A COMPARISON OF NEAR-SURFACE CODAR AND VACM MEASUREMENTS IN THE STRAIT OF JUAN DE FUCA, AUGUST 1978

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Because of the highly unconventional way CODAR measures and maps surface currents, i.e., by reflecting high frequency radar waves from 6-m long ocean waves, the obvious question to someone unfamiliar with the system is: does it really measure currents, and how accurately? In each of more than ten CODAR experiments done to date, independent estimates of currents were obtained for comparison with CODAR. Early experiments used Lagrangian drifters, drogued to one meter depth, the layer within which CODAR feels the mean current. Such comparisons of typical mean velocities obtained from a 1/2-hour Lagrangian track with a 36-min CODAR observation every hour over a 2 x 2 km radar-cell area produced standard deviations between the two of approximately 15 cm/s. Not all of this, of course, is due to error in each or both techniques, but to the different nature of the two measurements.

The following paper is a comparison of still a different nature entirely. Assuming that the tidal component of circulation differs little with depth from the surface to some ten meters, comparisons are made here of tidal current coefficents obtained by CODAR and current meters, filtered from the time-series data over several days. This type of study, done by a lead author at NOAA's Pacific Marine Environmental Laboratory (which has had no direct involvement in the development of CODAR) shows even less standard deviation between the two measuring systems when these tidal current coefficients are compared.

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A Comparison of Near-Surface CODAR and VACM Measurements in the Strait of Juan De Fuca, August 1978

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Three days of simultaneous near-surface current measurements made by Coastal Ocean Dynamics Applications Radar (CODAR) and surface-moored Vector-Averaging Current Meters (VACM) in the Strait of Juan de Fuca are compared. The study focuses on the mean flow and tidal components that contained approximately 79% of the kinetic energy. The mean speed and direction differences were less than 7 cm/s and 10°, respectively. The K_1 and M_2 tidal constituents agreed to within 14 cm/s with a mean difference of 5.2 cm/s. This study demonstrates that CODAR yields estimates of the near-surface currents that are comparable with conventional VACM arrays to 10–15 cm/s.

INTRODUCTION

Near-surface circulation patterns in estuarine and coastal environments are highly variable, being influenced by a wide variety of physical processes and forces. Until recently, conventional methods of sampling the near-surface current regime were confined primarily to drifter-tracking and surface-moored vector-averaging current meters (VACMs). These techniques are limited by poor spatial and temporal resolution as well as by contamination caused by improper coupling with and sampling of the fluid medium. In 1977, a new measurement technique was introduced that allowed the mapping of surface currents with two shore-based HF radar units [*Barrick et al.*, 1977]. Since its introduction, this sytem, called CODAR for Coastal Ocean Dynamics Applications Radar, has demonstrated its potential and promises to enhance significantly our understanding of near-surface coastal circulation and the forces that drive this complex regime [*Frisch and Weber*, 1980; *Frisch et al.*, 1981].

There are, however, important questions concerning CODAR's accuracy and comparability with more conventional techniques. *Barrick et al.* [1977] reported reasonable agreement between surface currents measured by CODAR and trackable floating drifters in the Gulf Stream off Florida. The reported rms difference was 27 cm/s; however, subsequent analyses showed that experimental errors in both sets of measurements were limiting factors. *Frisch and Weber* [1980] reported that rms differences of ~15 cm/s were found between CODAR and drifter observations made over 24 hours in lower Cook Inlet. In these studies, drifter velocities were affected to an unknown extent by wind and wave effects, temporal sampling differences, and inherent problems associated with comparing Lagrangian and Eulerian measurements. To date, no known current meter intercomparisons with CODAR have been reported.

During August 1978, an intensive set of CODAR measurements was made over a 3-day period in the eastern Strait of Juan de Fuca. These observations were obtained in support of a 3-month experiment to describe and characterize water circulation in the strait. Portable HF CODAR units were located at New Dungeness Spit and Point Wilson (Figure 1). These sites allowed current mapping over a ~500 km² area, which contained two surface moorings with AMF VACM's in the upper 20 m of the water column.

This report compares near-surface VACM currents at sites A and B with surface currents acquired by CODAR during its 3-day period of operation. Although perfect agreement between CODAR and VACMs should not be expected owing to

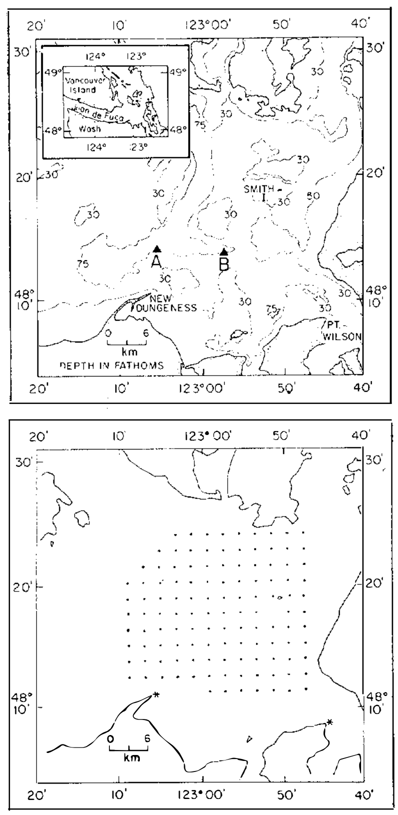

Fig. 1. Location diagram showing positions of surface moorings (A and B) containing VACMs (top) and CODAR grid coverage (bottom) in the eastern Strait of Juan de Fuca. CODAR shore installations (asterisks) were located at New Dungeness Spit and Point Wilson. Contours are in fathoms.

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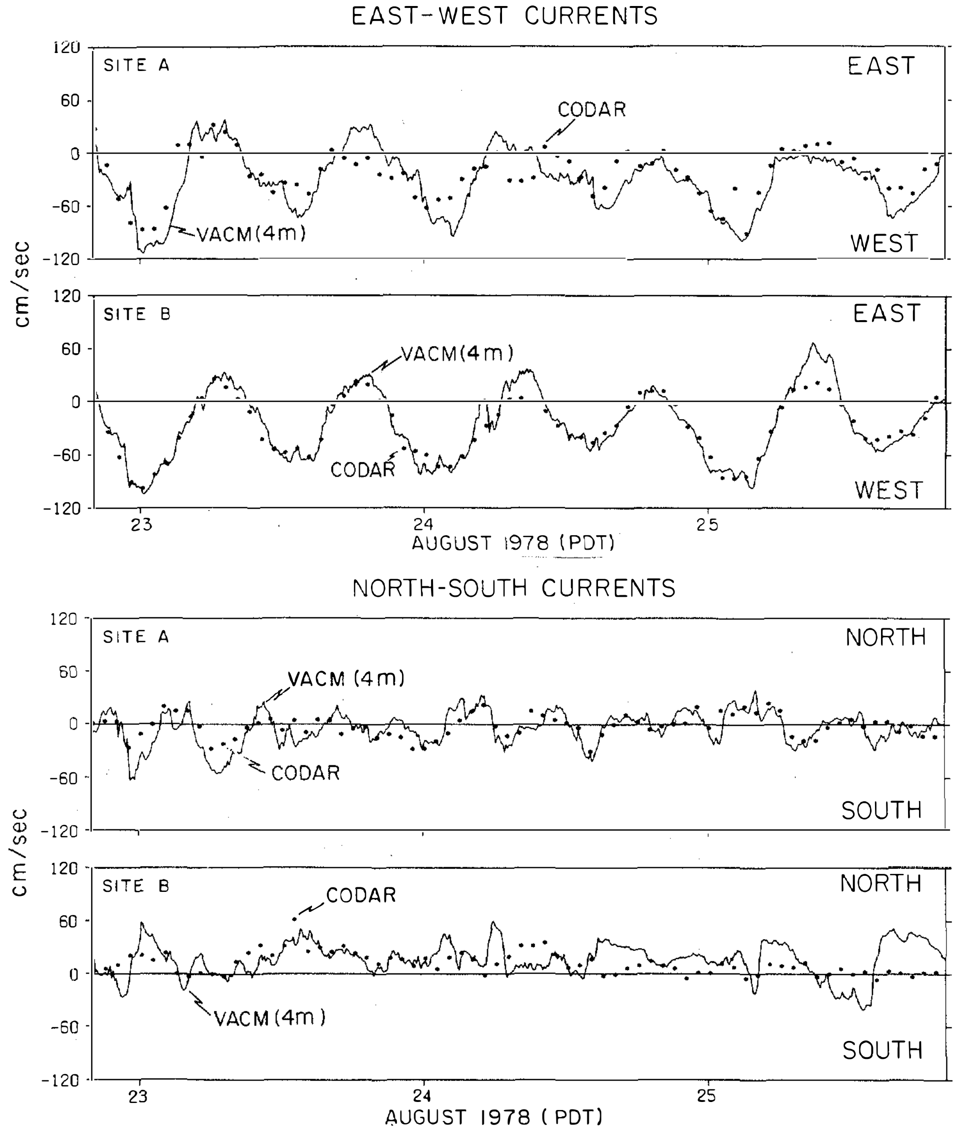

Fig. 2. Time series of east-west and north-south components of 7.5-min in values of VACM/4 m (solid lines) and hourly values of CODAR measured surface currents (dots) at sites A and B.

differences in spatial sampling, this study does demonstrate that CODAR and VACM current statistics are comparable.

OBSERVATIONS

CODAR operates on the principle that when the ocean surface is radiated with HF electramagnetic waves, a weak return signal results due to first-order Bragg scattering from surface waves whose wavelength (~6 m) is equal to one-half the transmitted wavelength [*Crombie*, 1972]. By measuring the echo Doppler shift, the CODAR system can resolve the velocity component of the scattering wave train measured radially from the antenna location, which to first-order consists of the

TABLE 1. Summary of Kinetic Energy Distribution at 4 m Depth at Sites A and B During Summer Conditions

Location	Mean	Subtidal (<0.60 cpd)	Diurnal (0.79–1.03 cpd)	Semidiurnal (1.82–2.04 cpd)	Remainder	Total
Site A/4 m						
E-W	391	47	251	715	127	1531
N-S	16	20	34	9	165	244
Total	407	67	285	724	292	1775
Site B/4 m						
E-W	338	61	214	591	110	1314
N-S	42	68	34	46	131	321
Total	380	129	248	637	241	1635

Kinetic Energy $(cm/s)^2$. Values were computed from 41-day VACM time series beginning on July 16.

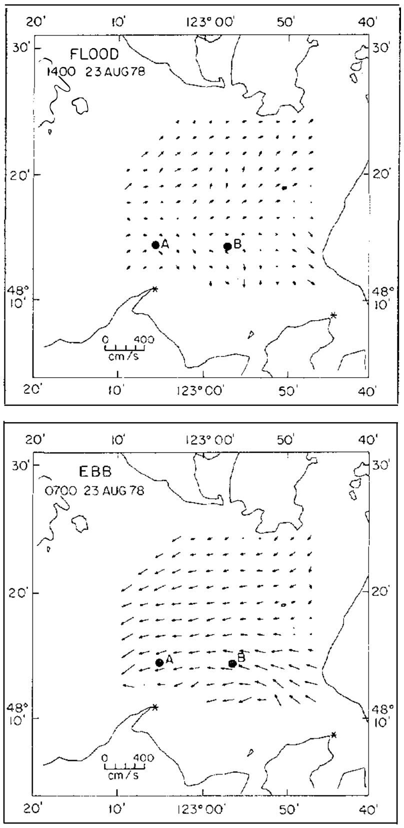

Fig. 3. CODAR maps of typical ebb and flood currents patterns. Mooring positions are denoted by circles.

sum of the radial components of the wave phase velocity and the underlying current field in the upper meter of the water column [*Barrick et al.*, 1977]. By sampling the Doppler shift over successive time steps as a function of return signal azimuth and by subtracting the deep water phase velocity, a map of radial components of surface velocity can be computed for each shore installation. Two properly spaced shore stations allow maps of the two-dimensional surface velocity field to be computed over the region of overlap. Theoretically, the accuracy of the CODAR current measurements is ~5 cm/s [*Barrick et al.*, 1977].

The CODAR measurement period lasted from 2200 LT August 22 to 2200 LT August 25, 1978. Hourly maps of surface current vectors were obtained over a 2.4 km grid spacing by recording Doppler shift data over 38 min at the beginning of each hour. Although calm sea states were observed during the experiment, the signal-to-noise ratio of the back-scattered return was at all times large enough to discern a Doppler shift. Signal and data processing were carried out as outlined by *Barrick et al.* [1977].

Time series measurements of near-surface currents were recorded at sites A and B by AMF VACMs suspended at 4, 10, and 20 m depths below taut-line surface moorings in water depths of 136 and 138 m, respectively. The VACMs continuously sampled current speed with a Savonious rotor and direction by a small vane. Vector averages of the east-west and north-south components were computed internally over 7.5-min intervals and stored on magnetic tape [*McCullough*, 1975]. Current meter intercomparisons have shown that the effect of a surface-following buoy upon VACM velocity fluctuations is negligible at frequencies less than 0.3 cph [*Halpern et al.*, 1981]. Later comparisons are made by using VACM time series computed by vector-averaging over 37.5 min intervals beginning each hour corresponding to the CODAR sampling scheme.

Time series plots of the east-west and north-south components of hourly CODAR and 7.5 min VACM/4m currents are shown in Figure 2. The time series are characterized by strong east-west tidal oscillations where maximum speeds reached 118 cm/s and by much weaker north-south variations.

CIRCULATION BACKGROUND

Circulation in the eastern Strait of Juan de Fuca is composed of three dominant modes: (1) quasi-steady gravitational convection, (2) atmospherically forced low-frequency motion, and (3) tidal oscillations [*Holbrook et al.*, 1980]. Gravitational convection consists of a vigorous two-layer estuarine circulation with a net seaward (westward) flowing surface layer with maximum speeds of ~30 cm/s and a landward (eastward) flowing deep layer with typical speeds of ~10 cm/s. This circulation pattern is maintained by the sea-surface slope, the internal density field, and vertical mixing. Atmospherically forced low-frequency motions have time scales of 3–20 days, are highly dependent upon both local and nonlocal winds, and vary with depth. At 4 m depth the wind induced currents have been observed to reach 20–30 cm/s in response to wind speeds of 20 m/s [*Holbrook et al.*, 1980]. Tidal oscillations are by far the most energetic signal that occurs in the eastern Strait. The M_2 and K_1 constituents are the largest with amplitudes reaching 60 and 30 cm/s, respectively. Both diurnal and semi-diurnal tidal currents are generated by sea-level fluctuations at the mouth of the Strait.

The distribution of kinetic energy in the eastern strait computed from 41-day records during summer conditions is tabulated in Table 1. Approximately 83% of the total kinetic en-

TABLE 2. Mean and Variance Statistics of 72-Hour CODAR and VACM Time Series

		East-West		North-South		Vector	
Location	Series	Mean (cm/s)	Variance (cm/s)^2	Mean (cm/s)	Variance (cm/s)^2	Speed (cm/s)	Direction (°TN)
A	CODAR	−23.6	748	−2.1	166	23.7	265
	VACM/4 m	−30.3	1119	−4.4	310	30.6	262
	VACM/10 m	−28.5	1376	−0.5	370	28.5	269
	VACM/20 m	−24.1	1477	−3.6	241	24.4	262
B	CODAR	−28.6	1054	11.7	154	30.9	292
	VACM/4 m	−25.8	1421	16.3	310	30.5	302
	VACM/10 m	−23.9	1331	13.2	217	27.3	299
	VACM/20 m	−17.2	1258	10.7	174	19.9	302

TABLE 3. Correlations (R) and Linear Regression ($Y = A + B \cdot X$) Coefficients Between CODAR and VACM/4 m Currents

Location	Y Series	X Series	Comp	R	A	B	rms Difference (cm/s)
A	CODAR	VACM/4 m	E-W	0.79	−4.1	0.64	16.9
A	CODAR	VACM/4 m	N-S	0.68	0.1	0.50	9.5
B	CODAR	VACM/4 m	E-W	0.96	−7.3	0.83	9.2
B	CODAR	VACM/4 m	N-S	0.17	9.7	0.12	12.2

ergy is contained in the east-west component. Of this, ~23% is contained in the mean flow, ~6% at low-frequencies (f<0.60 cpd), ~16% in the diurnal frequencies (0.79–1.03 cpd), and ~40% in the semidiurnal frequencies (1.82–2.04 cpd). The remainder, which accounts for ~15%, represents fluctuations that are associated with small-scale eddies and higher-frequency turbulence. The comparison results presented in the next section focus on the energy rich mean flow and tidal oscillations, which account for ~79% of the total kinetic energy.

A consequence of the dominant circulation modes is that during periods of low wind stress, flood tidal patterns tend to be weak and variable in the surface layer, while ebb patterns are stronger and more spatially coherent. For example, water ebbing from Puget Sound past Point Wilson behaves as a jet with large current speeds caused by to the confined channel. Figure 3 shows the horizontal distribution of typical flood and ebb patterns as measured by CODAR. These current maps provide a qualitative picture of the spatial complexity of circulation in the eastern strait.

COMPARISON RESULTS

Statistics of the 72-hour time series are given in Table 2. CODAR and VACM/4m vector-averaged east-west and north-south components were within 7 cm/s of each other. The differences between vector-averaged speed and direction were less than 7 cm/s and 10°, respectively. The variation in the mean VACM statistics in the upper 20 m was comparable to the VACM/4m and CODAR mean differences.

The variance contained in the CODAR observations was ~30% lower than the VACM/4 m variance. This may be expected, since CODAR currents are spatial averages over 5.8 km² and VACM currents are point measurements. First-order estimates of the reduction in variance that may result from spatial averaging can be made by using the statistics shown in Tables 1 and 2. Approximately 50% of the variance difference can be accounted for by assuming that the higher-frequency fluctuations were filtered out by averaging.

Linear regression coefficients are given in Table 3. Strong correlations existed in the more energetic east-west components. Some 62 and 92% of the CODAR variance was linearly related to VACM/4 m variance at sites A and B, respectively. The amplitudes of the CODAR currents were 17–36% lower than the VACM/4 m data as indicated by the slope of the regression fit. The correlation between the north-south components was poorer, reflecting the smaller tidal signal to total variance ratio. The rms error associated with the regression fit ranged from 9 to 17 cm/s.

The K_1 and M_2 tidal constituents were computed for each series by least squares fitting sine functions at frequencies of 1.00 and 1.93 cpd, respectively, to determine amplitude and phase (Table 4). Values obtained from this fit are consistent with tidal constituents obtained by harmonic analysis of 29-day records [*Holbrook et al.*, 1980]. The differences between CODAR and VACM/4 m amplitudes were less than 14 cm/s and averaged 5.2 cm/s. The poorest comparison occurred for the east-west M_2 constituent at site A, where the vertical M_2 shear as measured by the VACMs was strong. Phase differences were within 1.2 (18°) and 0.3 (9°) hours for the energetic east-west components of the K_1 and M_2 constituents, respectively. Phases for the north-south component varied widely owing to the weak signal strength.

Comparison between surface currents measured by CODAR and near-surface currents measured by VACMs may be biased by the near-surface vertical current shear, which results from the combined effects of gravitational circulation, local wind forcing, and baroclinic tides. In the eastern strait, vertical stratification was linear in the upper 50 m with typical gradients of 2.5 10^{-5} gm/cm³/m. Shown in Figure 4 are vertical profiles of east-west and north-south currents at site A during a 24-hour period commencing at 0000 LT August 23. Also plotted are CODAR currents at the surface. Typically, the current shear was of the order of 1 cm/s/m; thus ~4 cm/s difference may be expected between CODAR and VACM/4 m currents due to shear. However, large differences occurred that were inconsistent with the VACM shear. For example,

TABLE 4. Summary of Amplitude (U_0) and Phase (θ) Computed by Least Squares Fitting $U = U_0 \sin (t/T - \theta)$ to Each Time Series

		Amplitude (cm/s)				Phase (Degrees)			
		East-West		North-South		East-West		North-South	
Location	Series	K_1	M_2	K_1	M_2	K_1	M_2	K_1	M_2
A	CODAR	15.4	29.0	3.4	4.3	222	151	313	269
	VACM/4 m	14.2	42.4	2.9	2.6	224	142	44	254
	VACM/10 m	15.2	47.0	4.5	10.8	217	143	69	297
	VACM/20 m	16.2	50.6	6.7	5.4	215	149	163	270
B	CODAR	16.9	43.7	3.7	2.8	202	148	211	2
	VACM/4 m	21.0	50.0	6.2	14.7	220	147	90	265
	VACM/10 m	19.6	48.7	4.8	14.9	219	144	69	261
	VACM/20 m	18.6	46.8	1.0	12.5	200	143	186	253

K_1 and M_2 periods (T) were 23.93 and 12.42 hours.

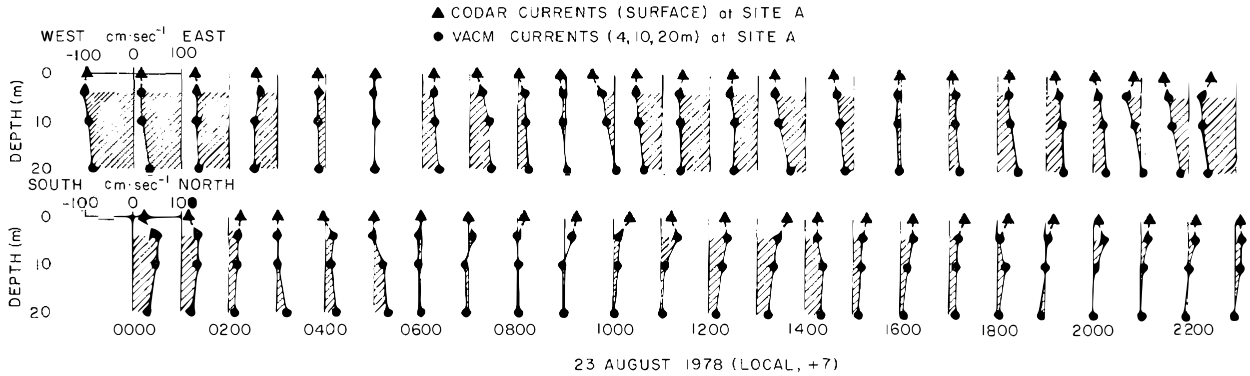

Fig. 4. 24-hour time series of hourly profiles showing typical near-surface current shear at site A.

during the 24-hour period shown in Figure 4, the sign of the east-west shear between 4 and 10 m was in the right direction to give a better extrapolated VACM surface current in 12 profiles and in the wrong direction for the other 12 profiles. The shear was strongest during tidal flow changes.

Local winds did not play an obvious role in modifying the near-surface currents and thus bias the comparison. Wind speeds measured at New Dungeness Spit were generally <4 m/s, except during 1800 LT August 23 to 1200 LT August 24 when easterly winds reached 10 m/s. During this period, flooding currents (eastward) were weaker at the surface than at 4 m depth, suggesting possible wind influence; however, ebbing currents were not similarly enhanced. During periods when winds were weak, current differentials of similar strength (20–50 cm/s) were measured that were seemingly unrelated to wind effects.

Conclusions

We have shown that the east-west component of CODAR and VACM near-surface currents were well correlated with a regression error of 9–17 cm/s over the 3-day comparison period. The most energetic portion of the frequency spectrum occurred at diurnal and semidiurnal periods, where the K_1 and M_2 constituents agreed to within 14 cm/s with a mean difference of 5.2 cm/s. The comparison of mean statistics showed that speed and direction differences were less than 7 cm/s and 10°, respectively. This overall agreement is better than previous reported drifter/CODAR comparisons [*Barrick et al.*, 1977; *Frisch and Weber*, 1980].

It must be remembered, that CODAR measurements represent flow in the upper meter of the water column averaged over a surface area of 5.8 km^2. It is this area average that was compared with point measurements at the mooring sites. Whether we can expect better agreement is questionable, since the spatial distribution of currents over scales small compared to the grid scale of 2.4 km is very complex, being affected by turbulence, fronts, eddies and shoal regions.

This study demonstrates that CODAR measured currents are comparable to estimates of the near-surface flow measured by conventional VACM arrays to within 10-15 cm/s. Coordinated experiments using both techniques hold great promise in unraveling complex and poorly understood surface circulation features in the critical coastal and estuarine environment.

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