order) echo floor between the peaks as an indicator of wind speed; this empirical correlation met with only limited success.

Scripps and the Stanford Research Institute (SRI) conducted skywave tests for several days in which they compared radar-deduced wind directions and speeds with those measured from a buoy, FLIP, northeast of Hawaii (Stewart and Barnum, 1975). (Their radar facility is located in California near San Francisco.) They employed an improved model for deducing wind direction, viz., the result of their LORAN-A Wake Island radar experiment discussed in Tyler *et al.*, (1974). They obtained quite acceptable direction accuracies of $\pm 16°$ with this model. For wind speed, they attempted to develop an empirical model, relating the width of the echo at the first-order peak position to the speed; the results were somewhat discouraging. The width of this peak is inherently insensitive to wave-height, and hence would be even less sensitive to wind speed. In addition, however, ionospheric smearing and poor Doppler processor resolution further degraded the accuracy of this technique.

Quite promising results have been obtained recently by SRI, using their skywave radar facility to locate and track hurricanes and severe storms over the ocean. Their radar is capable of looking into the Gulf of Mexico as well as the Pacific Ocean. During 1975 and 1976, they observed several hurricanes in the Gulf of Mexico. The primary output of these observations has been wind direction, using the ratio

* It should be stressed that at HF, a radar does not respond to winds, nor in fact to rain, snow, or other meteorological phenomena which are frequently used as microwave targets.

of the two first-order echo peaks to infer this quantity. The deduction of hurricane wind speeds from the echo has not thus far been successfully demonstrated, although the search for empirical relationships yielding this quantity from the echo is continuing. Figure 5 is an example of radar-inferred wind directions during

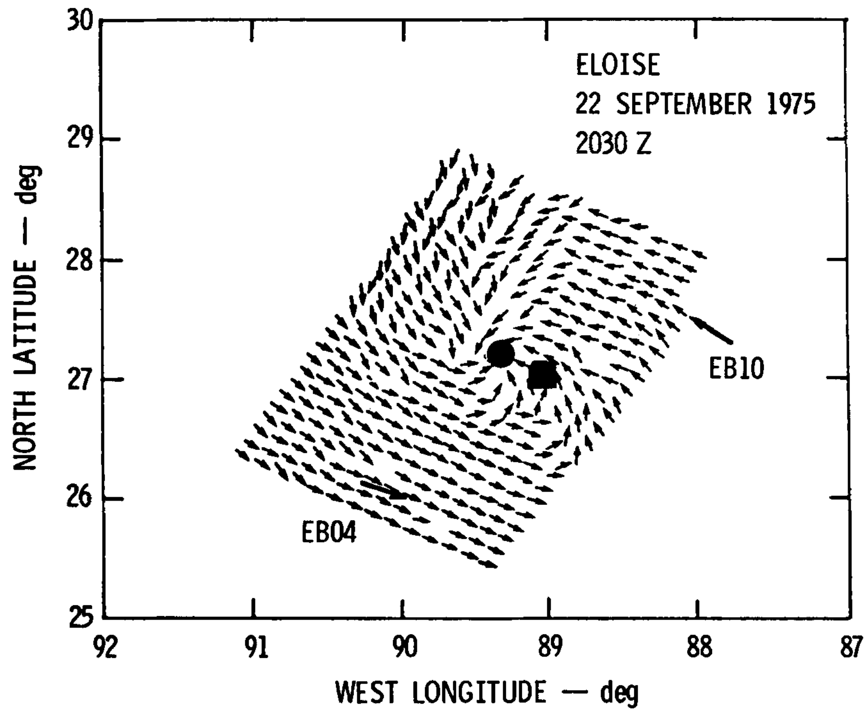

Fig. 5. Wind circulation estimates (direction only) for Hurricane Eloise in Gulf of Mexico measured by SRI over-the-horizon radar. Hurricane center estimated from radar denoted by circle; center estimated from satellite and aircraft reconnaissance denoted by square. Wind direction vectors shown as measured at NOAA buoys EB-04 and EB-10.

Hurricane Eloise in 1975 (Maresca and Barnum, 1977). The black circle represents the 'radar-inferred' hurricane center, and the black square is the hurricane center derived from satellite and reconaissance aircraft observations; the difference between these 'centers' is 35 km. The heavy arrows are wind directions measured at NOAA buoys EB-04 and EB-10. Further research in this area at SRI is aimed at deriving methods of determining the position, speed, size, circulation, and wind intensity throughout the hurricane at the ocean surface. They are also exploring the possibility of inferring wind intensity from skywave-derived ocean surface currents, in which land echo is used as a zero-velocity reference. There is little doubt that skywave observations of hurricane and storm areas will ultimately provide information which is difficult and expensive to obtain by other means.

5. Ocean Surface Currents

The first study of surface currents using an HF surface-wave radar was done by Crombie (1972). He located a radar on the east coast of Florida and looked toward the Gulf Stream. In these experiments he also pioneered another novel concept: the use of the phase between the echo signal at two omnidirectional receiving antenna elements as a technique for obtaining the angular direction of arrival. Thus the need for a long antenna array to determine direction was circumvented.

Additional experiments done at San Clemente Island in 1972 were aimed at studying the current velocity resolution (Stewart and Joy, 1974; Barrick *et al.*, 1974). The resolution – deduced from independent (buoy) drifter observations – appeared to be better than $10\,\mathrm{cm\,s^{-1}}$. The above investigators also analyzed the effect of a varying current profile with depth, and concluded that the radar senses the mean current speed to a depth of $\sim\lambda/8\pi$ from the (average) surface level.

NOAA's Wave Propagation Laboratory has undertaken a program to develop and test a small, transportable coastal backscatter radar system for mapping near-surface currents in real time (Barrick and Evans, 1976). The system consists of two radar units, because a single radar can measure only one component of the total current vector (that component pointing toward the radar). The two units are positioned along the coast about 40 km apart, and – operating in the surface-wave mode between 25 and 30 MHz – have a maximum range from the coast of about 70 km. Design and construction of the first radar unit pair was completed in June 1976.

These radar units – and others to be constructed in the near future – are to be used to map current patterns along the U.S. coasts. In particular, they are to be employed in environmental studies aimed at assessing the impact of possible offshore oil recovery operations. It is surface currents that will determine whether an oil spill or leak may dissipate harmlessly at sea or do irreparable damage to the coast. Oceanographic research experiments are also planned with these radars; with the ability to obtain thousands of current vectors every 3×3 km after only several minutes' operation, the oceanographer will have a wealth of data heretofore unobtainable.

The concept behind the NOAA radars is similar to that employed by Crombie (1972). Here, however, three receiving antennas (3 m apart) are used instead of two to obtain the echo's angle of arrival. This permits one to resolve signals unambiguously at the same Doppler frequency from two different directions.

Only several days data have been gathered thus far with the recently constructed radars, and these have been obtained using only one of the two units required to obtain a complete vector field. This radar was operated near Fort Lauderdale, Florida looking eastward into the Gulf Stream. The other site will soon be on the air simultaneously at Miami. Therefore the 'maps' obtained thus far show only the radial component of the current vector, pointing in the direction of the radar site. For comparison, current values for the Gulf Stream averaged over time are shown in radial map form in Figure 6a; these were obtained from Düing (1975). They show a South–North flow which reaches a maximum about 40 km from shore. Figure 6b is a map of radial currents measured by the radar based upon about five minutes of operation. It is obvious from the general agreement of the two maps that the radar does in fact provide massive amounts of surface current data. Further experiments using both sites will be conducted to measure more precisely the accuracy of the system; first indications are that this accuracy should exceed $10\,\mathrm{cm\,s^{-1}}$.

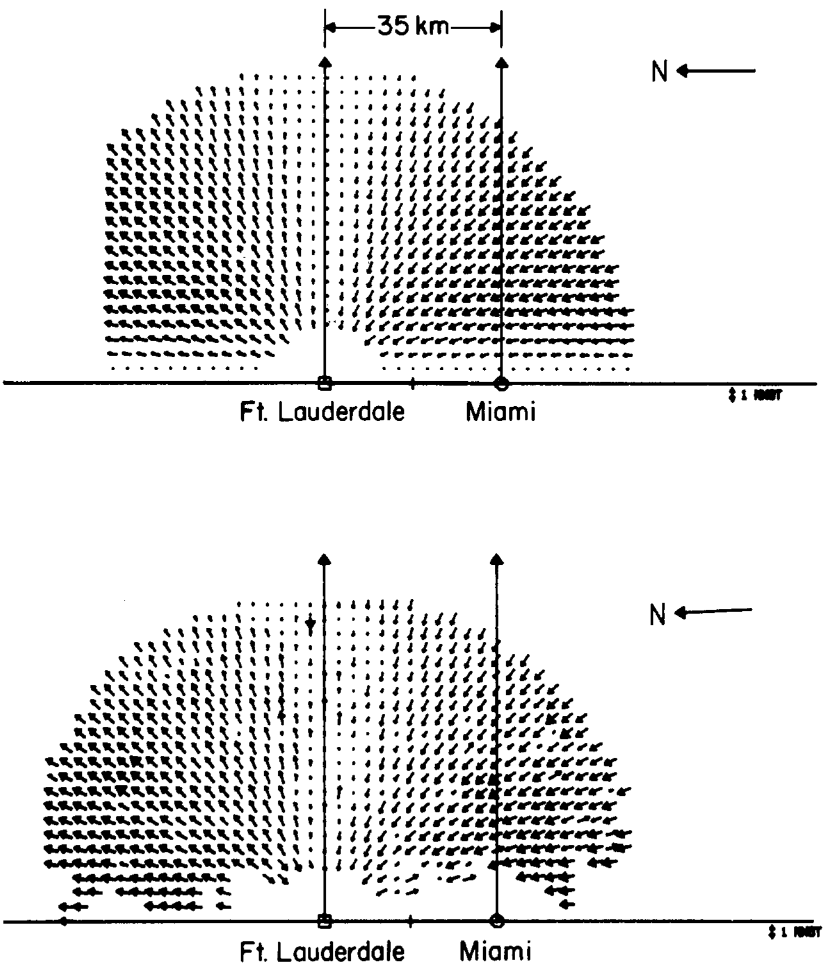

Fig. 6. Radial current-vector maps as seen by transportable NOAA HF surface-wave radar system at Ft. Lauderdale, Florida; comparisons of expected, typical flow pattern vs radar-measured data with no averaging or filtering. (Top) One-site map of typical, mean Gulf-stream current taken from Düing (1975). (Bottom) One-site map of radar-deduced Gulf Stream currents with no averaging or filtering.

6. Conclusions

Historically, radio oceanography began first at HF, both in terms of experiments and theory. The HF scatter mechanism is soundly established, and there is no question as to the adequacy of the theoretical scatter models, both to first and second order. Hence, as this paper has shown, the HF region presently offers a wider variety of radar remote sensing techniques than other regions of the radio spectrum.

Many of these techniques, such as low-HF synthetic aperture surface-wave radars and mid-HF phased-array systems, have already led to oceanographic discoveries. Others, such as current-mapping radars and possibly shipboard radars, will undoubtedly advance our knowledge and understanding of wave and current structures on the ocean's surface.

Skywave radars have for many years held out the exciting possibility of monitoring wave and wind fields over vast ocean areas. Because there are several such radars in the world which can observed the seas, measurements of sea surface conditions will certainly continue. The question of whether the ionosphere will permit sufficiently reliable and timely measurements to justify the implementation of operational skywave radars that will routinely monitor sea state has not yet been answered; present research programs should soon provide the answer.

References

Ahearn, J. L., Curley, S. R., Hèadrick, J. M., and Trizna, D. B.: 1974, 'Tests of Remote Skywave Measurement of Ocean Surface Conditions', *Proc. IEEE* **62**, 681–687.

Barrick, D. E. and Peake, W. H.: 1967, 'Scattering from Surfaces with Different Roughness Scales: Analysis and Interpretation', Battelle Research Report BAT-197A-10-3, Columbus, Ohio, available from Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia, Accession No. AD 662 751.

Barrick, D. E. and Peake, W. H.: 1968, 'A Review of Scattering from Surfaces with Different Roughness Scales', *Radio Sci.* **3**, 865–868.

Barrick, D. E. and Grimes, J. A.: 1970, 'Predicted and Measured Ground-wave Sea Clutter Spectrum at 6 MHz', presented at Fall USNC/URSI Meeting, Sept. 15–17, Columbus, Ohio.

Barrick, D. E.: 1970, 'The Interaction of HF/VHF Radio Waves with the Sea Surface and its Implications', *Electromagnetics of the Sea*, AGARD Conference Proceedings No. 77, available from Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia, Accession No. AD 716 305.

Barrick, D. E.: 1971, 'Dependence of Second-order Sidebands in HF Sea Echo upon Sea State, *IEEE G-AP International Symposium Digest*, Sept. 21–24, Los Angeles, California, pp. 194–197.

Barrick, D. E.: 1972a, 'First-order Theory and Analysis of MF/HF/VHF Scatter from the Sea', *IEEE Transactions on Antennas and Propagation*, AP-**20**, 2–10.

Barrick, D. E.: 1972b, 'Remote Sensing of Sea State by Radar', in V. E. Derr (ed.) *Remote Sensing of the Troposphere*, Ch. 12, U.S. Government Printing Office, Washington, D.C.

Barrick, D. E., Headrick, J. M., Bogle, R. W., and Crombie, D. D.: 1974, 'Sea Backscatter at HF: Interpretation and Utilization of the Echo', *Proc. IEEE* **62**, 673–680.

Barrick, D. E. and Evans, M. W.: 1976, 'Implementation of Coastal Current-mapping HF Radar System', Progress report No. 1, NOAA Technical Report ERL 373-WPL 47.

Barrick, D. E. and Snider, J. B.: 1977, 'The Statistics of HF Sea-echo Doppler Spectra', *IEEE Transactions on Antennas and Propagation*, AP-**25**, 19–28.

Barrick, D. E. and Weber, B. L.: 1977, 'On the Nonlinear Theory for Gravity Waves on the Ocean's Surface, Part II: Interpretation and Application', *J. Phys. Oceanog.* **7**, 11–21.
Barrick, D. E.: 1977a, 'Extraction of Wave Parameters from Measured HF Sea-Echo Doppler Spectra', *Radio Sci.* **12**, 415–424.
Barrick, D. E.: 1977b, 'The Ocean Waveheight Nondirectional Spectrum from Inversion of the HF Sea-echo Doppler Spectrum', *Remote Sensing of Environment* **6**, 201–227.
Crombie, D. D.: 1955, 'Doppler Spectrum of Sea Echo at −13.56 Mc/s', *Nature* **175**, 681–682.
Crombie, D. D., Watts, J. M., and Beery, W. M.: 1970, 'Spectral Characteristics of HF Ground Wave Signals Backscattered from the Sea', *AGARD Conference Proceedings No. 77*, available from Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia, Accession No. AD 716 305.
Crombie, D. D.: 1971, 'Backscatter of HF Radio Waves from the Sea', in J. R. Wait (ed.), *Electromagnetic Probing in Geophysics*, The Golem Press, Boulder, Colorado, pp. 131–162.
Crombie, D. D.: 1972, 'Resonant Backscatter from the Sea and its Application to Physical Oceanography', *IEEE International Conference Proceedings on Engineering in the Ocean Environment*, Ocean '72, Newport, Rhode Island, Sept. 13–15, 1972, IEEE Publication 72 CHO 660-1 OCC, 174–179.
Düing, W.: 1975, 'Synoptic Studies of Transients in the Florida Current', *J. Marine Res.* **33**, 53–73.
Hasselmann, K.: 1971, 'Determination of Ocean Wave Spectra from Doppler Radio Return from the Sea Surface', *Nature* **229**, 16–17.
Lipa, B. J.: 1977, 'Derivation of Directional Ocean-wave Spectra by Integral Inversion of Second Order Radar Echoes', *Radio Sci.* **12**, 425–433.
Long, A. E. and Trizna, D. B.: 1973, 'Mapping of North Atlantic Winds by HF Radar Sea Backscatter Interpretation', *IEEE Transactions on Antennas and Propagation*, AD-**21**, 680–685.
de Maistre, J. C., Broche, P., and Crochet, M.: 1978, 'Off-shore Wind Measurements by HF Doppler Ground-wave Radar', this volume, pp. 55–60.
Maresca, J. R. and Barnum, J. R.: 1977, 'Remote Measurement of the Position and Surface Circulation of Hurricane Eloise by Skywave Radar', accepted for publication in *Mon. Weather Rev.*
Munk, W. H. and Nierenberg, W. A.: 1969, 'High Frequency Radar Sea Return and the Phillips Saturation Constant', *Nature* **224**, 1285.
Peterson, A. M., Teague, C. C., and Tyler, G. L.: 1970, 'Bistatic Radar Observation of Long-period Directional Ocean-wave Spectra with LORAN A', *Science* **170**, 158–161.
Rice, S. O.: 1951, 'Reflection of Electromagnetic Waves from Slightly Rough Surfaces', in M. Kline (ed.), *Theory of Electromagnetic Waves*, Interscience Publishers, New York, 351–378.
Riverside Research Institute: 1974, Technical Reports T-1/278-4-00, Volumes I, II, and III, 'True Course, Phase I Program Reports', 80 West End Avenue, New York, N.Y. 10023.
Ruck, G. T., Barrick, D. E., and Kaliszewski T.: 1971, 'Bistatic Radar Sea State Monitoring', Battelle, Columbus Laboratories, Columbus, Ohio, Technical Report, Contract NAS6-2006, Dec. 1971.
Sommerfeld, A.: 1909, 'The Propagation of Waves in Wireless Telegraphy', *Annalen Physik* **28**, 665–682.
Stewart, R. H.: 1971, 'Higher Order Scattering of Radio Waves from the Sea, IEEE G-AP International Symposium Digest, Sept. 21–24, 1971, Los Angeles, California, pp. 190–193.
Stewart, R. H. and Joy, J. W.: 1974, 'HF Radio Measurements of Surface Currents', *Deep Sea Research* **21**, 1039–1049.
Stewart, R. H. and Barnum, J. R.: 1975, 'Radio Measurements of Oceanic Winds at Long Ranges: An Evaluation', *Radio Sci.* **10**, 853–857.
Teague, C. C.: 1971a, 'High-frequency Resonant Scattering Techniques for the Observation of Directional Ocean-wave Spectra', Technical Report No. 3615–1, Stanford Electronics Laboratory, Stanford University, August 1971.
Teague, C. C.: 1971b, 'Bistatic-radar Techniques for Observing Longwavelength Directional Ocean-wave Spectra', *IEEE Transactions on Geoscience Electronics* GE-**9**, 211–215.
Teague, C. C., Tyler, G. L., Joy, J. W., and Stewart, R. H.: 1973, 'Synthetic Aperture Observations of Directional Height Spectra for 7s Ocean Waves', *Nature* **224**, 98–100.
Tveten, L. H.: 1967, 'Ionospherically Propagated Sea Scatter', *Science* **157**, 1302–1304.
Tyler, G. L., Faulkerson, W. E., Peterson, A. M., and Teague, C. C.: 1972, 'Second-order Scattering from the Sea: Ten-meter Observations of the Doppler Continuum', *Science* **177**, 359–351.

Tyler, G. L., Teague, C. C., Stewart, R. H., Peterson, A. M., Munk, W. H., and Joy, J. W.: 1974, 'Wave Directional Spectra from Synthetic Aperture Observations of Radio Scatter', *Deep Sea Res.* **21**, 989–1016.

Wait, J. R.: 1966, 'Theory of HF Ground Wave Backscatter from Sea Waves', *J. Geophys. Res.* **71**, 4839–4842.

Ward, J. F.: 1969, 'Power Spectra from Ocean Movements Measured Remotely by Ionospheric Radio Backscatter', *Nature* **223**, 1325–1330.

Weber, B. L. and Barrick, D. E.: 1977, 'On the Nonlinear Theory for Gravity Waves on the Ocean's Surface, Part I: Derivations', *J. Phys. Oceanog.* **7**, 3–10.

Wetzel, L. B.: 1966, unpublished manuscript.