Sea Backscatter at HF: Interpretation and Utilization of the Echo

DONALD E. BARRICK, MEMBER, IEEE, JAMES M. HEADRICK, SENIOR MEMBER, IEEE, ROBERT W. BOGLE, AND DOUGLASS D. CROMBIE

Abstract—Theories and concepts for utilization of HF sea echo are compared and tested against surface-wave measurements made from San Clemente Island in the Pacific in a joint NRL/ITS/NOAA experiment. The use of first-order sea echo as a reference target for calibration of HF over-the-horizon radars is established. Features of the higher order Doppler spectrum can be employed to deduce the principal parameters of the wave-height directional spectrum (i.e., sea state); and it is shown that significant wave height can be read from the spectral records. Finally, it is shown that surface currents and current (depth) gradients can be inferred from the same Doppler sea-echo records.

I. INTRODUCTION

TWO YEARS ago Crombie [1] observed sea echo with an HF radar, and he correctly deduced the scattering mechanism which accounted for the peculiar and unique dominant peaks in the observed Doppler spectrum. This gave rise to further research and suggested the exciting possibility of measuring sea state at great distances with HF sky-wave radars. A current joint program involving NOAA, NRL, and ITS on San Clemente Island has provided data for testing three possible applications of HF sea echo: 1) as a standard or reference target for calibrating the sensitivity of sky-wave radars; 2) as a means of deducing sea state (viz., the dominant features of the wave-height directional spectrum); and 3) as a method for measuring surface-current features. HF, as considered here, extends from the broadcast band to VHF, including radar wavelengths between 10 and 200 m.

Although the heights of ocean waves are generally small in terms of these radar wavelengths, the scattered echo is nonetheless surprisingly large and readily interpretable in terms of its Doppler features. The fact that these heights are small facilitates the analysis of scatter using the perturbation approximation. This theory [2] produces an equation which 1) agrees with the scattering mechanism deduced by Crombie from experimental data; 2) properly predicts the positions of the dominant Doppler peaks; 3) shows how the dominant echo magnitude is related to the sea wave height; and 4) permits an explanation of some of the less dominant, more complex features of the sea echo through retention and use of the higher order terms in the perturbation analysis. Hence the dominant spectral features explained by the simple, lowest order terms of the perturbation analysis are referred to as “first-order” sea echo, while the remaining, less dominant features are termed “higher order” because they arise from the smaller (i.e., second-order, third-order, etc.) terms.

By way of introduction to the basic type of HF echo records upon which the discussion in this paper is based, we show a typical received Doppler spectrum in Fig. 1. This plot represents the received signal power versus normalized Doppler shift from the carrier (the carrier being located at zero, and the predicted positions of the dominant peaks at positions ±1). Details of the conditions and system behind this spectral record will be discussed later, but for now we refer to it to illustrate how the three previously claimed applications will be subsequently developed from data such as these. 1) The dominant, first-order peak (near ±1) will be tested for use as a standard or reference echo. 2) The higher order Doppler features (i.e., their shapes, peak positions, and amplitudes) will be used to deduce sea state. 3) The overall shift of the first-order echo peaks from ±1 will be used to deduce...
(radial) currents. Since the radar echo is produced by scatter from ocean waves, the approach taken in this paper is to relate the echo features to surface features. Ocean waves and currents are largely produced by winds, and thus one should be able to ultimately deduce wind features from these echoes; this is the approach taken in parallel analyses of HF sea echo by Ahearn et al. [3] and Long and Trizna [4].

II. BACKGROUND AND INTERPRETATION

Let us explain the simple interpretation of the first-order Doppler spikes of Fig. 1 as first deduced by Crombie [1]. Though the sea to a casual observer generally looks like a random, moving, scattering surface, the dominant, crisp, and equally displaced Doppler peaks lead one to believe that the radar is actually observing two targets moving radially at discrete readily identifiable velocities. The fact that these Doppler displacements are observed to vary with the square root of the carrier frequency would appear at center, with ±1 corresponding to Doppler shifts ±0.313 Hz from the carrier. Resolution is ∼0.01 Hz.

First-order sea echo

Higher-order sea echo

Example of an averaged radar sea-echo Doppler spectrum at 9.4 MHz. Carrier would appear at center, with ±1 corresponding to Doppler shifts ±0.313 Hz from the carrier. Resolution is ∼0.01 Hz. Example of an averaged radar sea-echo Doppler spectrum at 9.4 MHz. Carrier would appear at center, with ±1 corresponding to Doppler shifts ±0.313 Hz from the carrier. Resolution is ∼0.01 Hz.

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Doppler spectrum is also present, and these features appear to vary more significantly with sea state than do the first-order echo peaks. These additional features are referred to as "higher order," of which "second-order" effects are felt to be the dominant contributors. On the other hand, the larger first-order echo is for the most part constant and insensitive to sea state. The reason for this is that the waves producing scatter, being half the radar wavelength, vary in length between 25 and 5 m. Waves of this length on the open oceans are nearly always present and are developed to their maximum allowable height, as limited by breaking. This region of the wave-height spectrum in which saturation occurs is the equilibrium region; Phillips [6] has shown that the first-order resonant peaks are still evident and usually dominant, as shown in Fig. 1. However, other features in the Doppler spectrum are also present, and these features appear to vary more significantly with sea state than do the first-order echo peaks. These additional features are referred to as "higher order," of which "second-order" effects are felt to be the dominant contributors. On the other hand, the larger first-order echo is for the most part constant and insensitive to sea state. The reason for this is that the waves producing scatter, being half the radar wavelength, vary in length between 25 and 5 m. Waves of this length on the open oceans are nearly always present and are developed to their maximum allowable height, as limited by breaking. This region of the wave-height spectrum in which saturation occurs is the equilibrium region; Phillips [6] has shown that the first-order resonant peaks are still evident and usually dominant, as shown in Fig. 1. 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Fig. 2 is a buoy measurement of this spectrum at two different times for 20- and 25-knot wind-driven seas in the scattering area off San Clemente Island. The f^4 saturation region is clearly evident in these records; a scale at the bottom shows that the radar frequencies at which first-order scatter would be observed clearly fall in this saturated equilibrium region.

Fig. 2. Buoy-measured nondirectional wave-height spectra for morning (dashed) and afternoon (solid) of December 4, 1972. Triangle is model used in theory to approximate afternoon spectrum.
for all operating frequencies above about 2–3 MHz. The fact
that the first-order echoes at favorable ionospheric propa-
gation frequencies originate from waves of known height charac-
teristics suggests that these echoes can be used as a standard
target for radar system sensitivity calibration. Theory [2]
shows that the first-order scattering coefficient $\sigma^0$ should be a
constant, approximately $-17$ dB, independent of frequency
(above some lower $-HF$ limit) and sea state. In a large num-
ber of ground-wave operations on the Chesapeake Bay, $\sigma^0$ was
indeed found to increase to an upper limiting value corre-
spanding to $-17$ dB. Sky-wave radar operations by many
groups have also confirmed the constancy and absolute value
($-17$ dB) of first-order $\sigma^0$.

As mentioned previously, the higher order sea-echo Dop-
pler spectrum does appear to vary appreciably with sea state.
The features of this echo take several forms: 1) secondary
peaks appear around the first-order spikes, whose positions
and amplitudes vary with sea state; 2) a continuum or floor
around the first-order spikes appears which rises and spreads
with increasing sea state; and 3) the distribution of these
higher order peaks and continuum about the first-order lines
varies with wave direction. A theory for the second-order con-
tribution to these higher order echoes was advanced by
Barrick [7], and the agreement thus far with experimental
data is quite encouraging. A significant advantage of using
second-order echo to deduce sea state at upper HF is that one
is comparing this portion of the signal spectrum with the
saturated first-order peaks, which serve as the reference.
Hence unknown ionospheric path losses and Doppler transla-
dations do not hamper interpretation of the higher order echo
in terms of sea state.

Ocean currents can also be extracted from the sea-echo Dop-
pler spectrum. The first-order resonant Doppler peaks are
often observed to be shifted equally from their predicted
positions (see Fig. 1) by a small amount. This implies that the
waves causing first-order scattering are superimposed on a
sea surface which is physically moving due to surface cur-
rents. The radial component of this surface-current can thus
be calculated in terms of the Doppler translation of the
first-order lines to be $u = \Delta \sqrt{gc/(4\sigma_0)}$, where $g$ is the accelera-
tion of gravity, $c$ is the velocity of light, $f_0$ is the carrier fre-
cquency, and $\Delta$ is the normalized Doppler translation, as
measured in Fig. 1. Further interpretation of this concept will
be undertaken later in this paper.

III. EXPERIMENTAL FACILITY

A series of HF surface-wave measurements of sea echo
were undertaken in a joint experiment between NRL, ITS,
and NOAA/WPL on San Clemente Island off California.
Between November 1, 1972, and April 30, 1973, approximately
25 h of sea-echo Doppler spectra were gathered. The facility
is located on the northwest side of the island and looks west-
ward into the Pacific. It is capable of transmitting any num-
ber of frequencies (up to 100) simultaneously from 2 to 25
MHz in a pulse-to-pulse progression, and processing the re-
turns on each frequency coherently. Pulsewidths available are
20, 50, and 100 $\mu$s with a 200-pulse-per-second (pps) repetition
rate. The sea echo from several range gates can be processed
simultaneously: to provide adequate signal-to-noise ratio, the
echoes at 22.5, 30, and 37.5 km from the radar were found to
be optimal, and hence most sea-echo data were recorded at
these ranges. At these ranges, the water depth exceeds 1000 ft,
so that bottom effects on the wave characteristics are neg-
ligible.

The transmitter provided an output power of 75-kW peak.
The transmitting antenna was a twin-bay log-periodic monop-
ole array producing vertical polarization; with a gain of 14
dB, it provided a one-way beamwidth of 60° centered on
255° T. The receiving antenna was an 850-ft-long broadside
monopole array. Elements were switched in and out auto-
matically versus frequency so that the beamwidth did not
vary too drastically over the decade frequency range; as a
result, the one-way beamwidth was about 15° at 3 MHz and
7° at 24 MHz. Data were processed and recorded digitally on
magnetic tape, both in raw IF form and as 200-s coherent
spectra.

In order to check the radar data, a Datawell Waverider
buoy was moored in the scattering area. This device provided
both the sea-significant wave-height and nondirectional wave-
height spectra. The buoy output was confirmed and supple-
mented by wave hindcast tables prepared by OSI, Inc.; these
data indicated wave direction and also listed the height,
period, and direction of any swell present.

IV. FIRST-ORDER SEA ECHO FOR RADAR
SENSITIVITY CALIBRATION

Both theory [2] and surface-wave/sky-wave measure-
ments have shown that the first-order sea-echo energy in the
upper HF region approaches a constant value for the open
ocean, independent of sea state. As discussed previously, this
saturation occurs because the shorter ocean waves being ob-
served at these frequencies are developed to their maximum
possible heights. Referring again to the buoy-measured wave-
height spectra of Fig. 2, it is evident that for seas fully de-
developed by 20-knot winds, frequencies above about 2 MHz
are observing waves in the saturated or equilibrium range of
the spectrum; for 10-knot winds, frequencies above 8 MHz
will likewise fall in this region of the spectrum. For vertical
polarization, the average radar cross section per unit area, $\sigma^0$,
turns out to be about $-17$ dB, independent of frequency, and
nearly independent of incidence angle in the region within
about 30° of grazing. This suggests using the first-order sea
echo as a reference—or standard target—for calibration of
sky-wave radars operating over the oceans (where winds
nearly always exceed 10 knots). Such calibration is desirable
and necessary because, unlike microwave radars where trans-
mission loss is generally close to the predicted free-space value,
ionospheric absorption is highly variable and unpredictable.
Hence some sort of calibration (often involving the use of
beacons or repeaters of known reradiation levels) is required
in order to help select the optimal operating frequency and
determine expected signal-to-noise ratio and/or probability of
detection against a given class of radar targets.

One way of testing the concept of using first-order sea
echo as a reference target over the HF band is to show that
the measured value of some parameter in the radar range
equation follows predictions when one uses a constant value

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1 The average radar backscattering cross section per unit surface area.
The comparison between calculated and "measured" values of $G_T G_R$ versus frequency is shown in Fig. 4. Data plotted as points were obtained on the two different days, for the two antenna beam positions (at 270° and 240°) at frequencies from 2.4 to 20 MHz. The solid line represents the gain product at the center of the two receiving beam positions as measured via a standard target in a small boat versus frequency; the discontinuities in the predicted gain curve arise from the fact that different receiving array elements were switched in or out at certain frequencies so as to reduce the pattern variation over the decade frequency operating range.

The comparison is favorable, and shows that the first-order echo can indeed serve as a reliable reference target. The spread in points at the lower frequencies may be due to inaccurate assumptions in the sea description. However, the spread of points near 13.4 MHz is a true index of the variation in the results, and all points lie within ±2 dB of the mean. This spread is most likely due to the fact that the 1/2 h of incoherent spectral averaging represented in obtaining each of the points was not long enough to permit observation of a large ensemble of independent, random sea surfaces within the radar resolution area; hence the points were not true means. This ±2-dB spread, however, compares favorably with the accuracies of other types of sky-wave radar sensitivity calibrators which have been used, such as beacons and repeaters (where the output power level can fluctuate due to electronic instabilities and aging) or islands/mountains whose apparent cross sections can change due to surface moisture content and Faraday polarization rotation.

V. SECOND-ORDER SEA ECHO FOR SEA-STATE DETERMINATION

Theoretical explanations for second-order sea echo, present on nearly all records above 4 MHz, have been offered by Barrick [7] and Hasselman [9]; the reader is referred to these references for details of the mathematical derivation. The basic interpretation of this process is illuminating and worth some discussion. The theory shows that the radar waves interact with ocean wave trains as though the latter were diffraction gratings. Hence Bragg scatter and/or Feynman interaction diagrams are well suited to explain the various "orders" of scatter.

To first order the scattering and Doppler relationships are described in terms of Bragg scatter as follows:

$$k_{\text{a}} = k_{\text{b}} \pm x$$

where $R$ is the range to the scattering area $A$, $P_T$ and $P_R$ are the transmitted and received power (in the dominant first-order Doppler echo), and $L_{\text{sw}}, L_{\text{bw}}$ are "loss factors" accounting for two-way surface-wave propagation over the sea and Doppler line broadening, respectively. All of the factors on the right side of (1) are assumed known. The sea area $A$, within the resolution cell, is of course related to the antenna beamwidths (and hence gains), but in a known, calculable manner. Thus the antenna-gain product can be "measured" and compared with predictions. The excess two-way surface-wave propagation loss $L_{\text{sw}}$ over the sea out to 30 km versus frequency and sea state is shown in Fig. 3(a), prepared from Barrick [8]. The bandwidth loss $L_{\text{bw}}$ was calculated by forming the ratio of the observed width of the dominant first-order Doppler echo with the width at the lowest operating frequency; this is shown in Fig. 3(b). Data from December 4 and December 7, 1972, were selected for this comparison, since the seas for both were driven by 20-knot (or greater) winds, predominantly from the west, and hence could be expected to produce a saturated positive first-order Doppler echo at all operating frequencies. Therefore, a $\sigma^2$ was used in (1) corresponding to -17 dB (but normalized to the ground-wave definition of antenna gains).

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To first order the scattering and Doppler relationships are described in terms of Bragg scatter as follows:

$$k_{\text{a}} = k_{\text{b}} \pm x$$
Here \( k' \) and \( k' \) are the two-dimensional components of the three-dimensional incident and scattered wavenumber vector lying in the mean sea-surface plane, and \( \omega, \omega' \) are the radian temporal frequencies of the incident and scattered fields. The vector \( \mathbf{k} \) is the spatial wavenumber of the water wave responsible for scatter \( \left( i.e., k_0 = 2\alpha/L \right) \), where \( L \) is the water wavelength, and \( \Omega \), the temporal wavenumber, is related to \( \mathbf{k} \) through the first-order gravity-wave dispersion equation

\[
\Omega = \sqrt{gk_0}.
\]

Thus, as an example, for backscatter at grazing incidence we can choose our coordinate system so that the \((-x)\) axis coincides with the propagation direction. Thus \( \mathbf{k}' = k_0 \mathbf{a}' \) and \( k'_0 = -k_0 \mathbf{a}' \), so that the scalar first-order resonance condition stated previously is established from \( (2a): 2k_0 = \kappa \) or \( L = \lambda/2 \). Then the radian Doppler shifts of the energy—defined as the difference between the incident (carrier) frequency and the actual scattered frequency—are \( \omega' - \omega = \pm \sqrt{gk_0} \). Thus through simultaneous satisfaction of \( (2) \) we have established the length and direction of water waves responsible for first-order scatter, and also the unique square-root relationship for the discrete first-order Doppler echoes which had been established experimentally by Crombie two decades ago. The average spectral strength of the grazing first-order backscatter cross section per unit area (for vertical polarization) per radian/second bandwidth is found to be

\[
\sigma^0(\omega) = 2\pi k_0^4 S(\kappa_0, \kappa_0) \delta(\omega' - \omega + \Omega)
\]

\[
= 2\pi k_0^4 S(2k_0, 0) \delta(\omega - \omega + \Omega_1 \mp \sqrt{2gk_0})
\]

where \( S(\kappa_0, \kappa_0) \) is the spatial wave-height directional spectrum for the sea.

Understanding of the extension of this interaction mechanism to second order is now straightforward; in place of \( (2) \) we have

\[
\mathbf{k}'' = \mathbf{k}' \pm \mathbf{k}_1 \pm \mathbf{k}_2
\]

\[
\omega'' = \omega' \pm \Omega_1 \pm \Omega_2
\]

Now two water waves—with spatial wavenumbers \( \mathbf{k}_1, \mathbf{k}_2 \), and temporal frequencies \( \Omega_1 = \sqrt{gk_1} \) and \( \Omega_2 = \sqrt{gk_2} \)—enter into the process. For backscatter at grazing incidence, \( (5a) \) shows that there are a whole double set of interacting water wave trains which, if they are present, can produce second-order scatter. These water wavenumber combinations, \( \mathbf{k}_1 \) and \( \mathbf{k}_2 \), form two sides of a vector triad whose resultant third side is \( \mathbf{k}'' - k'' = 2k_0 \mathbf{a}' \); hence they need not be collinear with the radar propagation direction. Imposition of the scalar Doppler condition \( (5b) \) further constrains the relationship between \( \mathbf{k}_1 \) and \( \mathbf{k}_2 \), reducing the number of independent degrees of freedom from two to one. Thus, in place of \( (4) \), theory shows that the second-order spectral contribution takes the form

\[
\sigma^0(\omega) = 2\pi k_0^4 \int d^2 k \left( 1 \right) S(\kappa_1, \kappa_2) S(\kappa_2, \kappa_2) \delta(\omega' - \omega + \Omega_1 \mp \Omega_2)
\]

where the variable of integration \( \mathbf{k} \) may be either \( \mathbf{k}_1, \mathbf{k}_2, \) or any linear combination of the two. The quantity \( \Gamma \) is the coupling or interaction coefficient between the two sets of water waves. Two contributions to \( \Gamma \) have been identified as \( [7] \): 1) a hydrodynamic term arising from retention of the second-order (perturbational) terms in the nonlinear boundary conditions at the free water-air interface; and 2) an electromagnetic term arising from inclusion of second-order terms from the boundary perturbational expansion for the scattered fields at the water surface. The latter contribution is merely multiple scatter of the radar wave from one set of ocean waves to a second set and then back to the radar. The former contribution represents the nonlinear interaction of two water waves to form a small water-surface component with wavenumber \( \mathbf{k}_1 - \mathbf{k}_2 \); first-order radar scatter then takes place from this second-order water wave. Oceanographers refer to this second-order water wave as "trapped" or evanescent because it cannot carry energy away from the first-order wave spectra nor can it exist without or propagate independently of each of the first-order waves which produce it.

With the help of this theory, one can test various methods for inferring wave properties (such as significant wave height, dominant wave period, and dominant wave direction) from the second-order echo characteristics. An example of the success realized thus far in inferring significant wave height from the records will be discussed here; further details on dominant wave period and directionality will be presented elsewhere.

Radar records for December 4, 1972, were selected for examination here because: 1) buoy wave-height spectra are available on that day; 2) hindcasts have determined that winds and waves were predominantly from the west, nearly along the 270° radar beam; and 3) the measured wave-height spectra have the shape characteristic of fully developed wind-wave conditions (i.e., a saturated \( \Gamma \)-profile equilibrium region and a fairly sharp lower end cutoff). Thus the shape of the wave spectra can be modeled by triangles, one of which is shown in Fig. 2 representing the 1630 (afternoon) wave conditions; the spectral energy omitted by this type of modeling is not significant in these two cases.

In solving the integral \( (6) \) for these wave spectra models, it is assumed that the dominant wave direction is coincident with the radar propagation direction. Furthermore, two models of azimuthal wave patterns were tested in the integration of the directional spectra \( S(\kappa_0, \kappa_0) \): a cosine-squared pattern and a semi-isotropic pattern. This directional pattern has been a very difficult oceanographic quantity to measure, but the sparse data available indicate that most wind-wave patterns lie somewhere between cosine squared and semi-isotropic.

When calculating theoretical values for the integral \( (6) \), it is found that when the sea is fully developed a set of Doppler curves can be prepared as a function of a single universal parameter \( \beta \); this parameter is proportional to the carrier frequency times the rms wave height \( (\beta \approx 80m_0 h/c) \). Thus Doppler spectra calculated for a given wave height but for several radar frequencies can be interpreted in terms of a single radar frequency but different wave heights. This is illustrated in Table I, where in the first set of columns the actual frequencies used on December 4 are shown. Fig. 5(a)–(c) shows calculated versus measured Doppler spectra for

\[\text{significant wave height is an oceanographic term referring to the average peak-to-trough height of the highest one-third of the waves. It is related to rms wave height (for a Gaussian sea surface) by } H_{1/3} = 4H.\]
ing. The theoretical spectra include both the first-order and second-order contributions; only the dominant, positive measured spectra represent the sum of nine separate 200-s coherent power spectra, for a total of 1/2-h incoherent averaging. The theoretical spectra include both the first-order and second-order contributions; only the dominant, positive (up wind) sides of the spectra were calculated, with the dotted curve representing the cosine-squared and the dashed curve the semi-isotropic directional models. Both the measured and calculated spectra are normalized in frequency (with unity being the first-order Doppler position, i.e., $\delta f = \pm \sqrt{2g\delta/d/2\pi}$, smoothed by a Gaussian smoothing function of width $0.087 \times f_B$, normalized in amplitude to the top of the dominant first-order echo, and finally, the measured spectra are repositioned so that the current offset is removed. Thus Fig. 5(b) actually represents Fig. 1 after the smoothing process and removal of the current offset.

Several characteristics of the second-order echo vary with the parameter $\beta$ (i.e., with frequency or wave height), as evident from Fig. 5. The amplitude and positions of the two second-order peaks designated $P_{+1}$ and $P_{-1}$—with respect to the first-order peak—change with increasing $\beta$. We examine here only the amplitude of $P_{+1}$, and show in Fig. 6 the calculated and measured values of $P_{+1}$ in decibels below the first-order peak. The upper line is the cosine-squared theoretical model, the lower is the semi-isotropic theoretical model, while the points comprise all of the measurements taken at 22.5-km and 30-km range at the seven frequencies and for the morning and afternoon sea conditions represented by the wave spectra of Fig. 2. Besides illustrating the good agreement between theory and measurement, this plot demonstrates a more important point. A relationship can be established between the relative height of $P_{+1}$ and the parameter $\beta$; thus at a known radar operating frequency, the smoothed spectra could be re-normalized (using the dashed calibration curve of Fig. 6) so that significant wave height can be read out directly as the height of $P_{+1}$. This is demonstrated in Fig. 7(a) and (b), which are the smoothed spectra for 9.4 MHz at 22.5-km range for the morning and afternoon of December 5, respectively. The significant wave heights read from the two radar records are about 5.5 and 8.5 ft, while buoy measurements and hindcasts indicated actual wave heights of 5 and 8 ft for morning and afternoon. Similar displays on the other frequencies yielded these wave heights also, with an error commensurate with the point spread in Fig. 6, caused primarily by insufficient incoherent averaging time.

*Smoothing was used for two reasons: 1) so that the widths of the first-order echoes would be broadened by a known amount beyond any system resolution and/or higher order sea dispersion effects, permitting their amplitude to be a true measure of their total energy content; and 2) because ionospheric motions are expected to introduce broadening of the spectra by approximately the amount used here.*
VI. CURRENT MEASUREMENT

As mentioned in the Introduction and demonstrated in Fig. 1, currents are evident in the records as an overall offset of the first-order Doppler peaks from their expected (normalized) positions at ±1. Data obtained on several days at the San Clemente Island facility have been examined from the standpoint of deducing currents. Using the relationship $u = \Delta \sqrt{ge/(4\pi f)}$ mentioned in the Introduction, surface currents radial to the radar were deduced and plotted in Fig. 8. These plots show the radial current component in centimeters per second along 240º (circles) and 270º (crosses) as a function of the first-order sea wavelength $L$ corresponding to the seven operating frequencies. Error bars give an estimate of the current magnitude precision. The precision is limited by the resolution of the spectral analysis (1/200 Hz) at the longer wavelengths, while at the short wavelengths the limit is imposed by the natural broadening of the first-order lines due to higher order sea effects.

The data in Fig. 8 are for relatively high sea conditions, with the wind blowing roughly in the direction of the two antenna beams. In comparing the data in Fig. 8, several points are worthy of discussion. Note first of all that there is a considerable variability in the observed current velocities. In general, the apparent current magnitudes observed on the two bearings are different, which can be explained on the basis that the current flow is more nearly parallel to one radar beam than to the other. The data for March 13 are particularly interesting in this respect in that they show a reversal of the current in the 240º direction at the shorter sea wavelengths. On this occasion the wind was blowing roughly across the antenna beams. If the wind were coming from a direction somewhat south of west, a slight approaching velocity would be induced in the 240º direction as compared with the 270º record which would be less affected by the wind. If this wind had not been blowing very long the currents produced by it would not penetrate very deeply. Thus near the surface the current would be approaching, but below the surface it could still be receding. As a result, the short waves could be expected to be most affected by the currents closest to the surface and should indicate a different current direction than the longer waves. These longer waves ought to be more influenced by the deeper currents in the opposite direction. Somewhat similar results are shown in the data for December 4.

This influence of the deeper current structure on the longer surface waves is believed to explain the dependence of velocity on wavelength exhibited in Fig. 8. Similar results have been reported by Stewart and Joy [10], who were able to compare the radar data with simultaneous observations of the drift of a submerged drogue. This effect is much like the decrease in velocity of surface waves in shallow water, and one can expect here also that surface waves should be influenced significantly by currents to a depth comparable to their wavelength. If the current changes with depth, as is usually the case, the short waves will have a different velocity than the longer waves. This has been shown by Plate and Trawle [11], following Biesel [12], who showed that the observed wave phase velocity $v$ on infinitely deep water, having a linear vertical gradient of current velocity $du/dz$ with depth $z$, could be related to the surface-current velocity $u_s$ and the theoretical wave phase velocity in the absence of current $v_0$, by

$$v^2 = \frac{(v - u_s)^2}{1 + \frac{1}{\kappa} \frac{du}{dz}} = v_0^2$$

(7)

where $\kappa$ is the wavenumber. Note that when $1/\kappa = L/2\pi = 0$, $v = v_0 + u_s$. Thus we can estimate the surface current from Fig. 8 by inspection, as wavelength approaches zero.

Likewise, the vertical current gradient $du/dz$ can be inferred from the records by a perturbation on (7). We employ the fact that $u_s < v_0$, and set $\Delta u = u - u_s$, where $u$ is the apparent "surface" velocity as measured at sea wavelength $L$, to obtain

$$\frac{du}{dz} = - \frac{4\pi \Delta u}{L_1}.$$  

(8)

The observed currents on the open ocean are a combination of currents arising from large-scale circulation, tides, the frictional interaction between wind and the sea surface, and Stokes drift currents which are due to nonlinear wave-wave interactions [5]. The latter two components are local and transient, depending upon the local wind. Tidal components have yet to be observed and identified with this technique.

VII. CONCLUSIONS

Preliminary comparisons of theory with first-order surface-wave sea scatter lend confidence to the prospect of using this echo as a calibration standard for HF radars. This appears particularly well suited to over-the-horizon sky-wave (ionospheric) radars and/or communication systems operating over the ocean. Since path loss in such a system is highly variable...
and unpredictable, alternative sensitivity calibrators, including buoy beacons/repeaters or islands, will certainly be more expensive and/or sporadic in area coverage. Problems remaining to be resolved concern the expected variance in this sea echo as a function of incoherent integration (averaging) time and area of illumination. Obviously, as one increases either the incoherent averaging time (to several hours) or the geographic area over which incoherent averaging is performed (to dimensions several hundred kilometers in extent) the variance will decrease. On the other hand, the ionospheric path losses themselves will vary over such temporal and spatial extents, and hence one encounters a tradeoff between the fluctuation rates of the environmental factors and the granularity or resolution in time and space of the desired sea-echo calibration information itself. These questions will be answered by further analysis of the multifrequency surface-wave sea echo, and also by sky-wave research programs.

It appears that the important quantitative parameters describing sea state can be deduced from the characteristics of the higher order HF sea-echo Doppler spectrum. The use of this higher order echo is especially necessary with sky-wave radars because one of the first-order echo peaks is nearly always "saturated" or constant in the upper HF region in which ionospheric propagation conditions are favorable. This technique has the advantage of comparing one part of the signal spectrum with another, and hence absolute sensitivity calibration of the system, so critical for most sky-wave radar applications, is not necessary here. It is sky-wave radar which holds out the ultimate prospect of remotely sensing sea state out to several thousand kilometers from the U. S. coasts, with as few as two land-based sites. This paper has shown that significant wave height—perhaps the single most important descriptor of sea state—can be read directly from sea-echo spectral records. Further analyses of the San Clemente Island data will concentrate on deducing dominant wave period and propagation direction from the second-order echo features. A joint sky-wave radar research program is planned, which will determine the ultimate precision of such directional wave-height spectral parameters when subjected to the normal seasonal and diurnal vagaries of the ionosphere.

Preliminary success at inferring currents from the HF data must be explored further. Both surface-wave and sky-wave radars offer the prospect of current monitoring in large bays, estuaries, or near land masses. Surface-wave systems, limited in range to <200 km, can measure these currents directly from the translation of the first-order sea-echo lines from their predicted positions. Surface-wave operation at rather high frequencies (∼30 MHz) might be more attractive because resolution into smaller cells by short pulses and antennas with significant angular resolution is possible. Sky-wave Doppler records, on the other hand, are often contaminated by unknown ionospheric-layer motions and multipath, and hence one must use a stable reference to remove such motions. Land or island echoes, where they are available within the resolution cell, can serve this purpose. These concepts will be tested further by both surface-wave and sky-wave experiments.

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