Surface Current Measurements by HF Radar in Freshwater Lakes

Daniel M. Fernandez, *Member, IEEE*, Lorelle A. Meadows, John F. Vesecky, *Member, IEEE*, Calvin C. Teague, *Member, IEEE*, Jeffrey D. Paduan, and Peter Hansen

***Abstract*—HF radar has become an increasingly important tool for mapping surface currents in the coastal ocean. However, the limited range, due to much higher propagation loss and smaller wave heights (relative to the saltwater ocean), has discouraged HF radar use over fresh water. Nevertheless, the potential usefulness of HF radar in measuring circulation patterns in freshwater lakes has stimulated pilot experiments to explore HF radar capabilities over fresh water. The Episodic Events Great Lakes Experiment (EEGLE), which studied the impact of intermittent strong wind events on the resuspension of pollutants from lake-bottom sediments, provided an excellent venue for a pilot experiment. A Multifrequency Coastal HF Radar (MCR) was deployed for 10 days at two sites on the shore of Lake Michigan near St. Joseph, MI. Similarly, a single-frequency CODAR SeaSonde instrument was deployed on the California shore of Lake Tahoe. These two experiments showed that when sufficiently strong surface winds ($\geq$ about 7 m/s) exist for an hour or more, a single HF radar can be effective in measuring the radial component of surface currents out to ranges of 10–15 km. We also show the effectiveness of using HF radar in concert with acoustic Doppler current profilers (ADCPs) for measuring a radial component of the current profile to depths as shallow as 50 cm and thus potentially extending the vertical coverage of an ADCP array.**

***Index Terms*—HF radar, lake circulation, limnology, oceanography, suface currents.**

I. Introduction

OVER THE past three decades, and particularly since about 1990, HF (decameter) radar has become an increasingly important measurement tool for oceanography and related applications. The HF radar operates in the 3–30-MHz band at far longer wavelengths than microwave radar. This is required both for resonance with wind-driven ocean waves in the 5–50-m wavelength range and for propagation over the horizon. HF radar waves propagate via two modes to achieve significant range: 1) ground wave, along the surface out to ranges of at most a few hundred kilometers *over sea water* and 2) sky wave, refraction in the ionosphere, to ranges of a few thousand kilometers. This paper considers effects associated with ground-wave propagation only. Propagation of HF radar ground waves *over fresh water* has much higher propagation loss than over salt water. This paper explores the theoretical limitations of HF radar operation over freshwater lakes and provides discussion of actual operational capabilities during two freshwater experiments. While we discuss only surface currents here, HF radar is also capable of measuring surface wave characteristics [1], [2] and wind direction [3], [4]. Excellent sources for more detailed information on HF radar instruments and oceanographic applications are given in [5] and [6].

HF ground-wave radar echoes arise primarily from Bragg scattering of the radar energy by resonant ocean surface waves that have a wavelength of one half the radar wavelength and travel radially toward or away from the radar. These waves produce a Doppler shift that corresponds to their phase velocity, and thus two peaks (called Bragg peaks) appear in the Doppler spectrum, one caused by radially approaching resonant surface waves and one caused by radially receding resonant surface waves. In addition to the Doppler shift caused by the waves' phase velocity, a slight additional shift is observed in both peaks. Stewart and Joy [7] demonstrated that this slight shift can be exploited to estimate the underlying near-surface ocean current. In addition, through the use of different radar wavelengths, it may be possible to estimate the vertical structure of the current in the top 2 or 3 m of the water body [8]. By assuming a linear current profile with depth, Stewart and Joy estimated that the radar would be sensitive to a current at an "effective" depth of about 8% of the ocean wavelength. Ha [9] examined both linear and logarithmic current profiles and found that a logarithmic profile would result in a current estimate at a depth of about 4% of the ocean wavelength. Very few *in situ* near-surface current measurements are available to verify either profile assumption; however, recent observations using a horizontally directed acoustic Doppler current profiler (ADCP) [10] suggest that a linear current profile may be more appropriate.

It is well known that ground-wave propagation over the earth's surface is strongly dependent on the conductivity and permittivity of the surface material. Over salt water, the conductivity and permittivity are both high and HF radar ranges typically extend to about 30–50 km and more, depending on the system in use. Over fresh water, the conductivity is more than

Manuscript received September 14, 1999; revised August 17, 2000. This work was supported by the EEGLE (Episodic Events—Great Lakes Experiment) Program sponsored by the National Science Foundation and the National Oceanic and Atmospheric Administration Coastal Ocean Program under NSF Grant 9726683 and NSF Grant OCE-9731710 and by the Office of Naval Research, Remote Sensing Program under ONR Grant N00014-97-1-0375.

D. M. Fernandez is with California State University, Monterey Bay, Seaside, CA 93955-8001 USA.

L. A. Meadows is with the Department of Naval Architecture and Marine Engineering, University of Michigan, Ann Arbor, MI 48109-2145 USA.

J. F. Vesecky is with the Electrical Engineering Department, University of California, Santa Cruz, CA 95060 USA.

C. C. Teague is with Stanford University, Stanford, CA 94305-9515 USA.

J. D. Paduan is with the Naval Postgraduate School, Monterey, CA 93943 USA.

P. Hansen is with the Department of Atmospheric Oceanic and Space Science, University of Michigan, Ann Arbor, MI 48109 USA.

Publisher Item Identifier S 0364-9059(00)11472-4.

two orders of magnitude lower and the permittivity remains very nearly unchanged. The result is much higher propagation loss for ground-wave HF radars. This effect has been seen in freshwater plumes in the coastal ocean [11]. Further, the wave heights in freshwater lakes are most often significantly lower than in the coastal ocean and the HF radar echo power within the Bragg peak, which is proportional to the square of the wave height, is, correspondingly, also lower. Since echo power in the Bragg peaks is important for current measurements, operation of HF radar over freshwater bodies has seldom been pursued due to these expected limitations in echo signal strength and range.

In both fresh and saltwater environments, interplay between the physics, chemistry, and biology of the water body is important. Hence, the application of HF radar over freshwater lakes is attractive in spite of its limitations. For example, the Episodic Events Great Lakes Experiment (EEGLE) is exploring the impact of intermittent strong wind events on the circulation of Lake Michigan and the related resuspension of pollutants from lake-bottom sediments [12]. HF radar maps of surface currents together with moored ADCPs could provide measurements of the current profile from a depth of about 50 cm to near the bottom and cover an extended spatial area. Such integrated measurements would better define the circulation dynamics in the study area and thereby contribute to the overall understanding of episodic resuspension events in Lake Michigan.

Because of the potential usefulness of HF radar observations in the EEGLE program and the lack of direct knowledge regarding operation over fresh water, we deployed HF radars in pilot experiments at both Lake Michigan and Lake Tahoe. The radar systems used in these experiments were the Multifrequency Coastal Radar (MCR) in the Lake Michigan experiment and the Coastal Ocean Dynamics Applications Radar (CODAR) SeaSonde (www.codaros.com) in the Lake Tahoe Experiment. This paper describes the limitations imposed by freshwater lakes on HF radar operation and presents the results of successful observations over fresh water. We also demonstrate the integration of multifrequency HF radar with moored ADCP measurements to construct a current profile over virtually the entire water column.

II. Propagation and Scattering Considerations

The purpose of this section is to determine the impact of propagation loss over fresh water on HF radar observations in terms of the range achievable over the coastal ocean using typical HF radar systems, such as SeaSonde or MCR. The approach used is to compute the propagation loss and, based on that and the estimated radar cross section of the lake surface, to determine the fraction of the transmitted power received as a function of range. A full signal-to-noise ratio (SNR) calculation is not done here because of uncertainties in many factors, such as local noise level and coupling at the land–water boundary. We also comment on the typical wave heights expected in freshwater lakes as compared to the coastal ocean and the impact of this difference on HF radar operation. This analysis is meant to illustrate the factors that limit HF radar range in freshwater lakes. The general approach is summarized below along with relevant results and a description of factors that are and are not considered in the analysis.

A. Application of the Radar Equation

In this case, the relevant factors that affect the signal level at the receiver are the R^{-2} power spreading factor along the paths to and from the target area, the variable size of the patch of ocean from which scattering takes place, and the attenuation associated with dissipative loss to the water as the radar waves propagate along the surface. It is the latter factor that is dependent upon the permittivity and conductivity of the surface over which the radar wave propagates. Ocean water is much more saline than fresh water and thus has a higher conductivity and a much lower attenuation factor. Mathematically, considering the power spreading and attenuation factors, the power density $P_{\rm surface}$ (watts/m^2) received at a patch of water surface as a result of a transmitted radar signal may be expressed as

$$P_{\rm surface} = \frac{P_t G_t}{4\pi R^2} A^2 \tag{1}$$

where P_t is the transmitted power, G_t is the transmitting antenna's gain, R is the distance from the radar to the water surface patch, and A is the amplitude attenuation factor for propagation over a lossy dielectric surface, such as ocean or lake water.

The water surface, in this case, is a distributed target and backscatters a detectable amount of the incident power. A portion of this backscattered power is captured by the radar receive antennas, namely, $P_{\rm rec}$. This received power can be written as

$$P_{\rm rec} = \frac{P_{\rm surface}\sigma^o_{\rm surface} A_{\rm surface} A_{\rm rec}}{4\pi R^2} A^2 \tag{2}$$

where $\sigma^o_{\rm surface}$ is the normalized radar cross section of the water surface, $A_{\rm surface}$ is the (range-dependent) area of the surface scattering element (usually the radar resolution cell), and $A_{\rm rec}$ is the effective area of the receiving antenna. By combining the two expressions above, we obtain the following expression for the received power:

$$P_{\rm rec} = \frac{P_t G_t \sigma^o_{\rm surface} A_{\rm surface} A_{\rm rec}}{(4\pi R^2)^2} A^4. \tag{3}$$

Since the area of the scattering patch increases in a manner directly proportional to the range, the power received at the radar will have an R^{-3} dependence with range. The actual area of the scattering patch will depend on the range resolution and the angular resolution of the radar system. For both the MCR and the CODAR SeaSonde systems, the range resolution is independent of the range, although it is in general an adjustable parameter. For the purpose of this discussion, the range resolution is set to 1.5 km. The angular resolution of the system is dependent upon the radar frequency of operation. Since higher radar frequencies have narrower beam widths than lower radar frequencies for a given phased array configuration, lower frequencies of operation have a resulting greater swath of angles that they observe, and thus they cover a greater surface area of water. Since this discussion is primarily concerned with the relative effects of water conductivity on the propagation of signals, variations in radar swath as a function of frequency are not taken into account and $A_{\rm surface}$ is considered to be frequency-independent.

In order to limit the comparison of salt and fresh water to the two parameters of interest, the power received from (3) is scaled to remove constants that are independent of the propagation. The results are shown in

$$\gamma_p = \frac{kA^4}{R^3} \tag{4}$$

which represents the normalized fraction of transmitted power received. The parameter k in this equation is the constant necessary to normalize γ_p such that the received fraction of transmitted power from a range of 1 km at 4.8 MHz is 0 dB. We can thus observe how the parameter γ_p varies as a function of the water conductivity and radar wavelength.

The (unitless) attenuation factor A is a value that, since the advent of radio, many researchers have undertaken to determine under a variety of conditions. The following empirical determination comes from the work of Knight and Robson [13], [14] who generated an empirical expression for the attenuation factor in a fashion different from the classic Norton paper [15]. Their equation is as follows:

$$A = A_0 - (A_0 - A_{90}) \sin(b) \tag{5}$$

where

$$A_0 = \frac{2 + 0.33p}{2 + p + 0.6p^2}$$

$$A_{90} = \frac{2 + 170p}{2 + 210p + 310p^2}$$

$$b = \tan^{-1}\left[\frac{(\varepsilon + 1)}{60\sigma\lambda}\right]$$

$$p = \frac{\pi R}{\lambda} \frac{1}{\sqrt{(\varepsilon+1)^2 + (60\sigma\lambda)^2}}$$

and σ refers to surface conductivity, ε is the relative surface permittivity, and λ is the radar wavelength. This empirical expression is valid when both the transmitter and receiver are located on the ground on an approximately flat earth. When the conductivity is high, as is the case for ocean water, b is close to 0 and the attenuation factor is represented quite closely by the term A_0. The term p represents a “numerical distance” from the antenna and takes into account surface conductivity, the radar wavelength, and the relative permittivity of the surface material. We have now considered the R^{-3} and A^4 factors in (4). Below we discuss σ^o and we then make a comparison calculation in Section II-C.

B. Normalized Radar Cross Section (σ^o) for Lakes and the Ocean

Estimates of the first-order σ^o have been derived for the ocean surface, given the saturated wave conditions of fully developed seas. These conditions generally do not apply to the lake surfaces that were studied in the experiment and are likely not present during many data collection activities over ocean surfaces, particularly at the lower HF radar frequencies under low wind speed conditions. For example, under 4.8-MHz operation, fully developed wave conditions at the resonant surface wavelength of 31 m require a wind speed of at least 7 m/s blowing for an extended time over a significant fetch. Since it is beyond the scope of this paper to examine the development of the waves and the variation of the lake σ^o, fully developed wave conditions will be assumed with the understanding that the estimates made and graphs produced represent an upper limit on the expected power return at the ranges listed. Fully developed waves provide a σ^o for water surfaces of about -20 dB. This number represents an upper bound on the size of the radar cross section. Since σ^o would be the same for both salt and fresh water under these assumptions, it plays a neutral role in the comparisons below.

C. Comparison of HF Radar Propagation over Fresh and Salt Water

In Fig. 1, we compare values of γ_p from (4) for both freshwater and saltwater conditions. This figure implies that, at 10-km range, radar echo power over fresh water is reduced (with respect to salt water) by some 40 dB at 4.8 and 6.8 MHz and by more than 60 dB at 25 MHz. At 30 km, the relative freshwater loss is about 60 dB for 4.8 and 6.8 MHz and about 70 dB for 25 MHz. The figure also indicates that, for extended ranges, HF radar echoes are much more likely to be seen at lower frequencies, assuming sufficient waves exist to provide Bragg backscatter. One means of interpreting Fig. 1 to obtain maximum ranges for freshwater propagation is to compare the plot of the fraction of transmitted power returned for saltwater propagation with that for fresh water. Empirical data we have collected for these systems indicate maximum usable ranges over salt water to be about 60 km at the higher frequencies, although other sources indicate possible maximum ranges that exceed 100 km, particularly at the lower frequencies used by the MCR system [16]. Given these maximum possible ranges over salt water, the minimum required fraction of transmitted power received may be found from Fig. 1 and these values can then be used to determine the maximum possible ranges obtainable over fresh water using the freshwater curves at a given frequency. For instance, from Fig. 1, a 60-km maximum range over salt water at 25 MHz corresponds to approximately a 6 –km maximum range over fresh water. As discussed below, experimental tests at Lake Michigan and Lake Tahoe show echoes with SNR $>$ 6 dB at ranges above 10 km even from resonant waves that are likely below the heights of a fully developed sea. Thus, we suspect that inferences from Fig. 1 are overly pessimistic, but not greatly so. Below we discuss some factors not considered in Fig. 1 that may account for this situation.

D. Factors not Considered

Antenna Placement: The analysis above assumes that both the transmitter and receiver antennas are at the same height, essentially at water level. If one or both of the antennas were at a significantly different height, there would be some differences in the amount of energy received based on the fact that there would be several paths that the rays would follow, resulting in constructive or destructive interference patterns at the receiver. Indeed, this variation in signal strength is apparent and is manifested as a tidal signal in [17]. One possible reason for field performance exceeding the prediction of Fig. 1 is that the antennas

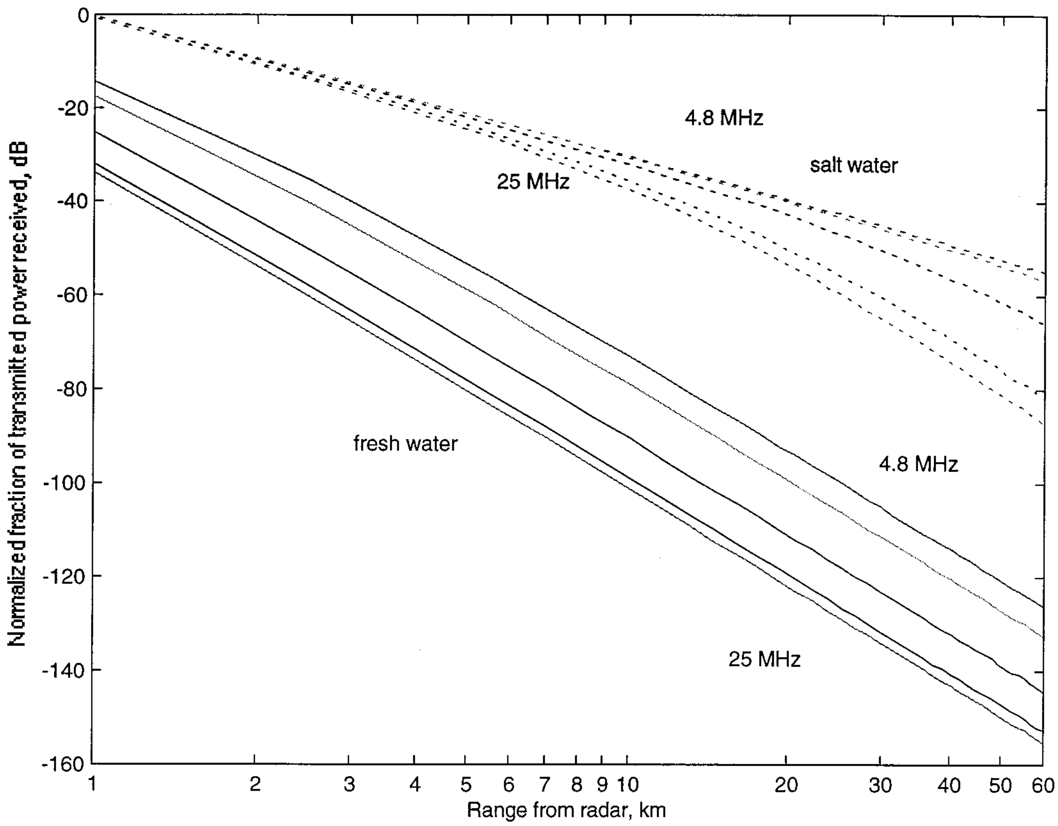


Fig. 1. Fraction of transmitted power received normalized to 0 dB for 4.8 MHz at a range of 1 km for five different frequencies (4.8, 6.8, 13.4, 21.8 and 25 MHz) over both salt water and fresh water. The 4.8-MHz curve follows very closely to an R^{-3} dependence with range. Note the dramatic increase in propagation loss (even at close ranges) over fresh water.

are significantly above the water level. At one of the sites at Lake Michigan, for instance, the antenna bases were all 2 m above the water line. Therefore, the effective height of the transmitter antenna (which is about 60% of the actual height for a tuned monopole [18]) for 4.8 MHz was about 12 m above water level. At this same site, the effective height of the receiver antennas was about 5 m above water level. This means that the radio horizon for the effective heights of the receiver and transmitter antennas was about 9 and 14 km, respectively. At the other MCR site at Lake Michigan, which was some 25 m above the water level, the effective antenna heights were even greater. For the short ranges relevant here, therefore, it is likely that line-of-sight propagation plays a significant role in the propagation from antenna to target and return. For the calculations of Fig. 1, such factors are not considered, but are site-dependent in practice.

Round versus Flat Earth: Also, since the ranges we are considering are 30 km or less, the effect of the round earth is not taken into account. The threshold at which the curvature of the earth starts to play a role in the evaluation of the attenuation coefficient is given by $R \geq 80/f^{1/3}$ where R is given in km and f is the frequency in MHz [19]. This corresponds to about 47 km at 4.8 MHz, 42 km at 6.8 MHz, 34 km at 13.38 MHz, 29 km at 21.77 MHz, and 27 km at 25.4 MHz. All of these ranges exceed the range over which usable echo was observed within freshwater lakes, so our flat earth assumption is valid for the case at hand.

Effects of Surface Roughness on the Attenuation Coefficient: The effects of surface roughness on propagation over ocean water has been thoroughly described by Barrick [20]. Based on his work, roughness on the water surface typically adds several decibels of loss whose exact size depends upon the wind speed, the radar frequency, and the range. For the cases considered here where the radar frequency is less than 26 MHz and the ranges are less than 30 km, maximum added one-way transmission losses over the ocean are less than 4 dB even under very high wind conditions. Since the added effect of roughness is rather small compared to the effects of conductivity and the roughness effects vary depending on the wind and wave conditions, they are not considered explicitly in this paper. Roughness effects would alter both the ocean and the lake echoes as a function of range in a similar fashion and so would not drastically affect the relative performance of the radar systems over different water types.

Matched Impedance at the Land–Water Interface: Another factor that is not taken into account in this analysis is the issue of the surface impedance discontinuity between dry land and water. Values for the relative permittivity and the conductivity of ocean water, fresh water, and land are illustrated in Table I. Since the conductivities of land and fresh water are of the same order of magnitude, but the conductivities of land and salt water are several orders of magnitude different, it is likely that a better match is present for the radar over fresh water and thus that more of the power transmitted over fresh water enters the ground-wave mode. This may help to explain why the ranges observed for the fresh water propagation are greater than what was expected based on the maximum ranges observed in the saltwater case.

TABLE I
CONDUCTIVITY AND PERMITTIVITY OF SEVERAL SUFACE TYPES

Terrain	Conductivity, S/M	Relative Permittivity
salt water	4.000	81
fresh water (Lake Tahoe[1])	0.006	81
dry, sandy flat coastal land [2]	0.002	10

[1] courtesy US Davis CE
[2] from Westman [21]

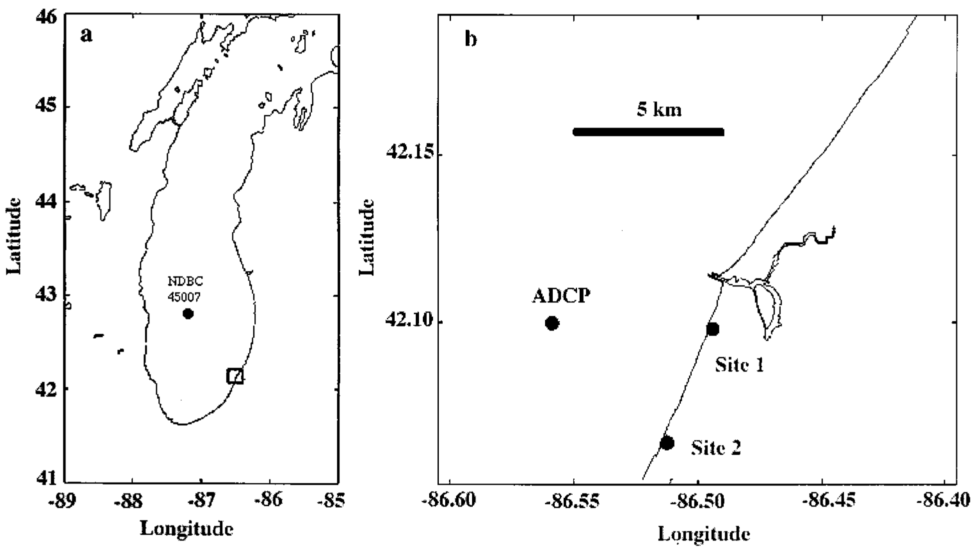


Fig. 2. Site locations for Lake Michigan experiment. (a) The location on Lake Michigan. (b) An expanded view of the study site near St. Joseph, MI. These sites are near a key experimental area for EEGLE. The waterworks site 1) is near lake level and the Lookout Park site 2) is about 25 m above water level.

Variations in Receiver Main Lobe Width as a Function of Radar Frequency: It has been mentioned that the curves in Fig. 1 do not take into account the variation in size of the patch of ocean viewed by the receive array as a result of the radar operating frequency. Lower frequencies of operation with phased array systems, such as the MCR, offer the potential for greater range not only because of lower propagation loss at these frequencies, but also because of the larger observed areas (although correspondingly poorer resolution). This offers an additional explanation for the greater coverage offered by the MCR system at 4.8 MHz.

Effects of Non-Fully Developed Seas: Particularly at the lower frequencies of radar operation, we do not expect the waves to be fully developed; thus, by assuming fully developed seas, we inflate the maximum expected ranges at the lower frequencies somewhat over both fresh and salt water. Since the effects of a fully developed sea would be similar over both fresh and salt water, and it only affects interfrequency comparisons, for simplicity, as was stated in the last section, we will assume fully developed seas in all cases.

III. LAKE MICHIGAN EXPERIMENT

A. Experimental Description and Environmental Conditions

The Lake Michigan pilot experiment was conducted at St. Joseph, MI, from April 28 to May 8, 1998. The University of Michigan MCR was deployed at two sites during this time period in order to test its operational capabilities over fresh water at near water level and atop a high bluff (greater than 25 m above water level). The first deployment site, at near water level, was 1 km south of the St. Joseph harbor structures, immediately south of the St. Joseph Waterworks Plant (HF Site 1 in Fig. 2). At this site, the bases of the MCR receive antennas were erected approximately 2 m above water level with a receive antenna boresight of 280 °T. The installation was completed April 29 and data acquisition commenced April 30 continuing to May 5. The MCR was then moved to Lookout Park, approximately 4 km south of the waterworks site (HF Site 2 in Fig. 2). This park sits atop a 25-m bluff overlooking Lake Michigan. Data were collected at this site from May 6 until May 8. HF radar data sets were collected for 12 min at the beginning of each hour.

Environmental conditions were recorded both at the St. Joseph Waterworks Plant and at the National Data Buoy Center (NDBC) Buoy 45 007 located about 85 km west-northwest of the radar observational area. During the entire pilot experiment period (April 28 to May 8), wind speeds were low, typically very low (Fig. 3). Usable radar echoes for the MCR require appreciable waves in the range from about 7.5 to 30 m in length. At very low wind speeds, these waves are not generated and the MCR cannot obtain useful echo data. Relatively high sustained winds (5 to 7.5 m/s) from the north coincide with the periods when usable radar echoes were observed: 1800 UT on May 3 to about 1200 UT on May 4, and near 1100 UT on May 8.

Fig. 4 is a histogram of usable echoes (SNR $\geq$ 6 dB) from the HF system throughout the pilot experiment period. Useful signals were observed for an extended period of time at the three lower MCR frequencies out to a range of approximately 6 to 9 km. For a limited time, the maximum range extended out to 15

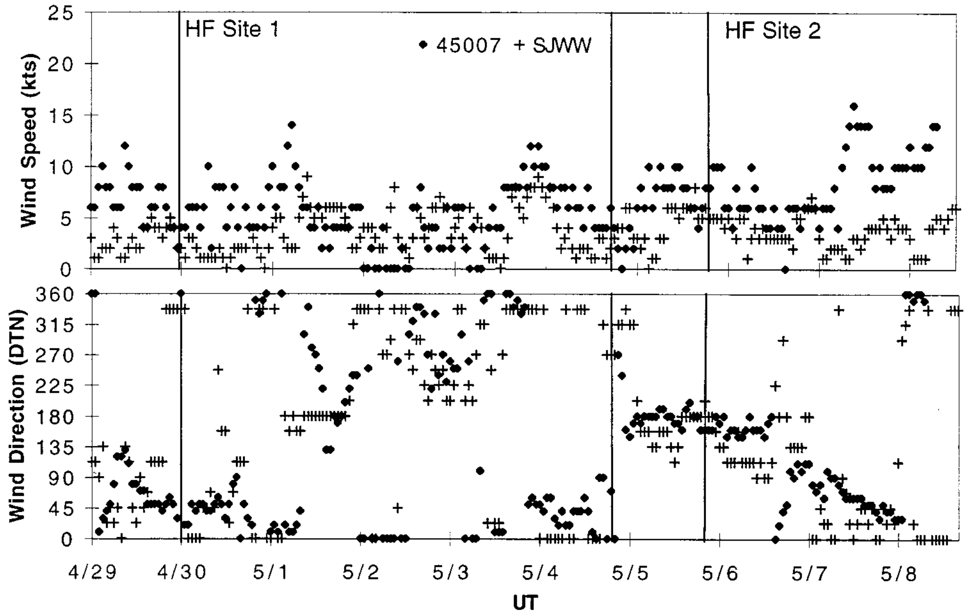


Fig. 3. Wind speed (in knots) and direction measured at NDBC Buoy 45 007 near the center of southern Lake Michigan and St. Joseph Waterworks Plant (SJWW) near HF Site 1 (+). The radar observation periods at each HF site are shown. Note the generally low wind speeds near the HF sites leading to low locally generated wave heights and low signal strengths of HF radar echoes, particularly at the higher frequencies of operation.

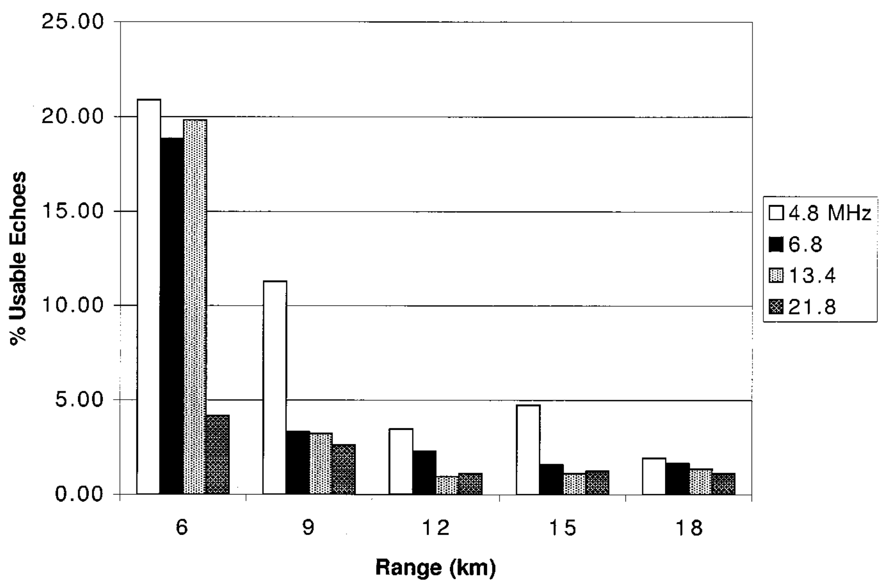


Fig. 4. Histogram of percent usable HF radar echoes for each MCR frequency for the Lake Michigan experiment. This includes data from both the water level 1) and bluff top 2) sites shown in Fig. 2.

km. Based on the discussion of the previous section, this fall-off in usable returns with distance is consistent with the decrease in expected return power over a freshwater body (Fig. 1), with the lowest frequency sustaining the highest capacity for significant return power with range. The pilot experiment was too short to evaluate the relative advantages of the two sites. However, useful echoes were obtained from both the water level and bluff top sites.

A sample HF Doppler spectrum is provided in Fig. 5. Because the radar system cannot exclude land echoes, there is a strong peak at zero Doppler. The strong signal peak near 0.2 Hz Doppler shift is echo energy scattered from approaching waves on the lake, i.e., onshore waves. This peak is the result of backscatter from Bragg resonant lake waves (one half of the radar wavelength) and has a Doppler shift caused by the (still water) wave phase velocity plus a small off-shore current that effectively slows down the observed waves. The radial surface current upon which the Bragg resonant waves are advected is determined by measuring the shift of the Bragg peak from where it is expected. A radial current component is one which lies along the radar line of site. For a single radar site, only radial components of surface currents are measurable. Measurements of the full vector surface current vector require at least two radar systems that operate simultaneously, which did not occur during these early pilot experiments. Within Fig. 5, the SNR is about 18 dB. In practice, an SNR of 10 dB is adequate and an SNR as

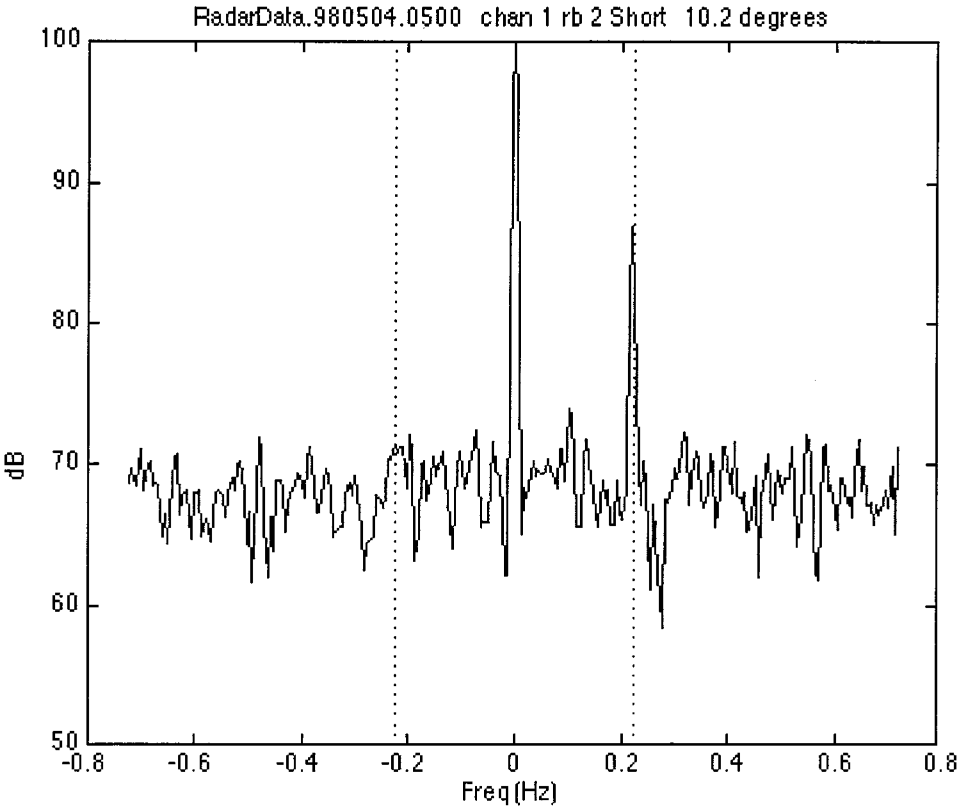


Fig. 5. Sample Doppler spectrum at 4.8 MHz from a range of 6 km observed on May 4, 1998, from HF Site 1 at near water level. The waves approaching the shore have a larger wave height and hence the positive (approaching) Doppler signal is much stronger. The dotted vertical line shows the expected Bragg peak location for waves on still water (no surface current).

low as 6 dB is usable, although current measurement precision is degraded.

B. *Comparison with ADCP Measurements*

ADCPs were moored in the lake offshore of St. Joseph by the NOAA Great Lakes Environmental Research Laboratory (GLERL). The A1 mooring, located approximately 6 km offshore near the bore site of each radar geometry, collected data at depths from near the bottom (20 m) to 2 m from the surface. A comparison of the HF radar and coincident ADCP current estimates is shown in Figs. 6 and 7. Fig. 6 provides a time-series comparison of the ADCP and HF radial current measurements approximately 6 km offshore from 18:00 UT on May 3 through 12:00 UT the following day. The 4.8- and 6.8-MHz HF estimated radial currents correspond to "effective" current measurement depths of approximately 1.4 m and 1.0 m, respectively. The ADCP horizontal current component along the radar line of sight was extracted for comparison purposes. In Fig. 6, we see that the HF radar and ADCP measurements show qualitative agreement ($\sim\pm 3$ cm/s).

Fig. 7 shows a 4-h comparison of radial current profiles obtained by both HF and ADCP techniques. The HF radar data were collected 6 km from shore, in a range cell that contains the ADCP location shown in Fig. 2. The HF frequencies whose data are shown in this figure are 4.8 MHz, 6.8 MHz, and 13.4 MHz. We note that the HF radar observations supplement the ADCP measurements, continuing the trend and defining the shear very near the surface. Qualitatively, these profiles show the interplay between a surface wind-induced shear and a remnant deep-water inertial oscillation. The accuracy of the ADCP data is estimated to be about ± 0.8 cm/s while the HF data are accurate to at best about 3–5 cm/s. Recall also that the ADCP provides a point measurement, whereas the HF radar measurement corresponds to an area some 3×7 km in size (21 km^2) at 4.8 MHz, 3×5 km (15 km^2) at 6.8 MHz, and 3×3 km (9 km^2) at 13.4 MHz. Given these caveats, the measurements appear to be fairly consistent with one another.

C. *HF Performance and Environmental Conditions*

As discussed previously, the capability of any HF system to measure near-surface currents is dependent upon the existence of sufficiently large waves of a particular wavelength (one half of the transmitted electromagnetic wavelength as viewed from the deployment site) traveling in a radial sense either toward or away from the radar. For the MCR, the 4.8-MHz channel is sensitive to the presence of surface gravity waves of approximately 0.223 Hz or 31.3 m wavelength. Fig. 8 provides a 64-h comparison of the SNR of the 4.8-MHz MCR channel and the wave energy recorded at NDBC Buoy 45 007. The total wave energy and the wave energy between 0.215 and 0.235 Hz are shown. During this time period, the wind was primarily from the northwest quadrant. Throughout this time series, there is a consistent lag between any significant increase in wave energy at the buoy, particularly in the Bragg scattering sub-region of the spectrum (0.215 to 0.235 Hz), and an increase in HF SNR. A cross correlation of the wave energy at 0.215 to 0.235 Hz and

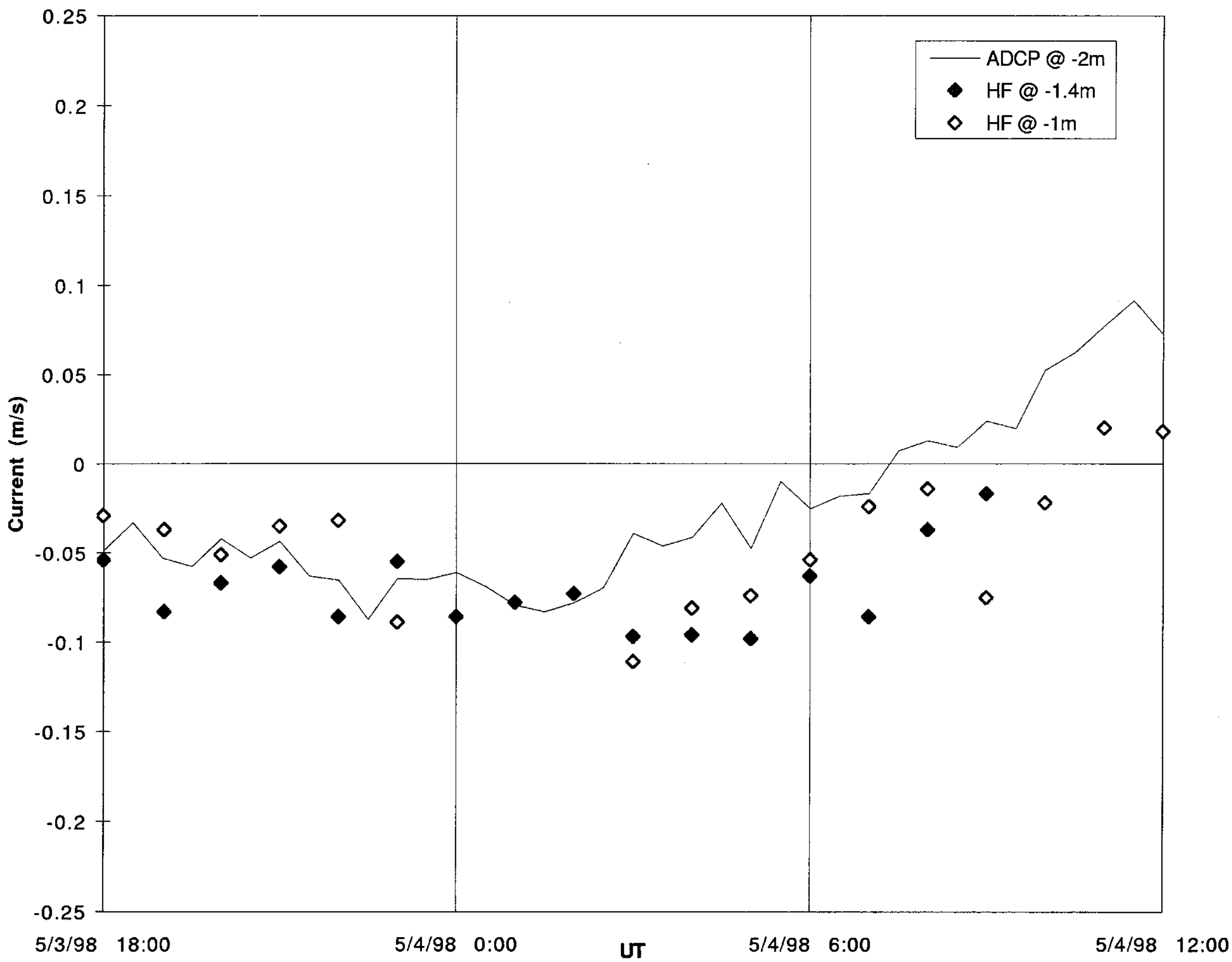


Fig. 6. Comparison of ADCP and HF current radial measurements near the A1 ADCP location, about 6 km offshore of St. Joseph, MI. Given that the ADCP and HF radar provide point and area-averaged measurements, respectively, and refer to slightly different depths, the measurements are consistent with one another.

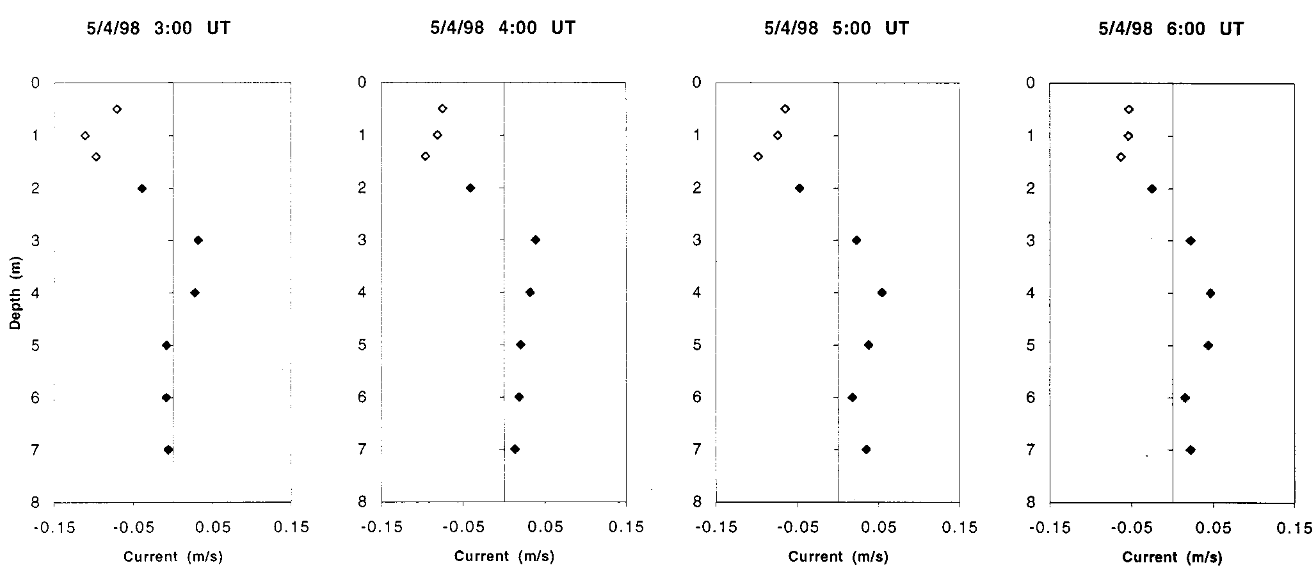


Fig. 7. Vertical profiles of radial currents showing ADCP (solid diamonds) and HF (open diamonds) measurements for four consecutive hours. Data from three radar frequencies are shown: 4.8 MHz, 6.8 MHz, and 13.4 MHz. Errors are approximately 5 cm/s for the HF radar measurements and approximately 0.84 cm/s for the ADCP measurements. Note that the HF radar measurements extend the ADCP vertical current profile toward the surface. Winds were from the north and north to northwest during these times, which is approximately perpendicular to the direction of the radial currents shown.

the HF SNR reveals a peak correlation at approximately 5 h. It is interesting to note that the group velocity propagation time for a wave of this size from the NDBC Buoy to the study site is approximately 6.75 h. Based on the low wind conditions at

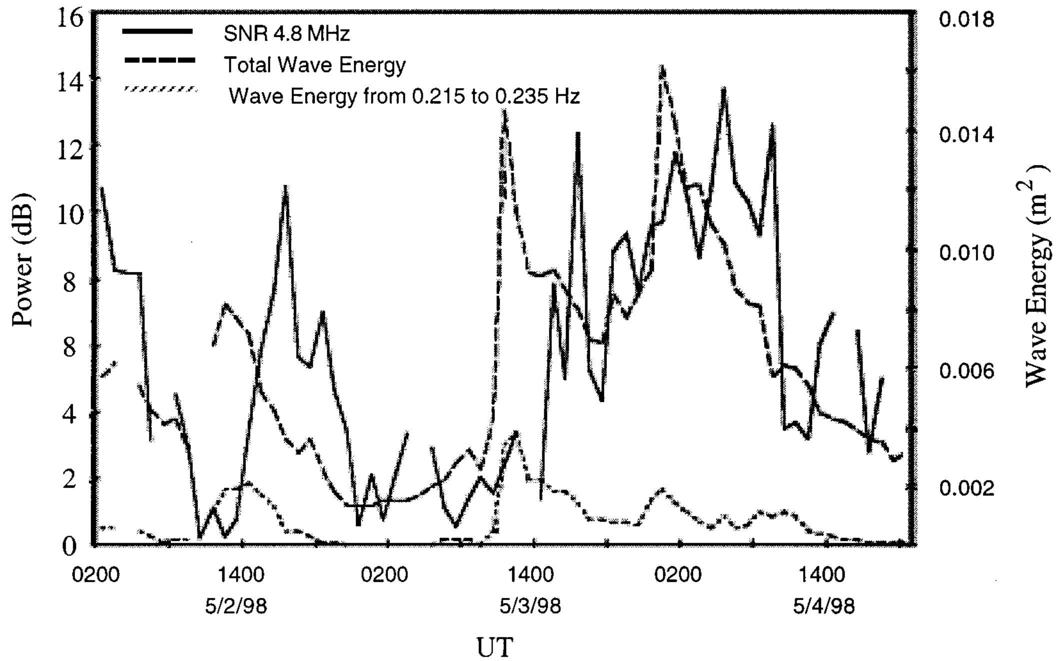


Fig. 8. Time series plot of 4.8 MHz SNR and NDBC Buoy 45 007 wave energy during the primary events of the Lake Michigan experiment. Radar data shown are from 6 km from the shore. Buoy 45 007 is approximately 85 km from the HF radar observational area. Note the time delay of about 5 h from wave energy peak to peak HF SNR.

the radar site, it is thus likely that the waves that were observed by the radar were generated near the center of Lake Michigan, i.e., near NDBC Buoy 45007, and propagated into the HF radar observational area rather than being generated locally. Significant backscatter at 4.8 MHz is evident when surface waves at the buoy in the 0.215–0.235 Hz band exhibit spectral wave energy of approximately 0.002 m^2. This corresponds to waves in this frequency band with a mean height of approximately 4 cm at the buoy.

Fig. 4 shows that current measurements were possible at the lower radar frequencies in the 6-km range bin approximately 20% of the time. It is interesting to note that this corresponds to a significant wave height at the NDBC Buoy of approximately 0.36 m and greater (i.e., 20% of the time, the significant wave height at the NDBC buoy met or exceeded 0.36 m). Unlike the Lake Tahoe measurements, which are discussed in the following section, the measurements made over Lake Michigan were made during a week of unusually low winds in the vicinity. For this reason, the percent radar return at the higher frequencies was much lower than it would have been with more typical winds. In terms of the general operational capabilities of the MCR at this site, under annual average climatological conditions, such as those reported under the U.S. Army Corps of Engineers Wave Information Study [22], one would expect to obtain useful current estimates approximately 75% of the time.

Since the data presented within this paper were all taken from single-site radar systems, no vector current measurements were possible. In order to demonstrate the potential for vector current measurements, data from a more recent deployment over Lake Michigan are presented in Fig. 9. These data were collected from two MCR systems that operated simultaneously at the same two sites discussed above during a 1999 deployment. A

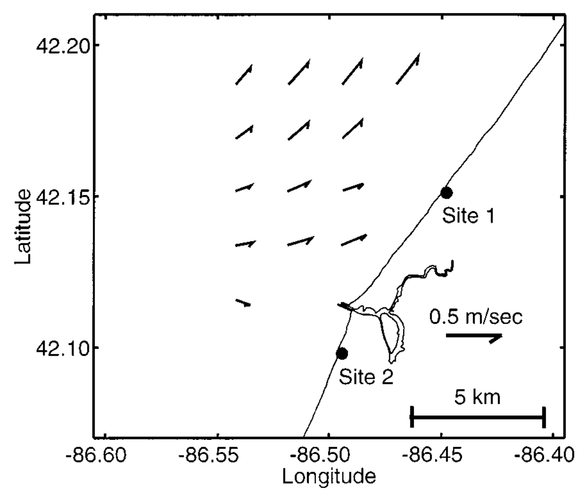


Fig. 9. Sample current vectors collected over Lake Michigan in 1999, which is a later deployment than the other ones discussed in the paper, based on simultaneous data collected from two MCR systems.

more thorough analysis of vector surface current measurements over fresh water will be presented in future studies.

IV. Lake Tahoe Experiment

A CODAR SeaSonde HF radar, similar to those deployed in Monterey Bay, California [23], was deployed on the northwest shore of Lake Tahoe in the Sierra Nevada mountains of California and Nevada from October 9–11, 1998 (Fig. 10). This system operated at 25.1 MHz for the first two days, during which time usable echoes were collected nearly 100% of the time up to ranges of 6 km. A sample map of radials measured over Lake Tahoe is also shown on Fig. 10 and a histogram of

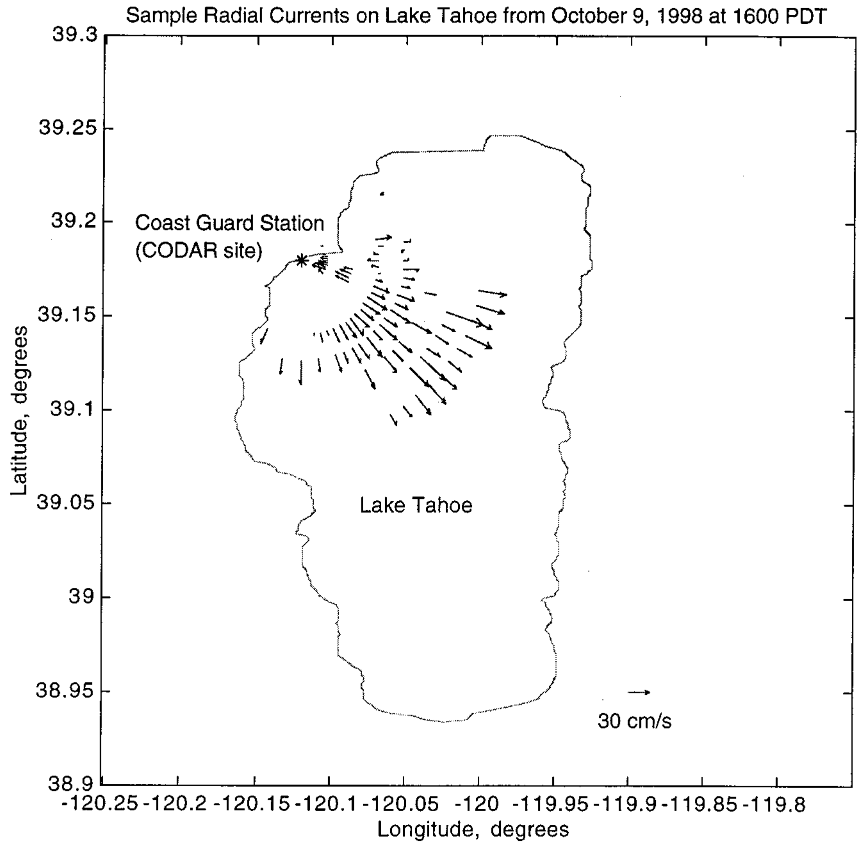


Fig. 10. Site map showing the deployment of a SeaSonde HF radar on the California shore of Lake Tahoe. Also shown are sample radial currents from 1 h of data.

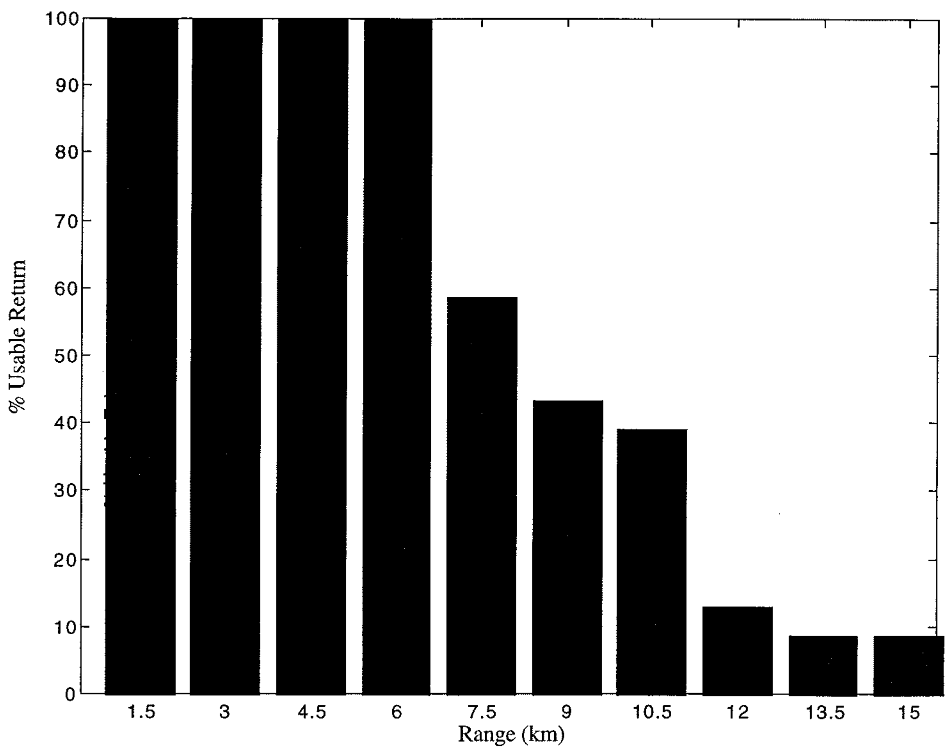


Fig. 11. Histogram of percent usable return versus range for CODAR Seasonde operating at 25.1 MHz deployed at Lake Tahoe (two-day operation).

percent usable return versus range for the two days of HF radar coverage at Lake Tahoe is shown in Fig. 11. On the third day, the system was tuned to 13.5 MHz, but no useful signals were collected at this frequency. Sample radar echoes collected at Lake

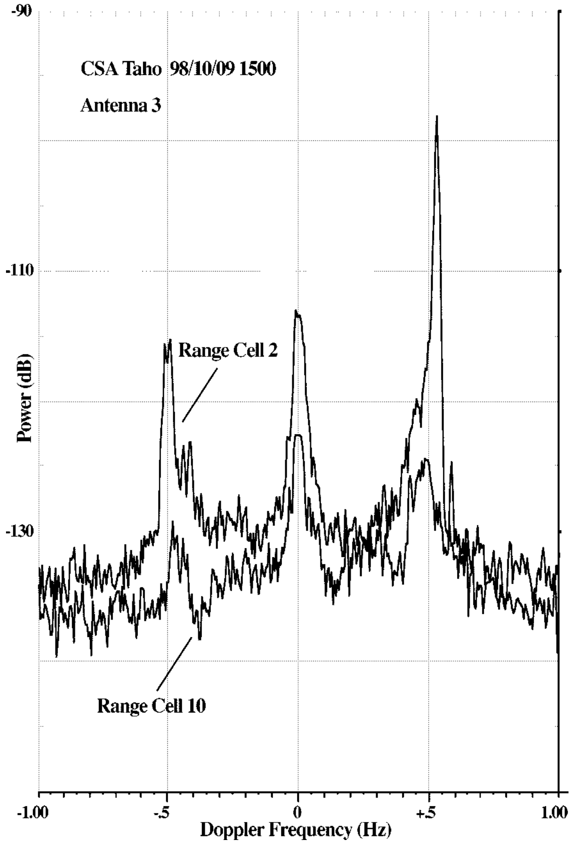


Fig. 12. Sample spectrum of HF radar echoes from Lake Tahoe at 25.1 MHz obtained under 3.5–5 m/s wind speeds at ranges of 3 and 15 km (ranges cells 2 and 10, respectively).

Tahoe are illustrated in Fig. 12. The two peaks shown are indicative of backscatter from Bragg resonant waves approaching and receding from the radar. Such peaks are evident from data collected at ranges as great as 15 km during this experiment. Since the SeaSonde 25.1-MHz frequency is sensitive to approximately 6-m-long waves and the 13.5-MHz frequency is sensitive to 11.1-m-long waves, fetches and/or wind speeds present during the morning of October 11 were insufficient to generate 11.1-m-long waves of sufficient height. This is in contrast to the situation at Lake Michigan (Section III) where higher wind speeds near the center of Lake Michigan and a much longer fetch distance produced resonant surface waves of sufficient height to cause usable HF radar echoes at lower frequencies. At Lake Michigan, scatter at the lower frequencies was more easily seen because of lower decay rates associated with the longer water waves and because lower frequency radar waves can propagate farther over poor conductors, such as fresh water, as is shown in Fig. 1.

From Fig. 10, it is clear that winds with strong components from the east and south would have the greatest fetch and thus the greatest potential to generate larger waves and enhanced lake echo from the waves that propagate toward the radar. Winds from the west or north, on the other hand, would tend to have shorter fetch in the vicinity at which the radar was most sensitive. Waves generated by these winds would tend to propagate away from the radar and would thus enhance the receding Bragg peak. Since nearly all of the spectra collected by the CODAR SeaSonde were dominated by approaching wave energy, we expect that the winds were more easterly over the lake waters at the time of the experiment. Easterly winds were indeed observed near the radar site, as described below.

Fig. 13 shows wind speed and wind direction measured close to the radar site, and maximum backscattered energy in the vicinity of the Bragg peak for several different range cells. Several features are of note in this figure. First, the wind speed has well-defined periods during which it is strong and weak. Winds typically picked up in the mid-morning and blew strongly until late afternoon. Wind direction at the site was highly variable, but followed patterns during the experiment that may offer some insight into the variability of the radar echo. For instance, during the first day of the radar operation, signal returns were at their strongest. Wind speeds were also at their highest (nearly 7 m/s) at this time and wind direction was primarily easterly. During the next day, maximum wind speeds were lower ($\sim$5 m/s) and wind direction during the time of maximum wind speed was southwesterly. Correspondingly, the radar return was 15–20 dB lower than during the previous day at the same time. There appears to be a high correlation between the shore wind speed and strength of radar return near the beginning of the experiment, but less so on the second and third days. The periods of poorer correlation may be because the winds over the lake are different from the winds measured near the shore-based radar site. Future experiments should incorporate longer observations so that the effects of day-to-day variation of the wind and waves far out over the lake can be better seen in the radar data. The results of the short experiment at Lake Tahoe clearly indicate the potential HF radar has to offer for monitoring fresh-water zones within 6 km of the shore and also potentially beyond 12 km from the shore.

V. Discussion and Conclusions

The use of HF radar systems over fresh water has been hindered by the expectations of large propagation loss over this much less conductive surface. Under fully developed wave conditions, the freshwater return signal strength is estimated to be, at best, 40 dB lower than that of salt water. However, recent advances in the use of the HF radar over salt water to measure not only currents, but waves and wind conditions as well, has produced an attractive instrument package that is now sought after by freshwater researchers. We demonstrated in this work that although ranges are more limited, with a single-site HF radar, radial surface currents can be mapped over fresh water. Thus, the utility of the HF radar in freshwater applications was explored.

The two radar systems (MCR and CODAR SeaSonde) utilized here have significantly different characteristics, although they use the same physical phenomena to make surface measurements. The MCR operates at four frequencies, transmits for 12 min out of each hour, and did not use pulse compression in these experiments. Thus, the MCR obtains surface currents at several "effective" depths, but generally has a shorter range capability than the CODAR SeaSonde radar. The SeaSonde operates at a single frequency, but transmits continually and uses a

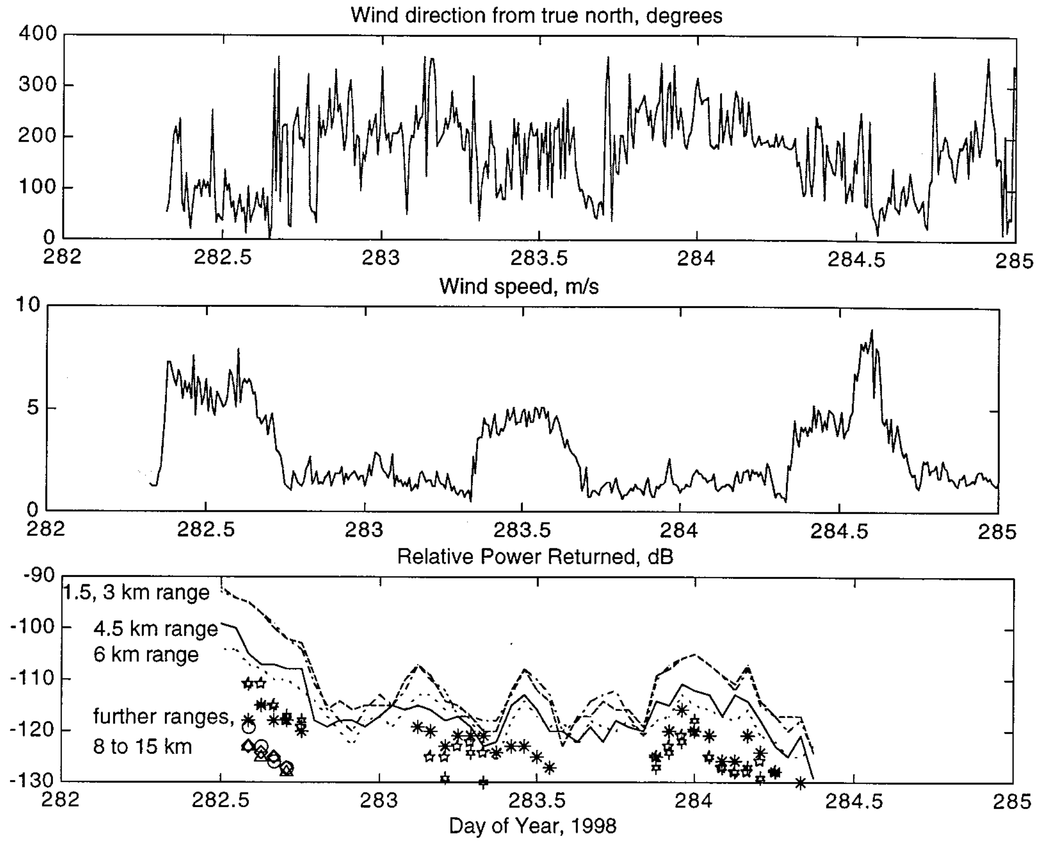


Fig. 13. Time series comparing the variation of HF radar echo power (lowest plot) with the variation in the wind speed and direction (upper plots).

pulse compression wave form. Thus, the SeaSonde obtains surface current measurements at a single depth, but, by emitting more energy in a given time, can obtain measurements at greater range (for a given operating frequency).

Both HF deployments at freshwater sites illustrate successful measurements of the radial component of surface currents at ranges, in some cases, exceeding 10 km. At Lake Michigan, the lowest frequency used (4.8 MHz) illustrates the greatest range, unlike at Tahoe where no usable echoes were seen from the lower frequency used (which was 13.5 MHz). This distinction may be the result of the larger fetches available on Lake Michigan allowing the generation of longer waves. Lower frequencies also exhibit lower propagation losses, so, assuming that the longer waves exist on the lake, they are more likely to have their echo detectable at the greater ranges. Also, from the data presented, it appears that a significant wave height of about 0.36 m could be sufficient to produce a usable SNR in the HF radar data at the lower frequencies over fresh water.

The results from Lake Michigan also show the potential for the HF radar to complement the measurement capability of an ADCP system by extending current estimates closer to the surface and extending spatial coverage. Ultimately, the coupling of these two systems should provide better estimates of the three-dimensional current structure of the near shore region. Thus, HF radar systems offer great potential for providing improved characterization of near shore surface circulation in fresh water bodies.

ACKNOWLEDGMENT

The authors wish to extend their thanks to the St. Joseph, MI, city officials (C. LaSata, R. Dost, and M. O'Malley) and waterworks employees who were extremely helpful in logistics, providing support for equipment shipments, telephone service, and suitable laboratory space. In addition, Dr. G. Miller of GLERL provided the ADCP data utilized in this study. The authors also wish to recognize the U.S. Coast Guard, Station Tahoe, for the use of their facility, Dr. G. Schladow and S. Sopalmarsson, U.C. Davis Department of Civil Engineering for the wind data and Tahoe salinity, and CODAR Ocean Sensors for the use of the CODAR SeaSonde. The authors also wish to thank the reviewers, who supplied many useful comments.

REFERENCES

[1] B. J. Lipa and D. E. Barrick, "Methods for the extraction of long period ocean wave parameters from narrow-beam HF radar sea echo," *Radio Science*, vol. 15, pp. 843–853, 1980.

[2] L. R. Wyatt, L. R. Thompson, and R. R. Burton, "Evaluation of high frequency radar wave measurement," *Coast. Eng.*, vol. 37, no. 3–4, pp. 259–282, Aug. 1999.

[3] D. M. Fernandez, H. C. Graber, J. D. Paduan, and D. E. Barrick, "Mapping wind direction with HF radar," *Oceanography*, vol. 10, no. 2, pp. 93–95, 1997.

[4] J. F. Vesecky, F. L. Ludwig, C. C. Teague, W. Nuss, R. G. Onstott, P. E. Hansen, D. M. Fernandez, J. M. Daida, and K. M. Fischer, "Estimating the surface wind field over coastal oceans using multifrequency high-frequency radar and *in situ* observations," in *Second Conf. on Coastal Atmosphere and Oceanic Prediction and Processes, American Meteorological Society Preprints*, January 1998, pp. 115–121.

[5] J. D. Paduan and H. C. Graber, Eds., "Special issue on high frequency radars for coastal oceanography," in *Oceanography*, 1997, vol. 10.

[6] J. F. Vesecky, C. C. Teague, D. M. Fernandez, J. D. Paduan, J. M. Daida, R. G. Onstott, K. Laws, and P. E. Hansen, "HF radar observations of surface currents on Monterey Bay, California," *Backscatter*, August 1998.

[7] R. H. Stewart and J. W. Joy, "HF radio measurement of surface currents," *Deep-Sea Res.*, vol. 21, pp. 1039–1049, 1974.

[8] D. M. Fernandez, J. F. Vesecky, and C. C. Teague, "Measurements of upper-ocean surface current shear with high-frequency radar," *J. Geophys. Res.*, vol. 101, pp. 28 615–28 625, 1996.

[9] E. C. Ha, "Remote sensing of ocean surface current and current shear by HF backscatter radar," Ph.D. dissertation, Stanford Univ., Stanford, CA, 1979.

[10] G. O. Marmorino, C. L. Trump, and Z. A. Hallock, "Near-surface current measurements using a ship-deployed 'horizontal' adcp," *J. Atmospheric Oceanic Technol.*, to be published.

[11] K.-W. Gurgel, H.-H. Essen, and T. Schlick, "Tracking of fresh-water plumes in Dutch coastal waters by means of HF radar," in *IGARSS '99 Conf. Proc.*, 1999, vol. V, pp. 2548–2550.

[12] D. J. Schwab, D. Beletsky, and J. Lou, "The 1998 coastal turbidity plume in Lake Michigan," *Estuarine, Coastal and Shelf Science*, pt. 1, vol. 50, pp. 49–58, 2000.

[13] P. Knight and J. A. W. Robson, "Empirical formula for groundwave field-strength calculation," *Electron. Lett.*, vol. 20, no. 18, pp. 740–742, 1984.

[14] K. A. Norton, "The calculation of ground-wave field intensity over a finitely conducting spherical earth," in *Proc. IRE 29*, 1941, p. 623.

[15] P. Rohan, *Introduction to Electromagnetic Wave Propagation*. Boston, MA: Artech House, 1991.

[16] E. D. R. Shearman, "A review of methods of remote seansing of sea-surface conditions by HF radar and design considerations for narrow-beam systems," *IEEE J. Oceanic Eng.*, vol. OE-11, pp. 150–157, April 1986.

[17] D. Fernandez, "High-frequency measurements of coastal ocean surface currents," Ph.D. dissertation, Stanford University, 1993.

[18] J. D. Kraus, *Antennas*, 2nd ed. New York, NY: McGraw-Hill, 1988, pp. 40–42.

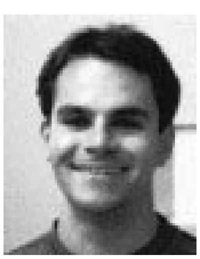
[19] E. C. Jordan, *Electromagnetic Waves and Radiating Systems*. Englewood Cliffs, NJ: Prentice-Hall, 1950.

[20] D. E. Barrick, "Theory of ground-wave propagation across a rough sea at dekameter wavelengths,", Battelle Memorial Institute Technical Report, ARPA Order no. 1178, Contract no. DAAH01-70-C-0312, January 1970.

[21] H. P. Westman, *Reference Data for Radio Engineers*. New York, NY: International Telephone and Telegraph Corporation, 1956, p. 1151.

[22] J. M. Hubertz, D. B. Driver, and R. D. Reinhard, "Hindcast wave information for the great lakes: Lake Michigan," US Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS, WIS Report 24, October 1991.

[23] J. D. Paduan and K. L. Rosenfeld, "Remotely sensed surface currents in Monterey Bay from shore-based HF radar (coastal ocean dynamics application radar)," *J. Geophys. Res.*, vol. 101, no. C9, pp. 20 669–20686, September 1996.



Daniel M. Fernandez (S'86–M'93) received the B.S. degree in electrical engineering from Purdue University, West Lafayette, IN, in 1987 and the M.S. and Ph.D. degrees in electrical engineering from Stanford University, Stanford, CA, in 1988 and 1993, respectively.

Since 1996, he has been a faculty member at California State University, Monterey Bay, where he teaches physics, does outreach to encourage science among elementary/middle schools in his local tri-county area, and conducts research in high-frequency radar and its applications to the marine environment. He has been an author or co-author on over two dozen conference and journal papers related to high-frequency radar.

Dr. Fernandez is a member of the American Geophysical Union and Tau Beta Pi.

Lorelle A. Meadows received the B.S. degree in 1983 and the M.S. degree in physical oceanography from the University of Michigan, Ann Arbor, in 1985. She is currently working toward the Ph.D. degree at the University of Michigan.

Her background involves near-shore and coastal sediment and hydrodynamics as well as air–sea interaction problems. In 1987, she joined the staff of the Department of Naval Architecture and Marine Engineering at the University of Michigan. As a Research Associate in the Ocean Engineering Laboratory, her research has focused on the response of the coastal environment to atmospheric forcing, including climate variability, and the application of high frequency (HF) radar systems in coastal oceanography. She is the co-author of 20 publications and numerous technical reports related to the physics of the coastal ocean and Great Lakes.

Ms. Meadows is a member of the American Shore and Beach Preservation Association, the American Society of Limnology and Oceanography, and the International Association for Great Lakes Research.

John F. Vesecky (S'61–M'67) received the B.A. and B.S. degrees in electrical engineering from Rice University, Houston, TX, in 1962 and 1963, respectively, and the M.S. and Ph.D. degrees from Stanford University, Stanford, CA in 1965 and 1967, respectively.

He was Research Fellow in astronomy from 1967 to 1969 at Leicester University, U.K., where he taught in the Astronomy Department from 1971 to 1976, and specialized in radio, radar, and X-ray observations of the sun and planets. He did research in radio wave propagation at the Communications and Radio Physics Laboratory at SRI International from 1964 to 1971 and was with the Electrical Engineering Department at Stanford University in several capacities from 1969 to 1971 and 1979 to 1995, becoming a Research Professor in 1983. He then became a Professor of Atmospheric, Oceanic and Space Science at the University of Michigan, Ann Arbor, from 1990 to date. From 1991 to 1993, he served as Director of the Space Physics Research Laboratory at Michigan. He has now been appointed the founding chairman of the new Electrical Engineering Department in the Baskin School of Engineering at the University of California, Santa Cruz. His current research and teaching interests are in remote sensing and satellite system design. Most recently, he has been working with the design and construction of multifrequency HF radar with applications in coastal oceanography and limnology. A further research interest is the use of active and passive microwave techniques to retrieve surface wind vectors over the ocean.

Calvin C. Teague (S'62–M'68) received the B.S. (with great distinction) M.S., and Ph.D. degrees, all in electrical engineering from Stanford University, Stanford, CA, in 1963, 1964, and 1971, respectively.

He held a National Science Foundation Fellowship from 1963 to 1966 and was a Research Assistant at Stanford University during 1966–1968 and 1970–1971. During 1963–1970, he worked part time at Hewlett-Packard, Stanford Research Institute, and Philco-Ford Corporation. In 1971, he joined the research staff of Stanford University, where he remained full time until 1991 as a Senior Research Associate, and remains there now part time. His primary research has been a study of resonant scatter of radio energy by ocean surface waves as a remote sensing tool. Other areas of research include the design, construction, and testing of special-purpose hardware for the efficient computation of large Fourier transforms, the design of inexpensive data collection systems, including the installation of several automatic weather stations in the Antarctic, and the design of a buoy to measure ocean-water surface tension. Recently, he has been involved in experiments which monitor extremely low-frequency signals in the range of 0.01 Hz to 20 kHz and participated in a field experiment in Alaska in 1992 to record ground-level data from a rocket flight. Since 1992, he has consulted for the University of Michigan, Ann Arbor, where he is working with a group there and at the Environmental Research Institute of Michigan on the design and use of an upgraded version of the multifrequency HF ocean-scatter radar started at Stanford in the 1970's. He is the author or co-author of over 40 journal articles and meeting papers in the fields of radio oceanography and remote sensing.

Dr. Teague is a member of the American Geophysical Union, the Institute of Electrical and Electronics Engineers, and URSI Commission F. He is also a member of Phi Beta Kappa and Tau Beta Pi.

Jeffrey D. Paduan received the B.S.E. degree from the University of Michigan, Ann Arbor, in 1982 and the Ph.D. degree from Oregon State University in 1987.

His background involves upper-ocean currents and air-sea interaction problems. In 1991 he joined the faculty in the Department of Oceanography at the Naval Postgraduate School (NPS), Monterey, CA, where his research focused on the application of radar systems in coastal oceanography. In 1997, he co-edited a special issue of the Oceanography Society's journal (*Oceanography*) devoted to this topic and, in March, 1999, he overviewed this research area as the keynote speaker for the IEEE 6th Working Conference on Current Measurement Technology. Prior to moving to NPS, he was a Research Scientist at Scripps Institute of Oceanography, La Jolla, CA, where his research focused on larger-scale current structures as measured by satellite-tracked surface drifters. In that time frame, he also served as manager of the Global Drifter Center whose function was to coordinate drifter construction and deployments for the WOCE/TOGA Surface Velocity Program. He is the author of 15 papers and numerous technical reports related to the physics of the upper ocean.

Dr. Paduan is a member of the American Geophysical Union, the Oceanography Society, the Marine Technology Society, and the American Meteorological Society (AMS). He serves on the AMS committee for Meteorology and Oceanography in the Coastal Zone.

Peter Hansen, photograph and biography not available at the time of publication.