

# Multifrequency HF Radar Observations of Currents and Current Shears

CALVIN C. TEAGUE, MEMBER, IEEE

(Invited Paper)

**Abstract**—Techniques have been developed for using high-frequency (HF) surface-wave radar to measure ocean currents and vertical current shears in the upper 1 or 2 m of the ocean surface. An HF radar can precisely measure the phase velocity and direction of propagation of ocean waves whose wavelength is one-half the radar wavelength. In the absence of a current, the speed of the waves is given by the still-water dispersion relation. An underlying current will modify this speed. The radar measures the actual phase velocity through a Doppler shift, and the wavelength of the ocean wave is known through the first-order Bragg scattering relation, so a difference between observed and theoretical still-water phase velocity can be calculated. In addition, longer ocean waves are affected by currents at deeper depths than are shorter ocean waves. By measuring the phase velocity at several different wavelengths, it is possible to measure a vertical current shear in the top 1 or 2 m of the ocean surface. This is a measurement that is very difficult to make by any other means.

A portable coherent pulsed-Doppler HF radar system was developed at Stanford and used in several experiments, both on land on the California coast and on board a ship during the Joint Air-Sea Interaction (JASIN) experiment. The land-based experiments demonstrated that a current could be measured by an HF radar, and that its value agreed well with that measured by *in-situ* drifting spar buoys. In addition, there was evidence of a vertical current shear, both from the radar measurements and from the buoy measurements. The JASIN experiment was an attempt to apply these techniques to the measurement of surface current and current shear in the open ocean. The radar system was installed on board a ship, along with a receiving antenna consisting of a steerable phased array of eight wide-band loops. The steerable antenna was quite rugged and performed as expected. It produced antenna patterns consistent with the physical aperture of the array. The wind velocity during the JASIN experiment was quite low, so wind- and wave-generated currents were quite small. Nevertheless, there is some evidence of a current shear. Its magnitude is small and near the resolution limit of the radar, but it appears to be somewhat higher than estimates based on either the wind or wave conditions alone, but less than the estimates based on the sum of the two components.

## I. INTRODUCTION

**D**URING the period January 1975 to January 1982 techniques were developed for using high-frequency (HF: 3–30 MHz) radar to measure ocean currents and vertical current shears in the upper 1 or 2 m of the ocean surface. Some of the research was conducted using land-based equipment (at a site on the California coast near Pescadero), and some was conducted from a shipborne platform (the R. V. Atlantis II

during the Joint Air-Sea Interaction (JASIN) experiment). The radar equipment, specially developed at Stanford for this research, was the same in both cases, but the antenna systems differed widely between the two experiments.

The measurement of current velocity with an HF radar depends on the ability of the radar to precisely measure the phase velocity and direction of propagation of ocean waves whose wavelength is one-half the radar wavelength. This is first-order scattering [2], and in contrast to second-order scattering [1], [3] which involves two or more ocean wave trains often traveling in different directions, the first-order lines are usually very sharp, often only a few millihertz wide at a radar carrier frequency of several megahertz. The Bragg scattering mechanism has been well established as responsible for first-order echoes [2], [6]. Thus it is possible to relate the phase velocity of the ocean waves, as determined by the Doppler shift of the radar echoes, to the wavelength of the ocean waves, as determined by the wavelength of the radar signal. The difference between the observed phase velocity of the ocean waves and its value predicted by the deep-water dispersion relation has been attributed to surface currents [16]. Furthermore, this difference often is a function of ocean (or radar) wavelength, and this is attributed to a vertical current shear, since longer wavelength ocean waves are influenced by currents at deeper depths than are shorter ocean waves. It is this wavelength dependence which suggests that an HF radar can be used to measure a vertical current shear.

The first-order scattering mechanism is highly selective in terms of the direction of wave propagation: only those ocean waves that are traveling radially toward or away from the radar contribute appreciable energy to the first-order echo. Consequently, ocean-wave directional resolution is obtained by radar antenna directivity. Other techniques, such as those used by the CODAR [5], can provide high directional resolution with smaller antennas than those used here, but they were not employed because of the need to operate over a wide range of radar frequencies in order to measure a vertical current shear.

Early observations were carried out by Stewart and Joy [16], who showed that surface currents could be measured by an HF radar system. More importantly, they demonstrated that the observed current was a function of radar wavelength, implying that a vertical current shear could be measured by HF radar. To determine the accuracy of the technique, and to extend these early observations, we conducted a series of

Manuscript received July 17, 1985; revised February 10, 1986. This work was supported by ONR under Contract N00014-75-C-0356.

The author is with the Center for Radar Astronomy, Stanford University, Stanford, CA 94305.

IEEE Log Number 8608307.

experiments at Pescadero, California, and we participated in the JASIN experiment. The same HF radar system was used in both experiments, but with different antenna systems. In both experiments, the Scripps pitch-roll buoy [15] was used to measure the directional ocean-wave spectrum. These experiments were conducted jointly by Stanford University and Scripps Institution of Oceanography.

## II. THEORY

### A. First-Order Radar Scattering

Crombie [6] first made the observation that radio signals scattered by the ocean surface consisted of a pair of very narrow sidebands displaced above and below the carrier frequency by a small amount (a fraction of a hertz at HF). This frequency corresponded exactly to the Doppler shift of an object moving at the phase velocity of an ocean wave whose wavelength was one-half the radio wavelength. He deduced that the scattering mechanism was Bragg scattering, in which the contributions from each individual wave crest all add up coherently to produce the scattered signal. Hasselmann [9] showed that a vertically polarized radio wave propagating at grazing incidence, with a wavenumber  $k_i$  and frequency  $\omega_i$ , is scattered into two waves of wavenumber  $k_s$  and  $\omega_s$  such that

$$\begin{aligned} k_s &= k_i \pm k \\ \omega_D &= \omega_s - \omega_i = \pm \omega \end{aligned} \quad (1)$$

where  $\omega_D$  is the Doppler shift of the scattered radio wave and  $k$  and  $\omega$  are the wavenumber and frequency of the ocean surface wave. For the case of backscatter (colocated transmitter and receiver)  $k_s = -k_i$ , so that  $2k_s = \pm k$ . Barrick [3] examined the scattering mechanism in more detail and extended the geometry to include nongrazing incidence.

The ocean-wave velocity  $c$  depends on an underlying current. Let the still-water wave velocity be  $c_1$  and the velocity in the presence of a current be  $c_p$ . By definition,  $c_p = \omega_p/k$  and  $c_1 = \omega/k$ . Their difference  $v$  is

$$v = k^{-1}(\omega_p - \omega) = k^{-1}\Delta\omega \quad (2)$$

where  $\Delta\omega$  is the difference between the observed Doppler shift and its expected value. The still-water frequency  $\omega$  is calculated from the dispersion relation  $\omega = (gk)^{1/2}$ , where  $g$  is the gravitational acceleration [13]. The dependence of  $v$  on the vertical current distribution is discussed in the next section. Stewart and Joy [16] discuss this theory in more detail.

When the ocean surface roughness is calculated to second order, it is found that the Bragg line itself has sidebands. Barrick [1] showed that this continuum depends on all of the ocean waves present, not just the Bragg component, and Hasselmann [10] suggested that this can be used to measure the entire ocean-wave spectrum using a single radio wavelength. However, the presence of the second-order sidebands does not alter the position of the first-order line, so as long as its position can be accurately determined, the second-order continuum does not affect the current measurement capability of the radar system. Only the first-order line will be used in the remainder of this paper.

It is important to note that an HF radar provides unique independent measurements of the ocean-wave *spatial* frequency (by means of the resonance wavelength match) and its *temporal* frequency (by means of Fourier analysis of a long train of coherent pulses of radio energy). Conventional oceanographic point measurements often infer one from the other.

### B. Vertical Current Shear

The relationship between radar wavelength and the effective depth of the current measurement was first examined by Stewart and Joy and has recently been examined by Ha [8]. If the current is small compared with the wave speed, then the difference in velocity between a wave in a current field and one in still water is

$$U(k) = 2k \int_0^\infty u(z) \exp(-2kz) dz \quad (3)$$

where  $u(z)$  is the component of the horizontal current in the direction of the radar beam at depth  $z$ , and  $k = 2\pi/L$  is the ocean wavenumber in resonance with a radar with wavelength  $\lambda = 2L$ . If the current profile is logarithmic, that is

$$u(z) = u_s - \frac{u_*}{K} \ln \left( \frac{z}{z_0} \right) \quad (4)$$

where  $u_s$  is the surface drift,  $u_*$  is the friction velocity,  $K = 0.4$  is Von Karman's constant, and  $z_0$  is the reference depth, then the radar probes the logarithmic current at a depth of approximately 4.4 percent of the ocean wavelength [8]. If a linear profile is assumed, as was done by Stewart and Joy, then the current is probed at a depth of approximately 7.8 percent of the ocean wavelength. For example, in the JASIN experiment the ocean wavelengths were 31.2, 22.1, 11.2, and 6.9 m. For this case, if a logarithmic profile is assumed, the radar system probes the current at depths of approximately 137, 97, 49, and 30 cm, and if a linear profile is assumed, the depths are 244, 173, 88, and 54 cm, respectively. Substituting (4) into (3), and assuming  $2kz_0 \ll 1$

$$U(k) = u_s + \frac{u_*}{K} \ln(2k\gamma z_0) \quad (5)$$

where  $\gamma = 1.781072$ . Differentiating,

$$\frac{dU(k)}{d \ln f_r} = \frac{u_*}{K} \quad (6)$$

where  $f_r$  is the radio frequency used to observe ocean wavenumber  $k$  and  $U(k)$  is the current velocity seen by this radio frequency [17], [21].

An alternative model for the effects of a vertical current profile was developed in Barrick *et al.* [4]. In [4, eqs. (7) and (8)], Crombie shows that for a linear current profile, the current is probed at a depth of  $L/4\pi$ , or 8.0 percent of the ocean wavelength. Although his equation is not an integral form as is (3), this is remarkably close to the 7.8 percent obtained by Ha, and tends to confirm both theoretical results.

### C. Wind-Induced Shear

It is believed that the wind produces a vertical current shear, because the wind blowing over the sea drags the surface layers along in the direction of the wind, and these surface layers further influence deeper water. In order to estimate the magnitude of the wind-induced shear, it is assumed that the velocity profile in the water is logarithmic and given by (4). For flows past a free boundary, the stress  $\tau$  is given by  $\tau = \frac{1}{2}\rho u_*^2$ , where  $\rho$  is the fluid density and  $u_*$  is the friction velocity. The stress  $\tau$  is assumed constant across the air-sea boundary, so

$$\tau_{\text{air}} = \frac{1}{2} \rho_{\text{air}} u_{* \text{air}}^2 = \frac{1}{2} \rho_{\text{water}} u_{* \text{water}}^2 = \tau_{\text{water}} \quad (7)$$

The stress is given by  $\tau = \rho_{\text{air}} C_D U_{\text{air}}^2$ , where  $C_D = 1.3 \times 10^{-3}$  is the drag coefficient in the air and  $U_{\text{air}}$  is the air velocity at 10 m, so that

$$u_{* \text{water}} = \left( \frac{\rho_{\text{air}}}{\rho_{\text{water}}} \right)^{1/2} (C_D)^{1/2} U_{\text{air}} \quad (8)$$

For  $U_{\text{air}} = 10 \text{ m} \cdot \text{s}^{-1}$  this would predict a current shear of  $5 \text{ cm} \cdot \text{s}^{-1}$  between the top layer and the bottom layer probed by the radar.

### D. Wave-Induced Shear

The ocean surface waves also are believed to produce a vertical shear through the Stokes drift. The Stokes drift arises because a wave of finite amplitude, accompanied by irrotational fluid motion, requires that the water particle orbits are not quite closed; there is a small net mass transport in the direction of wave propagation [12, p. 256]. Van Dyke [19, p. 110] displays some striking photographic examples of this effect. In order to estimate this drift, the vertical current profile is predicted using Stokes' theory of wave-produced currents and the pitch-roll buoy measurements of the entire set of ocean surface waves present during the radar measurements. The vertical current distribution as a function of depth  $z$  is estimated from

$$u(z) = \frac{2}{\rho g^2} \int_0^\infty F(\omega) \omega^3 \exp(-2\omega^2 z/g) d\omega \quad (9)$$

where  $g$  is the gravitational acceleration and  $F(\omega)$  is the surface elevation energy density at frequency  $\omega$  [11]. Then for each of the waves to which the radar system is sensitive, the integrated effect of this current profile on the wave phase velocity is computed by using the current distribution (9) in (3). In performing this calculation, it is assumed that the Lagrangian current produced by a wave spectrum advects a short wave, thus changing its phase velocity. This is not precisely true, but the influence of other wave interactions is small. That is, the influence of wave interactions is to produce a current which modifies the phase velocity of individual wave components; other interactions which directly change the wave phase velocity, without producing currents, are small. The shear predicted in this manner is on the order of  $1\text{--}6 \text{ cm} \cdot \text{s}^{-1}$  over

the depth probed by the radar for the wave conditions encountered in the experiments.

Weber and Barrick [20] derived a general expression for the change in phase velocity directly in terms of the ocean wave-height directional spectrum in [20, eq. (29), part I], and reduced this to integral form and specialized it to the case of colinear waves in [20, eq. (19), Part II]. The latter was also derived by Longuet-Higgins and Phillips [14]. Weber and Barrick's equation is given in terms of the fractional correction to the dispersion relation, but it also represents the fractional correction to the phase velocity. Although their more direct approach is quite different from the one described here, the two approaches should give very similar results.

## III. HF RADAR SYSTEM

The radar system used in the experiments was developed at Stanford specially for this program. It is a pulsed coherent Doppler radar which can transmit and receive pulse-interleaved signals simultaneously on four different frequencies in the range of 4–30 MHz. The exact frequencies are selectable in 10-kHz steps. The frequencies are generated by a set of phase-locked loops. The same signals are used in both the transmitter and receiver, thus minimizing the amount of hardware required and ensuring coherence between the transmitter and receiver internal signals. The radar system includes a digital sampling and recording system. The entire radar, exclusive of the power amplifier, occupies 12 in (0.3 m) of panel space. The power amplifier occupies another 10 in.

### A. Transmitter

The transmitter and receiver frequencies are generated by a set of four phase-locked loops. These each generate signals in the range of 34–60 MHz. A fifth phase-locked loop is fixed at 30 MHz. The transmit signal is obtained by mixing the signal from one of the first four loops with the 30-MHz signal, producing a signal in the range of 4–30 MHz. The signals from each of the four oscillators are selected, one at a time at 400- $\mu\text{s}$  intervals, to provide the interleaved transmitter pulse train. The pulsewidths are selectable from 10 to 200  $\mu\text{s}$ . The pulse rise and fall times are controlled to minimize the occupied bandwidth. The signals are then amplified to a 50-W peak power level by a commercial wide-band amplifier to form the final transmitter output. All of the phase-locked loops are referenced to a stable 3-MHz crystal oscillator. The use of the double loops means that the original 8:1 frequency range can be covered by oscillators which need cover only a 2:1 frequency range.

### B. Receiver

The receiver consists of four separate amplifiers, each fixed tuned to one of the transmitter frequencies and followed by a balanced mixer driven by one of the same 34–60-MHz loops used to drive the transmitter (but gated on for a full 400  $\mu\text{s}$ ). The outputs of all four mixers are common. This generates a first intermediate frequency (IF) of 30 MHz. After amplification at 30 MHz, the signal is mixed with the same 30-MHz transmitter translation loop in a second mixer to produce a second IF centered at 0 Hz. The use of in-phase and

quadrature local oscillator signals at the second mixer allows the separation of positive and negative Doppler shifts, so that approaching waves can be distinguished from receding waves.

### C. Data Sampling and Recording

After suitable amplification at the second IF, the echoes are sampled with 8-bit resolution at four different time delays (corresponding to four different radar range cells) after the transmit pulse. Both the time delay from the transmit pulse and the spacing between samples can be selected in 10- $\mu$ s steps. In normal operation, the samples are taken at intervals of 40  $\mu$ s, starting 50  $\mu$ s after the transmitted pulse, which gives a range resolution of 6 km. A number of such complex samples are added together in a 16-bit accumulator, both to improve the signal-to-noise ratio and to allow the use of a low peak power transmitter by using a high pulse repetition rate. The number of such pulses added together can be varied, but it was usually set so that the effective sampling rate was approximately 2 Hz. This allows Doppler frequencies in the range of  $-1$  to  $+1$  Hz to be resolved.

The samples are accumulated in 16 separate accumulators, one for each range cell at each frequency. Each one is 32 bits wide: 16 bits for the real part and 16 bits for the imaginary part. There are two complete sets of buffers, so that one set can be filled while the other set is being recorded. The resulting 16-bit sums, along with all the radar system parameters, are recorded digitally on a tape recorder. (For the shipborne experiment, the receiving antenna was composed of eight elements and each one was sampled separately, so a total of 128 separate complex time series were recorded.)

## IV. THE PESCADERO EXPERIMENTS

The Pescadero experiments were designed to study the effects of vertical current distribution, determined by *in-situ* measurements, on the radar signals. Consequently, a one-dimensional geometry was adequate, and the antenna system provided a narrow beam for all four frequencies fixed in one direction. On the other hand, the JASIN measurements were an application of the technique to obtain oceanographic data in the open ocean, and some degree of antenna-steering capability was required. As a result, the antenna systems were quite different for the two experiments.

### A. Radar Installation

On several occasions between May 1975 and January 1978, HF radar backscatter observations of the ocean surface were made from a site on the California coast near Pescadero. A map of the site of the experiment is shown in Fig. 1. The site was located about 1 km from the coast. For these experiments, the radar was operated on frequencies of 6.78, 13.38, 21.77, and 29.80 MHz. These frequencies are in Bragg resonance with ocean waves of length 22.1, 11.2, 6.9, and 5.0 m.

The transmitting antenna was a vertical half-rhombic antenna, approximately 250 m long and 45 m high at the apex, supported by a large helium-filled balloon. This antenna system was chosen to provide a moderately directional wide-band transmitting antenna at a reasonable cost. It required no fixed towers to install and maintain. It did have the disadvan-

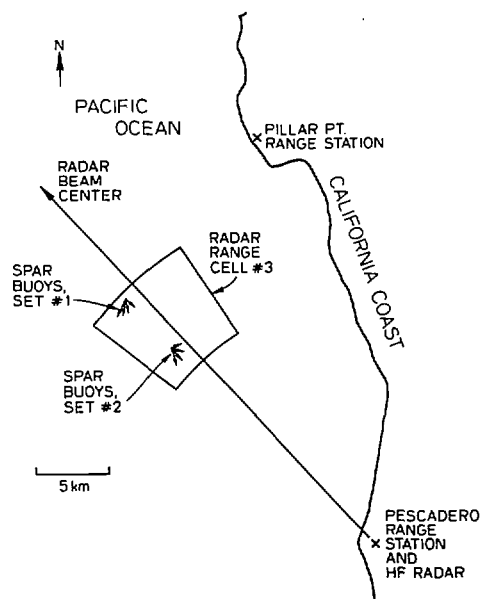


Fig. 1. Site of the Pescadero experiment, showing the locations of the spar buoys and range stations (from [8]).

tage that the balloon had to be filled with helium before each experiment, so it required about 1 h to set up the antenna. Operation of the antenna was limited to wind speeds of about  $15 \text{ m} \cdot \text{s}^{-1}$  at the radar.

The receiving antenna was a single wide-band air-core loop 1 m in diameter, manufactured by Hermes Company. The loop had a matched preamplifier installed right at the loop. The combination of the loop antenna and matched preamplifier resulted in an antenna which had an effective height of 1 m over the entire 3–30-MHz frequency range. Because of the fixed transmitting antenna, the system antenna pattern was fixed about a nominal center direction of  $315^\circ\text{T}$ . The 3-dB full width of the composite radar beam varied between  $50^\circ$  and  $12^\circ$ . The measured beam center direction varied from  $320^\circ\text{T}$  at 30 MHz to  $290^\circ\text{T}$  at 4 MHz as a result of the propagation path over land.

Observations were usually made four times each month and typically consisted of four half-hour runs, each with a different radar pulsewidth. Wind speed was recorded locally and at several coastal sites operated by the National Weather Service. Several observations which included both the Scripps pitch-roll buoy [15] and *in-situ* drifter measurements of the ocean current were made from January 19–27, 1978. The locations of the spar buoys and the radar range cell footprint are shown in Fig. 1. For these observations, the wind speed was also recorded on the boat used to deploy the buoys.

### B. Spar Buoys

The drifters were four lengths of spar buoys made of plastic pipes loaded with sufficient lead shot so that they immersed upright in water to predetermined depths of 1, 3, 6, and 12 m. The locations of the buoys were determined by a microwave tracking system which had a range resolution of a few meters. The boat used to deploy the buoys carried the master station which continuously interrogated two transponders located

about 30 km apart on the coast. The position of each buoy was measured by carefully maneuvering the boat to within a few meters of the buoy and then noting the range to each of the two transponders. The position measurements were repeated at time intervals of 1 h or longer, and velocities were calculated from the differences in position. Because the buoys typically drifted on the order of 1 km, the uncertainty of the drift velocity was less than 1 percent [8].

The buoys were not completely immersed in the water; for visibility, a portion of the buoy, 10–25 percent of the buoy length, was exposed to wind drag above the water surface. Ha calculates that the effect of the wind drag on the buoy velocity is less than the statistical uncertainty in the buoy-inferred drift. He also demonstrates that a buoy immersed to depth  $d$  will drift with a speed equal to the current at a depth of  $0.5d$  and  $0.27d$  for a current varying linearly and logarithmically with depth, respectively.

To obtain an indication of the variation of ocean current within a single radar range cell, two sets of buoys separated by approximately 5 km were deployed within the third range cell of the radar system. Because only one boat was used, the measurements of current at these two points were also separated by 30–60 min, the time required by the boat to move from one location to the next and to find the buoys.

### C. Data Processing

The radar echoes at four different frequencies were each sampled at four range cells approximately twice a second for a total period of 2–4 h for each data run. Fourier transforms were computed for each 10-min data segment. The first-order echoes were extracted by first searching for the peak of the power spectrum in a narrow region centered on the theoretical position of the Bragg line. Then the null between the first-order peak and the second-order continuum on either side of the Bragg line was found by searching for the points at which the local slope of the smoothed frequency spectrum changed sign. The nulls thus found defined the limits of the first-order energy band. The centroid of the first-order spectrum (the first-order moment) was found by integrating the spectrum over this range. The frequency corresponding to the centroid of the spectrum was taken as the measured frequency of the Bragg line. The theoretical Bragg frequency was subtracted from the measured frequency, and this difference was converted to a current velocity by  $v = f\lambda/2$ . Details of the data processing are described by Ha [8]. The use of this centroid calculation was quite effective because the antenna beamwidth was relatively narrow.

It was found that the nulls between the first-order lines and the second-order continuum were well defined. They usually could be found reliably by the above algorithm. The algorithm was not sensitive to the land echoes centered at dc, or to signals beyond a narrow region centered on the Bragg line.

### D. Results

Radar-inferred currents as a function of time are shown in Fig. 2. There is a strong time-dependent tidal component, but in addition, there is variation both in range and with radar frequency. Figs. 3 and 4 show the comparison between the

radar-inferred current and the spar-buoy drift on January 19 and January 25, 1978, respectively. For these figures it was assumed that the current varies logarithmically with depth, an assumption which appears to be justified by numerical inversion of some of the radar data [8].

The radar and the buoy measurements show similar changes of current with time which are apparently related to the tidal cycle. Also, the radar and buoy measurements show similar decreases of current with depth. On January 25, both the radar and buoy data show a vertical gradient in the measured current which increases with time. This can be explained in part by a rise in the wind speed in the direction toward the radar. However, the magnitude of the vertical shear as measured by the radar is 4–6 times the value predicted by (8) from the wind speed, and the shear measured by the buoys is also higher than would be predicted from the waves alone.

Fig. 5 illustrates the difference in the drifts of spar buoys released in the same range cell on January 25. The two sets of buoys were separated by 5 km when they were released, yet they gave quite different results. In fact there is better agreement between the radar measurements and either set of buoy measurements than between the two sets of buoy measurements. This illustrates the horizontal variability of the current field, and points out the difficulty in comparing buoy and radar results. Because the radar illuminates a finite-sized range cell approximately 7.5 km deep, the radar measurement represents an average rather than a point measurement, so the two methods cannot be directly compared. The problem is probably worse near a coastline than it is in the open ocean. Even though the water was oceanographically deep, apparently there was still some influence of the coastline on the current patterns.

Fig. 6 illustrates the current shear measured by the radar on January 24, and shows that a logarithmic variation of current with depth provides a good fit to the data. The slope of a visual fit to the data points provides an estimate of  $1.6 \text{ cm} \cdot \text{s}^{-1}$  for  $u_*$ , a value about twice what would be predicted from the wind speed of  $6 \text{ m} \cdot \text{s}^{-1}$ .

Table I summarizes the vertical current shears measured by the HF radar system in several experiments during January 1978. Also listed are values of vertical current shear which would be predicted by (8) and (3) from the wind and wave conditions present at the times of the experiment. The radar measurements showed a wide variability, but in general they were several times higher than would be predicted by the wind or waves alone, or the sum of the two predictions, assuming colinear directions.

## V. THE JASIN EXPERIMENT

During the summer of 1978, the JASIN experiment was conducted in the North Atlantic Ocean off the coast of Scotland. The overall goal of this international experiment was to measure the momentum transfer between the wind and the waves. Most of the oceanographic measurements were conventional, depending on tethered buoys supporting current meters, thermistors, and anemometers; pitch-roll buoys for measuring wave height and direction; and instruments lowered from ships for measuring the temperature, salinity, and

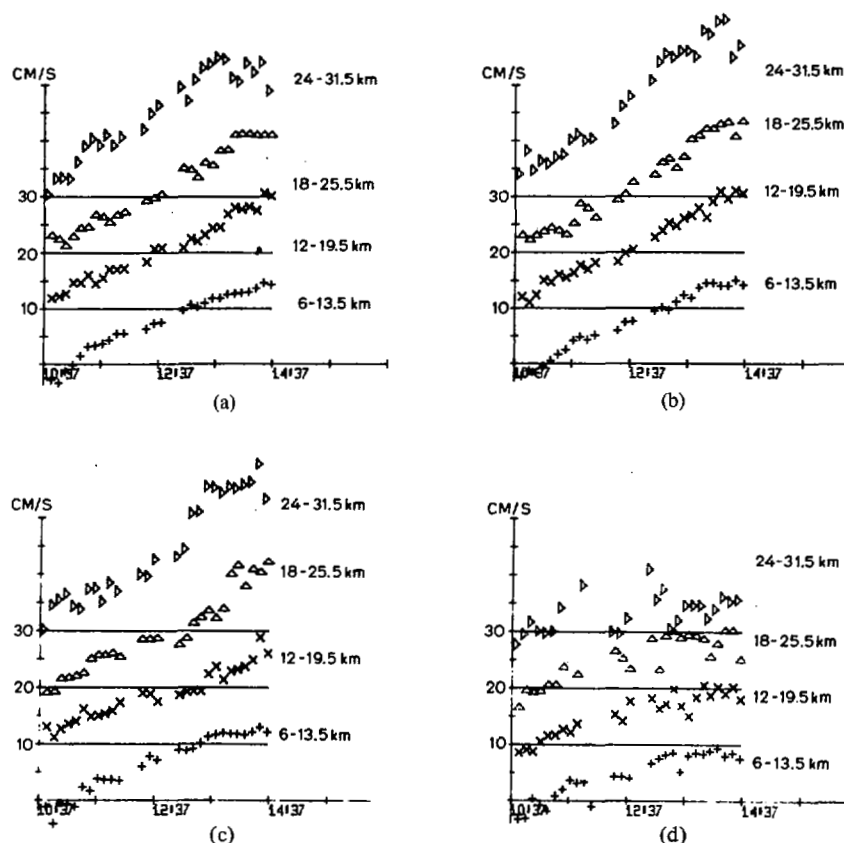


Fig. 2. Radar-inferred depth-averaged current at four range cells versus time during January 25, 1978. Horizontal lines are the baselines for the different range cells (from [8]). (a) 29.75 MHz. (b) 21.7 MHz. (c) 13.3 MHz. (d) 6.8 MHz.

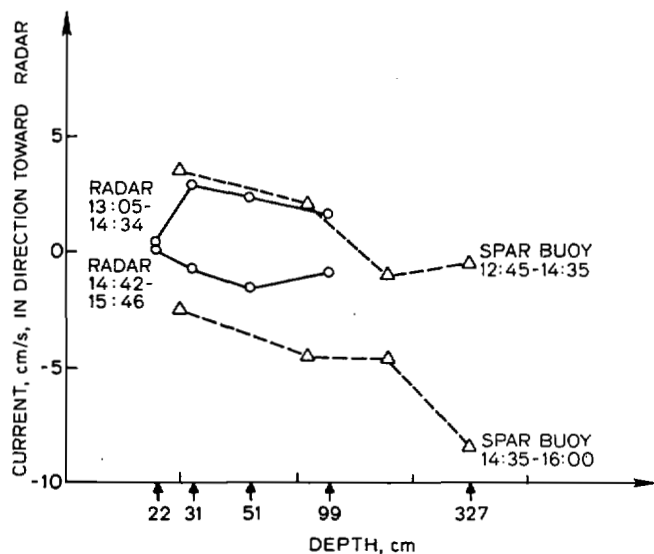


Fig. 3. Comparison of radar-inferred drift and spar-buoy drift (cluster 2) obtained on January 19, 1978. The horizontal axis is logarithmic in depth, and a logarithmic profile is assumed. The approaching Bragg line was used (from [8]).

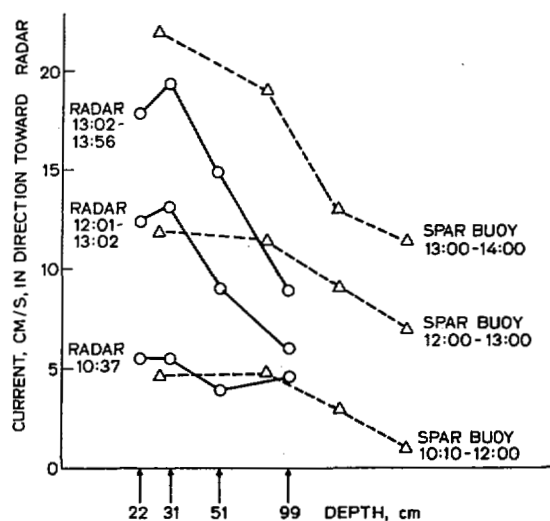


Fig. 4. Comparison of radar-inferred drift and spar-buoy drift (cluster 1) obtained on January 25, 1978. The horizontal axis is logarithmic in depth, and a logarithmic profile is assumed (from [8]).

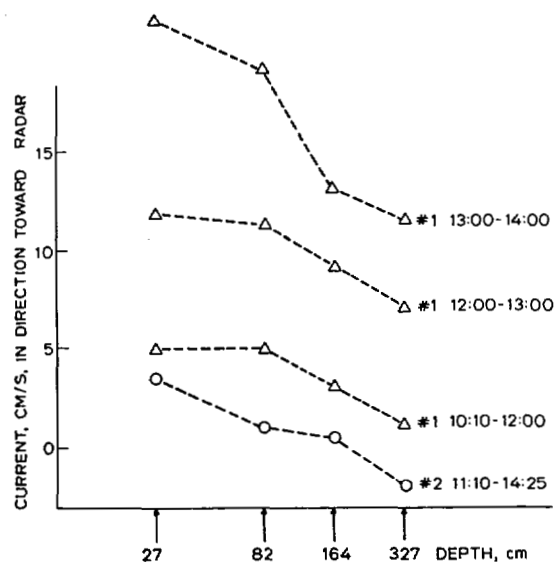


Fig. 5. Variance in drifts of spar buoys released in the same range cell. Cluster 1 was released at 25.8 km from Pescadero, and cluster 2 was released at 20.5 km. Data were collected on January 25, 1978 (from [8]).

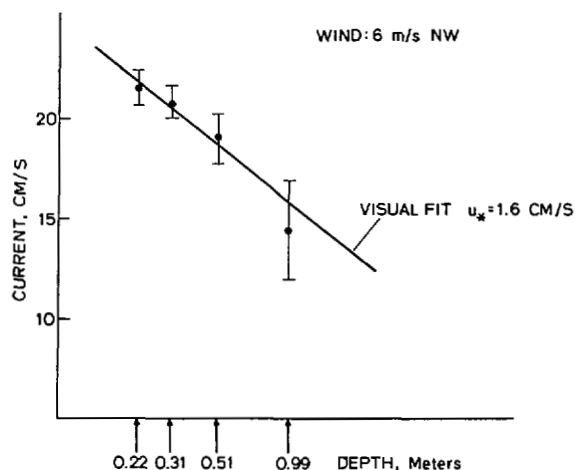


Fig. 6. Logarithmic current shear measured by the four-frequency radar. The horizontal axis is logarithmic in depth, and a logarithmic profile is assumed in the inversion. Vertical bars indicate the resolution limited by a finite-time Fourier transform. Data were obtained at Pescadero at approximately 14:15 to 15:15 local time; range 6-13.5 km (from [8]).

TABLE I

SUMMARY OF PESCADERO RADAR MEASUREMENTS AND WIND- AND WAVE-PREDICTED VALUES FOR THE CURRENT SHEAR

Summary of Measured and Predicted Shears - Pescadero				
Date, 1978	Radar meas.	Total est.	Wind est.	Wave est.
19 Jan	0.91	4.81	1.78	3.03
24 Jan	4.69	2.73	1.55	1.18
24 Jan	9.50	2.73	1.55	1.18
25 Jan	1.07	1.74	1.40	0.34
25 Jan	7.08	1.74	1.40	0.34
25 Jan	9.80	1.74	1.40	0.34
27 Jan	9.95	4.95	3.18	1.77
27 Jan	13.31	4.95	3.18	1.77

The radar values represent the difference in  $\text{cm} \cdot \text{s}^{-1}$  between the current velocities obtained from radar measurements of 5.0- and 22.1-m ocean wave phase velocities. The wind and wave estimates of the shear are based on the difference in current velocities predicted for depths of 21 and 93 cm, respectively. These are the depths at which the 5.0- and 22.1-m waves are coupled to the currents, assuming a logarithmic current profile.

density of the deep ocean water. In addition, daily observations of HF radar backscatter were made throughout the experiment to determine if a vertical current shear could be measured from a platform in the open ocean.

### A. Radar Installation

The four-frequency radar was installed on the R. V. Atlantis-II and measured velocities relative to that platform; ship drift was estimated from the shipboard Loran-C navigation system. The ocean-wave directional spectrum was measured simultaneously with the radar observations by a pitch-roll buoy. The directional spectrum of the ocean waves could also be inferred from the directional distribution of the echo energy arriving at the radar. Several synthetic aperture runs were made, and Elabdalla [7] examined the use of super-resolution spectral estimation techniques to determine the ocean-wave directional spectrum directly from the signals recorded on the individual loop antennas.

The transmitting antenna consisted of a set of quarter-wave vertical radiators and was nominally omnidirectional. Fig. 7 shows the transmitting antenna. System directivity was provided by an array of eight broad-band loop receiving antennas, six on the port side of the ship and two on the starboard side. The six antennas on the port side are shown in Fig. 8, and the individual elements are shown in more detail in Fig. 9. The loop elements, approximately 1 m high, were constructed as half-loops and made use of the ship hull to provide an image half-loop. A wide-band preamplifier was mounted immediately above each loop. The preamplifiers were designed as balanced push-pull amplifiers, using moderate-power cable TV distribution amplifier transistors (2N5109). They were designed to provide low noise and low distortion in the presence of strong interference, and had a third-order intercept point of approximately +10 dB re 1 mW at the input.

The loops were selected, one at a time, by an electronic switch preceding the radar receiver. Thus the signals from the individual loop elements were recorded separately. By varying the relative complex weights applied to the signals from each receiving element, the radar beam could be steered in several directions, so that the velocity measurement could be made in several directions.

The beam formation was done in software in the frequency domain. The total array aperture was approximately 40 m, and the half-power beamwidth was between  $45^\circ$  and  $15^\circ$ , depending on the frequency and direction of steering the array. The azimuthal response of each of the loop elements (in combination with the transmit antenna) was measured by using a transponder on another ship, the R. V. Meteor. The transponder responded linearly to its input power, and retransmitted an amplified, time-delayed, and modulated replica of the signal it received. The modulation allowed the transponder return to be distinguished from any dc bias in the radar IF amplifiers and from ocean echoes, since the modulation frequency was chosen to be different from the ocean Doppler shift. The beam was steered by adjusting the complex weights for each of the loop antennas, and the combined array pattern was computed using the data from the transponder. The weights were adjusted to maximize the ratio of the area of the antenna power



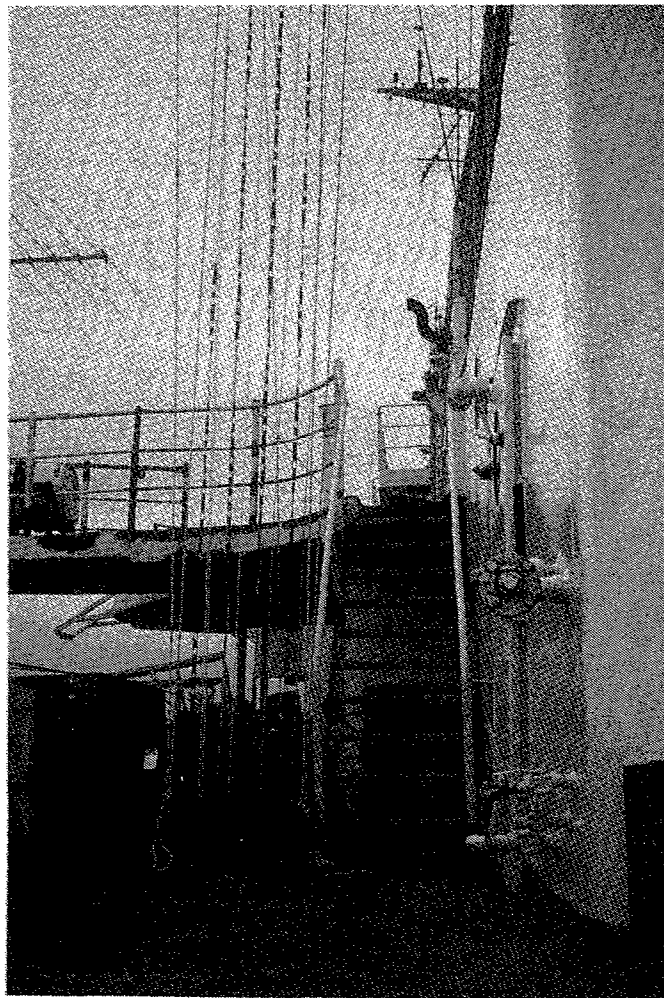


Fig. 7. View of the base of the JASIN transmit antennas. There were four quarter-wavelength antennas, all fed in parallel from a common cable. The ship was used as the ground plane. The elements themselves were made of two-conductor transmission line (with both leads tied together) to lower the  $Q$  of the antenna so that the  $50\text{-}\mu\text{s}$  pulse could be passed without severe distortion caused by a narrow-bandwidth antenna. The elements were suspended from the mast and kept taut by individual ropes.

response pattern in desired directions to its area in all other directions. The shape of the array pattern changed as the beam was steered; it was not a fixed pattern which was simply rotated in space. Fig. 10 shows the antenna power patterns which were achieved at 13 MHz.

The radar was operated on frequencies of 4.80, 6.78, 13.38, and 21.77 MHz, which are in Bragg resonance with ocean waves of length 31.2, 22.1, 11.2, and 6.9 m. Coherent processing of the radar signals for a period of approximately 10 min provided a frequency resolution of 1.6 mHz, from which the Doppler shift of the radar target could be measured with a resolution of  $4.8\text{ cm}\cdot\text{s}^{-1}$  for the longest wavelength and  $1.2\text{ cm}\cdot\text{s}^{-1}$  for the shortest.

### B. Data Processing

The data processing was complicated by the drift of the ship (which was comparable in magnitude to the total current), by the narrow ocean-wave directional spectrum, and by the moderate antenna beamwidth. The straightforward centroid calculation used in the Pescadero experiments could not be

used here. Instead, it was necessary to use a parameter estimation technique based on postulating a model for the shape of the radar frequency spectrum in the immediate vicinity of the Bragg lines, and then adjusting the parameters of the model to achieve a best fit in the least-squares sense. The ocean-wave directional spectrum was taken from the pitch-roll buoy measurements, and the antenna patterns were known from measurements using a transponder. The ship drift was estimated from Loran-C position fixes during each run. The model parameters for current magnitude and direction at each radar frequency were adjusted for a best fit to the observed radar frequency spectra.

The ocean-wave directional spectrum was modeled as a single-peaked distribution of the form  $\cos^s((\theta - \theta_0)/2)$ . The values for the ocean model parameters  $s$  and  $\theta_0$  were obtained from the Scripps pitch-roll buoy measurements, from synthetic aperture HF radar data taken during the experiment, or left as free parameters. Typically, the directional distributions during JASIN had a half-power beamwidth of  $30^\circ$  or less, much narrower than were found by Tyler *et al.* [18] at Wake Island.



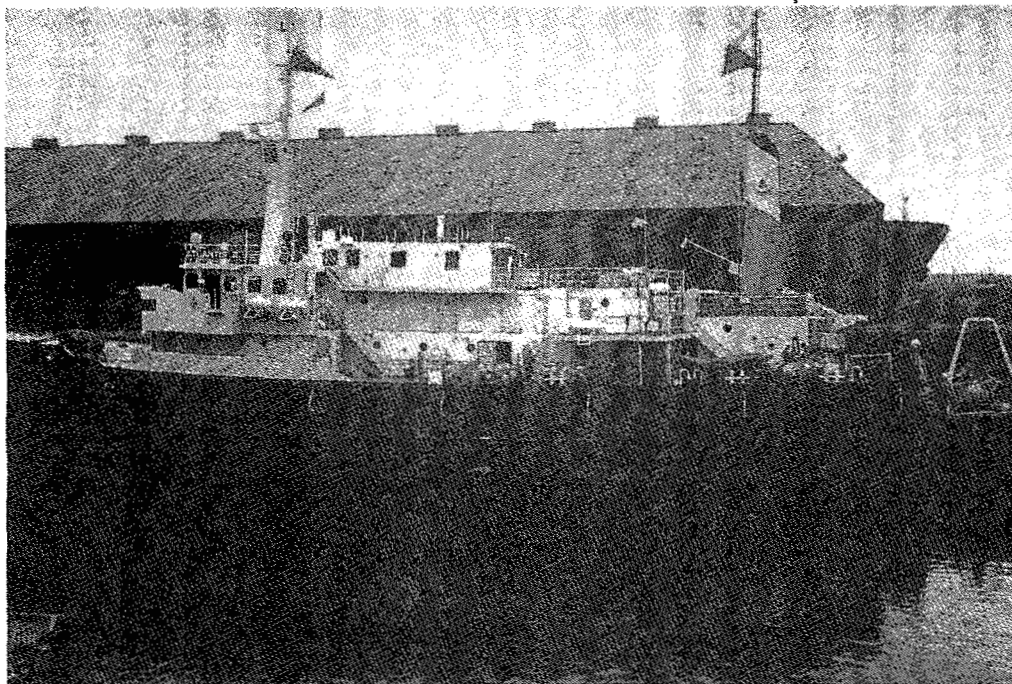


Fig. 8. View of port side of Atlantis-II at the dock in Glasgow. The receiving array is visible along the side of the ship as six light-colored loop antennas (seen edge on), each with an associated preamplifier immediately above the antenna element. The transmitting antenna was not installed at this time.

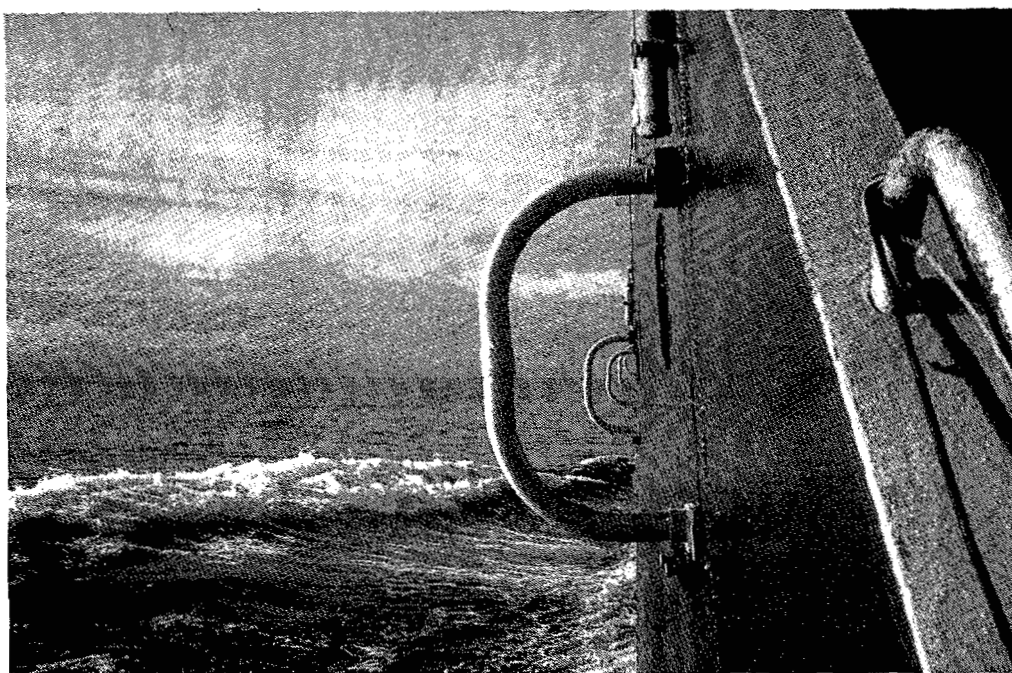


Fig. 9. View along the axis of the receiving array, showing several of the individual elements and preamplifiers. The loops and preamplifiers were broad band, covering the 3-30-MHz range without tuning. The elements were designed so that they could easily be removed from their mounting brackets when the ship docked.

In this case, the effective direction in which a current measurement is made depends more on the ocean directional distribution than on the antenna pattern.

The antenna beam was formed in five different directions

covering a  $90^\circ$  range, and the frequency spectrum of the radar echo was computed for each of these directions. An estimate of the radar echo spectrum was computed based on the ocean-wave directional spectrum, the antenna pattern, and the ship

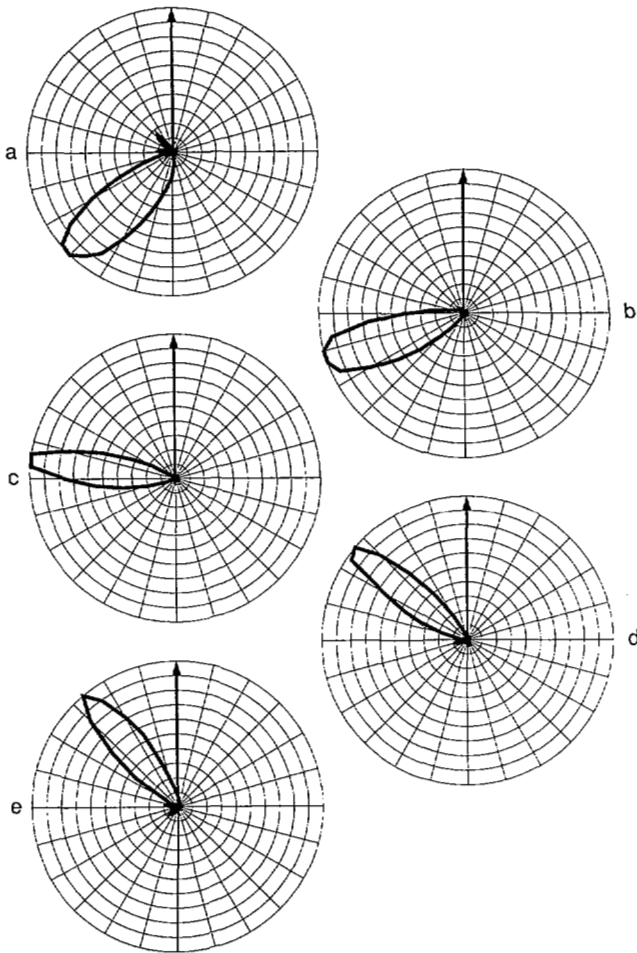


Fig. 10. Plots of the combined transmit-receive pattern at 13.38 MHz. The plots are linear in power. The direction of the bow of the ship is indicated by the arrows. The beam has been steered in all five directions from the same data set by multiplying the signals from the individual elements by appropriate complex weights. The patterns were measured by using a transponder on the Meteor while the Atlantis-II was slowly turned in a circle.

drift, and it was compared to the measured spectrum. An error measure over all five directions was then computed, and this was minimized by varying the parameters of current magnitude and direction (and in some cases the ocean-wave directional spectrum parameters  $s$  and  $\theta_0$  as well) until a minimum overall error was achieved.

Once the apparent current was obtained for each radar wavelength, a linear regression analysis was applied to the radar-inferred current as a function of the logarithm of the ocean wavelength. The shear was taken as the difference in currents given by the intercepts of this line at the minimum and maximum depths probed by the radar. The shear value was retained only if the correlation coefficient of this fit was greater than 0.20, and only if at least three of the four radar frequencies were used (in some cases, individual frequencies were omitted because of strong interference identified by inspection of the smoothed radar frequency spectra). This gave the shears for the individual runs. Finally, the relation between the shear and the wind and wave conditions was examined by applying another linear regression analysis to the daily shear values as a function of the shear predicted by (9)

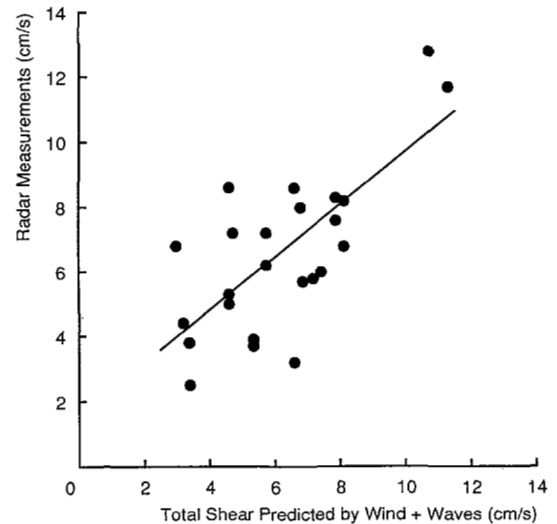


Fig. 11. The radar-measured shear versus the shear predicted by the sum of the wind- and wave-induced components, assuming that they are colinear. The radar shear is the difference in the deviations of the phase velocities from their still-waver values for the 6.9- and 31.2-m ocean waves, averaged over all range bins. The velocity is the difference in current velocity at depths of 30 and 137 cm. These are the depths at which the 6.9- and 31.2-m ocean waves are effectively coupled to the currents if the current distribution is logarithmic with depth. From (6), these can be converted to  $u_{*water}$  by dividing by 3.78. The straight line is the least-squares fit to the data points.

for the waves and by (8) for the wind, and a multiple linear regression analysis was performed against both the wind- and wave-predicted shears.

### C. Results

The results of the JASIN experiment are summarized in Table II and are indicated graphically in Fig. 11. As in the Pescadero experiments, the estimate of the wind- and wave-generated current shear was made with the assumption of a logarithmic current profile.

The wind velocity during JASIN was generally low, reaching  $10 \text{ m} \cdot \text{s}^{-1}$  on only two or three occasions. The wave heights were correspondingly small. Under these conditions, the expected shear generated by the wind and the waves are nearly identical, as indicated in Table II. The radar measurements indicated vertical shears larger than predicted by either the wind alone or the waves alone, but somewhat less than would be expected if the wind- and wave-induced components were assumed colinear and added together. For this data set, the single-variable regression on the waves alone resulted in a slightly higher correlation coefficient than the single-variable regression on the wind alone (0.71 versus 0.70), although the difference is not significant. The two-variable regression on both the wave- and wind-induced shears was slightly better, resulting in a correlation coefficient of 0.72, with the regression equation

$$u_{*radar} = (1.05 \pm 0.80)u_{*waves} + (0.59 \pm 0.71)u_{*wind} + (1.54 \pm 1.18) \quad (10)$$

where  $u_{*radar}$  is calculated from the radar-measured shear through (6),  $u_{*wind}$  is estimated from (8), and  $u_{*waves}$  is

TABLE II  
SUMMARY OF JASIN RADAR MEASUREMENTS AND WIND- AND WAVE-PREDICTED VALUES FOR THE CURRENT SHEAR

Summary of Measured and Predicted Shears - JASIN				
Date, 1978	Radar meas.	Total est.	Wind est.	Wave est.
4 Aug	6.8	2.98	1.34	1.64
5 Aug	7.2	4.72	1.91	2.81
6 Aug	8.0	6.80	3.20	3.60
7 Aug	3.7	5.35	2.34	3.01
7 Aug	3.9	5.35	2.34	3.01
8 Aug	3.8	3.38	1.79	1.59
8 Aug	2.5	3.40	1.80	1.60
10 Aug	5.8	7.19	3.50	3.69
11 Aug	7.6	7.88	3.87	4.01
11 Aug	8.3	7.88	3.87	4.01
13 Aug	6.8	8.13	3.57	4.56
13 Aug	8.2	8.13	3.57	4.56
14 Aug	4.4	3.18	1.72	1.46
24 Aug	6.0	7.43	3.87	3.56
25 Aug	5.0	4.60	2.73	1.87
25 Aug	8.6	4.60	2.73	1.87
25 Aug	5.3	4.60	2.73	1.87
28 Aug	5.7	6.87	3.40	3.47
31 Aug	8.6	6.61	3.51	3.10
31 Aug	3.2	6.61	3.51	3.10
1 Sep	6.2	5.74	2.96	2.78
1 Sep	7.2	5.74	2.96	2.78
5 Sep	11.7	11.29	5.68	5.61
5 Sep	12.8	10.71	5.37	5.34

The radar values represent the difference in  $\text{cm} \cdot \text{s}^{-1}$  between the current velocities obtained from radar measurements of 6.9- and 31.2-m ocean wave phase velocities. The wind and wave estimates of the shear are based on the difference in current velocities predicted for depths of 30 and 137 cm, respectively. These are the depths at which the 6.9- and 31.2-m waves are coupled to the currents, assuming a logarithmic current profile.

estimated from (9), (3), and (6). The standard errors are based on a 90-percent confidence level.

The assumption of a logarithmic profile (4) is generally considered to be an empirical relationship, based on many observations. It is certainly related to the wind, but so is the wave-height directional spectrum. So at least some of the Stokes drift is effectively included in (4), except in the rare case where there is no local wind and the only waves are swell from a distant source. Thus it is very difficult to separate the purely wind-induced shear from the purely wave-induced shear, because the waves themselves are driven by the wind. This may explain why the observed radar shear is somewhat less than the sum of the wind and wave components considered separately.

## VI. SUMMARY AND CONCLUSIONS

The Pescadero experiments demonstrated that a current could be measured by an HF radar, and that its value agreed reasonably well with that measured by *in-situ* drifting spar buoys. In addition, there was evidence of a vertical current shear, both from the radar measurements and from the buoy measurements. The shear was higher than would be expected from the wind and wave conditions at the times of the experiments. The design of the equipment was proven and the data processing techniques were developed in the Pescadero experiments.

The JASIN experiment was an attempt to apply the techniques developed in the Pescadero experiments to the measurement of surface current and current shear in the open ocean. The radar system offered the possibility of making a measurement that no other instrument could make. The radar was successfully installed and operated on board a ship with tolerable interference to the normal shipboard activities. The beam formation of the receiving antenna was done in software in the frequency domain. The steerable antenna proved to be quite rugged and successful. The antenna patterns which were achieved were consistent with the physical aperture of the receiving array.

The wind velocity during all of the JASIN experiment, except during the period when the ship was in port, was much lower than had been expected, so wind- and wave-generated currents were quite small. Nevertheless, there is some evidence of a current shear. Its magnitude is small, however, and it is near the resolution limit of the radar system. There were many steps involved in the data processing, including the Fourier processing of the radar echo signal, the formation of a narrow antenna beam in several different directions at each radar frequency, and the estimation of the Doppler shift of the radar echo by the estimation of four parameters of a model for the ocean directional spectrum (center and width) and relative motion between ship and water (magnitude and direction). Consequently, it is very difficult to compute the overall precision of the radar measurements. The internal consistency of the radar measurements from one range cell to the next suggests a figure of about  $5 \text{ cm} \cdot \text{s}^{-1}$ . Although the two-variable regression indicates that the wave-induced component of shear may have a slightly higher correlation with the radar measurements than the wind-induced component (and this was also the case when individual range bins were processed separately), this may be the result of noisy data. However, as in the Pescadero experiments, the radar measurements indicate a shear higher than would be expected from either component alone.

## ACKNOWLEDGMENT

R. Stewart of the Scripps Institution of Oceanography has worked very closely with Stanford throughout the entire HF radar ocean-wave backscatter research program. The analysis of the data from the Pescadero experiments was performed by E. C. Ha, and the work leading to his dissertation provided the basis for our participation in the JASIN experiment. The JASIN experiment described here required the cooperation of the officers and crew of the R. V. Atlantis-II, operated by the Woods Hole Oceanographic Institution, and the West German R. V. Meteor. The JASIN experiment was coordinated by the British Royal Society. Several individuals at Stanford including T. Howard, K. Price, A. Elabdalla, F. Orabona, and B. Crosby provided invaluable assistance.

## REFERENCES

- [1] D. E. Barrick, "Dependence of second-order sidebands in HF sea echo upon sea state," in *IEEE G-AP Int. Symp. Dig.* (Los Angeles, CA), Sept. 21-24, 1971, pp. 194-197.
- [2] D. E. Barrick, "First-order theory and analysis of MF/HF/VHF scatter

- from the sea," *IEEE Trans. Antennas Propagat.*, vol. AP-20, pp. 2-10, 1972.
- [3] D. E. Barrick, "Remote sensing of sea state by radar," in *Remote Sensing of the Troposphere*, V. E. Derr, Ed. Washington, DC: GPO, 1972, ch. 12.
  - [4] D. E. Barrick, J. M. Headrick, R. W. Bogle, and D. D. Crombie, "Sea backscatter at HF: Interpretation and utilization of the echo," *Proc. IEEE*, vol. 62, pp. 673-680, 1974.
  - [5] D. E. Barrick, M. W. Evans, and B. L. Weber, "Ocean surface currents mapped by radar," *Science*, vol. 198, pp. 138-144, 1977.
  - [6] D. D. Crombie, "Doppler spectrum of sea echo at 13.56 Mc/s," *Nature*, vol. 175, pp. 681-682, 1955.
  - [7] A. M. Elabdalla, "Remote sensing of the directional ocean wave spectra using HF backscatter radar," Ph.D. dissertation, Stanford Univ., Stanford, CA, 1982.
  - [8] E. C. Ha, "Remote sensing of ocean surface current and current shear by HF backscatter radar," Ph.D. dissertation, Stanford Electron. Labs., Stanford Univ., Stanford, CA, Tech. Rep. D415-1, Aug. 1979.
  - [9] K. Hasselmann, "Feynman diagrams and interaction rules of wave-wave scattering processes," *Rev. Geophys.*, vol. 4, pp. 1-32, 1966.
  - [10] K. Hasselmann, "Determination of ocean wave spectra from Doppler radio return from the sea surface," *Nature, Phys. Sci.*, vol. 229, pp. 16-17, 1971.
  - [11] K. E. Kenyon, "Stokes drift for random gravity waves," *J. Geophys. Res.*, vol. 74, no. 28, pp. 6991-6994, 1969.
  - [12] B. Kinsman, *Wind Waves*. Englewood Cliffs, NJ: Prentice-Hall, 1965.
  - [13] H. Lamb, *Hydrodynamics*. New York: Dover, 1932.
  - [14] M. S. Longuet-Higgins and O. M. Phillips, "Phase velocity effects in tertiary wave interactions," *J. Fluid Mech.*, vol. 12, pp. 333-336, 1962.
  - [15] R. H. Stewart, "A discus-hulled wave measuring buoy," *Ocean Eng.*, vol. 4, pp. 101-107, 1977.
  - [16] R. H. Stewart and J. W. Joy, "HF radio measurement of surface currents," *Deep-Sea Res.*, vol. 21, pp. 1039-1049, 1974.
  - [17] C. C. Teague, G. L. Tyler, and R. H. Stewart, "Studies of the sea using HF radio scatter," *IEEE Trans. Antennas Propagat.*, vol. AP-25, pp. 12-19, 1977.
  - [18] G. L. Tyler, C. C. Teague, R. H. Stewart, A. M. Peterson, W. H. Munk, and J. W. Joy, "Wave directional spectra from synthetic aperture observations of radio scatter," *Deep-Sea Res.*, vol. 21, pp. 989-1016, 1974.
  - [19] M. D. Van Dyke, *An Album of Fluid Motion*. Stanford, CA: Parabolic, 1982.
  - [20] B. L. Weber and D. E. Barrick, "On the nonlinear theory for gravity waves on the ocean's surface, Parts I and II," *J. Phys. Ocean.*, vol. 7, pp. 3-21, 1977.
  - [21] J. Wu, "Wind-induced drift currents," *J. Fluid Mech.*, vol. 68, part 1, pp. 49-70, 1975.



**Calvin C. Teague** (S'62-M'68) was born in Oakland, CA, on September 3, 1941. He received the B.S., M.S., and Ph.D. degrees in electrical engineering in 1963, 1964, and 1971, respectively, from Stanford University, Stanford, CA.

Currently he is a Senior Research Associate at Stanford University, where his research has concerned the application of HF Bragg scattering techniques to the measurement of directional ocean wave spectra, ocean currents, and current shear. He is currently involved in the design and operation of a network of several large general-purpose computers and personal workstations. He has also been engaged in the design and installation of automatic weather stations in the Antarctic, and the design of special-purpose Fourier processing hardware for radar and radio astronomy applications. While a student at Stanford he was a National Science Foundation Fellow during 1963-1966 and a Research Assistant during 1966-1968 and 1970-1971. He has worked at the Hewlett-Packard Company in Palo Alto, CA, and Böblingen, West Germany, SRI International in Menlo Park, CA, and Philco-Ford Corporation in Palo Alto, CA. He has been at Stanford since 1970.

Dr. Teague is a member of Commission F of the International Union of Radio Science, the American Geophysical Union, Phi Beta Kappa, and Tau Beta Pi.