Comparison of Upper Ocean VACM and VMCM Observations in the Equatorial Pacific*

DAVID HALPERN**

School of Oceanography and Department of Atmospheric Sciences, University of Washington, Seattle, WA 98195

(Manuscript received 8 January 1986, in final form 9 May 1986)

ABSTRACT

Measurements from a Savonius rotor and vane vector-averaging current meter (VACM) and dual orthogonal propeller vector-measuring current meter (VMCM) placed 1 m apart beneath a surface-following buoy moored on the Pacific equator for 6-month intervals are described. Experiments at 13, 98, 120 and 160 m depths were completed in light winds ($\approx 5 \text{ m s}^{-1}$), small surface wave heights (1–2 m), strong current speeds (monthly averaged speeds $\approx 65 \text{ cm s}^{-1}$) and large current shears (0.01 s^{-1}). Excellent coherence was found between each VACM-VMCM doublet's data. As expected, the near-surface VACM recorded slightly larger speeds ($\approx 10\%$ for monthly mean 15-min vector-averaged values) than the VMCM. The only kinetic energy density mismatch at the 95% confidence level was between the 13–14 m dyad and occurred above 1.3 cph. The most striking feature of these intercomparison tests was that the VACM and VMCM observations were virtually identical below the near-surface layer. Below 98 m the average rms amplitude difference within a decadal frequency interval was $<1 \text{ cm s}^{-1}$. The average maximum usable frequency and mean frequency of the 50% noise level were 1.8 and 1.5 cph, respectively.

1. Introduction

Long-term, upper ocean current measurements in deep water regions are usually made from a relatively inexpensive, easily deployable (and recoverable) mooring system involving a surface-following float which moves horizontally and vertically to follow the contour of the sea surface. Uncertainties in moored current measurements arise from mooring motion, surface wave motions, inadequacies of the sensors, and from complex, not fully understood, unpredictable interactions between them. Vertical motions of a wave-following float are transmitted nearly undiminished throughout the instrumented upper portion of the mooring because wire rope is used for protection against fishbite.

Most current meters are designed to measure horizontal flows; they have poor response to the vertical flows caused by the surface-following buoy. Surface wave and buoy motions affect the measurements because of 1) the speed sensor's sensitivity to vertical tilt caused by the sensor's imperfect cosine response, 2) overspeeding of the speed sensor, 3) speed and velocity sensors measuring over a range of depths where the vector velocity profile is not constant, and 4) fluctuations of a vane with limited time response alters measurement of current direction. The frequency at which measurement error caused by the composite effect of

surface wave motions and mooring motions becomes negligible is unknown. The accuracy of moored current measurements recorded in the upper ocean beneath a surface-following buoy is difficult to determine because of the lack of suitable reference measurements. Thus, comparison of different current meters or of the same current meters placed on different platforms have substituted for accuracy tests.

A Savonius rotor (Savonius, 1931) and vane vector-averaging current meter (VACM; manufactured by EG&G Sea-Link) and dual orthogonal propeller vector-measuring current meter (VMCM; manufactured by EG&G Sea-Link) were paired vertically (with 1 m separating the sensors) beneath surface-following buoys moored for approximately 6-month intervals in the east central equatorial Pacific Ocean. Intercomparison tests were made at 13–14 m and 98–99 m (April–October 1983) and 120–121 m (April–October 1984) at 0° , 110°W (called 110°W) and 160–161 m (April–October 1984) at 0° , 140°W (called 140°W) (Table 1). The objective of these comparison tests was to examine the performance of a VACM operating in the equatorial Pacific relative to a VMCM. The latter according to laboratory tests (Weller and Davis, 1980) and in situ data in midlatitudes (Halpern et al., 1981) is indicated to be more accurate.

2. Instrumentation

Current meter observations were made from a long, compliant, single-point, taut-line (scope ≈ 0.98), compound mooring with a toroidal surface float (net buoyancy $\approx 3000 \text{ kg}$) supporting meteorological and

* Contribution Number 1688 of the School of Oceanography, University of Washington.

** Present affiliation: Earth and Space Sciences Division, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109.

aids-to-navigation instrumentation. Seven VACMs (and sometimes 1–5 Sea Data temperature recorders and 1–2 VMCMs) were placed in the mooring line. The uppermost 750 m of the mooring line consisted of nonrotating plastic coated wire rope, primarily to avoid severe fishbite damage. Rigid cable fairing was clipped onto the upper 250 m of the mooring line to reduce 1) vortex shedding and cable strumming (Every et al., 1982) and presumably the amount of rotor-pumping produced by cable vibrations, 2) fatigue failure of wire terminations and 3) mooring line drag force produced by the swiftly flowing currents. Approximately 2800 m (110°W where the water depth is 3700 m) and 3450 m (140°W where the water depth is 4400 m) of nylon rope (prestretched to 1600 kg) was used between the end of the wire at 750 m depth and ≈ 75 m above the anchor. Below the nylon were a backup recovery system of glass spheres and an EG&G Sea-Link acoustic release.

During 20 January–2 May 1979, the tilt angles from vertical were recorded at 110°W with Humphrey model CP 17 precision pendulums (resolution = 0.8°) added to several VACMs. Mean ($\pm$ standard deviation) tilt angles increased with depth from 2.7° ($\pm 1.5^{\circ}$) at 50 m to 9 – 10° ($\pm 3.5^{\circ}$) at 150, 200 and 250 m. If the mooring line tilt angle increased linearly from the surface to 150 m, then the tilt angles expected during expts. I, II and perhaps III corresponded to less than a 3% correction factor for estimating Savonius rotor speeds. Because of the stronger current and current shear occurring in 1979, the mooring line tilts in 1983 and 1984 were probably smaller. Thus, no correction was applied to any of the records described herein.

The VACM measures polar components of the velocity field with a 16×18 cm Savonius rotor to sense speed, a 9×17 cm pivoted vane to sense current direction, and a magnetic compass to record direction of the instrument relative to magnetic north. The magnetic declination was 9° at both sites. The rotor is omnidirectional and unidirectional, i.e., it always spins the same way regardless of the direction of the current. Every $\frac{1}{8}$ rotor revolution, corresponding to approximately 5 cm of fluid displacement, the sine and cosine of the flow direction relative to magnetic north are computed from compass and vane measurements and accumulated over the recording interval in east–west (u ; positive eastward) and north–south (v ; positive northward) registers to produce time-averaged u and v displacements (McCullough, 1975). At a current speed of 50 cm s^{-1} , the VACM samples at the rate of about 11 samples per second. This rapid sampling scheme is intended to avoid aliasing high frequency oscillatory current components due to waves or mooring motions. Laboratory tests have shown that the response time of a VACM-caged Savonius rotor was twice as fast for decelerating flows than for accelerating flows (Saunders, 1980); in a shear flow this can rectify vertical mooring displacements into apparent currents and in

a high frequency wave environment this can produce overspeeding. The relatively sluggish 1.5-second time constant of the vane direction causes the VACM to overestimate currents in the presence of high frequency oscillating velocities (Kalvaitis, 1974).

The VMCM continuously measures averaged orthogonal components of the flow with two highly accurate cosine response, unshrouded, 22 cm diameter propeller sensors mounted orthogonally along a shaft (Weller and Davis, 1980). A compass determines the orientation of the instrument relative to magnetic north. Every $\frac{1}{4}$ revolution of one of the propellers, corresponding to approximately 10 cm of fluid displacement parallel to a propeller axle, the sine and cosine of the instrument heading are determined and added to appropriate registers so that at the end of a recording interval the u and v registers contain the displacement components of horizontal velocity. About 5 samples per second are recorded in a 50 cm s^{-1} speed.

Mechanical degradation of the VACM and/or VMCM bearings was expected to be most severe near the surface. Insufficient evidence of this type of error was found, assuming that the difference in speed measurements between the instruments would increase with time. The 13 m VACM and 14 m VMCM monthly mean differences of 15-min vector-averaged speeds were about 2.3 cm s^{-1} less during the final 3 months than during the first 3 months of observations.

Potential sources of error are greater in the VACM than in the VMCM. Inertial response of the VACM rotor and vane system tend to produce overestimates of the speed when measurements are made in a wave environment and/or from a surface-following buoy. The VMCM directly measures the horizontal components of flow, unlike the VACM which requires a nonlinear transformation of polar coordinate data. The cosine response of the VMCM propeller is more accurate than the VACM rotor. While laboratory tests conducted in composite steady and unsteady flows indicate that VACM and VMCM errors occur when the ratio of the mean flow to the maximum unsteady velocity was less than 3, the VMCM error was less than the VACM and the VMCM (VACM) error decreased (increased) as the mean current decreased relative to the amplitude of the oscillating flow (Weller and Davis, 1980).

3. Data processing

The sampling rate of the VACM and VMCM measurements was 15 min. Spectral estimates of the u and v [called $S(u)$ and $S(v)$] time series with zero mean value and zero least-squares linear trend were computed from a Cooley–Tukey fast Fourier transform algorithm (Brenner, 1967) using the Daniell frequency window of variable width w . The Daniell spectral window is equal to the arithmetic mean of successive non-overlapping w periodogram estimates; the resulting

spectral estimates have a chi-square distribution with $2w$ degrees of freedom. For each u and v spectrum the sum over positive frequencies was equal to the total variance. The horizontal kinetic energy density (KED) spectrum, defined as $[S(u) + S(v)]/2$, was equivalent to the frequency distribution of one-half the variance of the vector-averaged current speed. The average root-mean-square (rms) amplitude of u or v current fluctuations within a frequency band Δf (f = frequency) is equal to the square root of the sum of the spectral estimates within Δf multiplied by Δf ; the amplitude of the fluctuation is equal to $\sqrt{2}$ times the rms amplitude. The maximum usable frequency (muf) is defined as the frequency beyond which two spectra diverge and the spectral difference is significant with 95% confidence.

The coherence is a measure of consistency or stability of the relative phase angle between the same frequency constituents of the two time series. The magnitude of the coherence function represents the frequency distribution of the correlation coefficient and the phase difference determines lead or lag relationship. A positive phase difference indicates that the VACM series leads the VMCM series by a time interval equal to the inverse of the frequency multiplied by the ratio of the phase difference to 360° . The noise and/or nonlinear relationship between two series is defined by the quantity $1 - C^2$ where C is the magnitude of the coherence function and $100C^2$ is the percentage of the total variance explained by a linear relationship. Velocity fluctuations are usually not considered to be linearly related if the coherence is below the 50% noise level (i.e., $C < 0.71$), even if the coherence is greater than the 95% confidence limit. Because the coherence magnitude typically decreases with increasing frequency, the frequency of the 50% noise level generally represents the high frequency limit of the linear relationship between the VACM and VMCM measurements.

4. Overview of environmental conditions

a. Surface wind and wave conditions

At 110°W and 140°W the vector-mean wind directions measured from the buoys during April–October 1984 were southeasterly and easterly, respectively. Monthly averaged speeds and directions were similar to the 1947–72 climatological-mean wind distribution computed by Wyrski and Meyers (1976). Record-length mean 15-min speed values were 3.8 m s^{-1} (110°W) and 5.4 m s^{-1} (140°W). Winds were steady and without the occurrence of intense storms having high winds and waves. The magnitudes of the variability of 15-min vector-averaged speed observations, as measured by the standard deviations, were 48% (110°W) and 31% (140°W) of the mean values. Throughout the April–October 1984 tests (and similarly for the tests in 1983) the winds were light, with the maximum 15-min av-

eraged value less than 10.5 m s^{-1} and with less than 1% of the 15-min speeds greater than 9 m s^{-1} .

Surface wave observations were made along the equator between 110°W and 140°W from research vessels. During April and October, 1983 and 1984, the average sea and swell heights were less than 1 and 2 m, respectively. On several occasions waves reached heights of about 4 m. Light airs and calm seas were typical. At times when ships were not present to record wave data, the typical local wind wave height inferred from the moored wind observations was less than 1 m height. For linear surface waves the amplitude of the water particle velocity (u') at depth z is equal to $a(2\pi)/T \exp(-4\pi^2 z/gT^2)$, where a , g and T are wave amplitude (i.e., one-half crest-to-trough height, $H = 2a$), gravity and wave period, respectively. Assuming that observed wave heights represented maximum values so that the upper limit of u' is considered, then u' for $H = 1 \text{ m}$ (and $T = 4$ seconds, Sverdrup et al., 1942) is 4 cm s^{-1} at 13 m and $<1 \text{ cm s}^{-1}$ below 18 m. For $H = 2 \text{ m}$, $u' = 24 \text{ cm s}^{-1}$ at 13 m and $<1 \text{ cm s}^{-1}$ below 42 m. The 15-min vector-averaged speed values recorded by the 13 m VACM were typically much greater than the u' associated with 1–2 m surface waves, e.g., only about 0.3 and 8.8% of the 18 360 speed samples were less than 4 and 24 cm s^{-1} , respectively.

b. Oceanographic conditions

Because current meters cannot occupy the same location in a mooring, the natural variability in the sea limits the agreement to be expected. The experiments described herein were made in the westward flowing South Equatorial Current and eastward flowing Equatorial Undercurrent; on many occasions speeds were greater than 150 cm s^{-1} . The vertical distributions of mean and standard deviation values of the upper ocean current field during the intercomparison tests are shown in Fig. 1; profiles of mean temperature are also displayed.

In experiment I, a VACM/VMCM doublet at 13–14 m at 110°W was placed near the bottom of the thermal mixed layer, which was not always present, or at the top of the thermocline (defined arbitrarily as the region between the 25 and 15°C isotherms where the temperature gradient was about 0.1°C m^{-1}), and in a region of very low vector-mean zonal currents but of large speed (Table 1). As indicated by the record-length standard deviation of u , which was 17 times larger than the mean value, the magnitude of the variations of the near-surface currents at 10–15 m depths was many times greater than the annual mean. Because the 1982–83 El Niño Southern Oscillation (ENSO) episode continued in the far eastern Pacific until about July 1983, higher than normal currents and temperatures occurred at 110°W during this test. The April–October 1984 data represented the typical non-ENSO condition. At 110°W and 140°W the near-surface currents are typ-

FIG. 1. Mean values of (a) east-west velocity (u ; positive eastward); (b) north-south velocity (v ; positive northward), and (e) temperature. Standard deviations of (c) u and (d) v . Depths of intercomparison tests shown by triangles.

ically eastward in March, April and May, reaching a maximum monthly averaged speed of about 60 cm s^{-1} . In May 1983 (experiment 1), the near-surface monthly averaged zonal current was greater than 125 cm s^{-1} , perhaps as a result of the highly anomalous westerly winds associated with the ENSO episode. In addition to large annual and interannual variations of

the near-surface zonal current, the meridional component contained 21-day oscillations with an amplitude of about 50 cm s^{-1} which decreased rapidly with depth.

In experiment II, a doublet was placed near 100 m depth at 110°W where the mean temperature was about 16°C , which is near the bottom of the thermocline. During this test, which was made about 25 m

below the Equatorial Undercurrent core depth, the mean vector-averaged speed was 71 cm s^{-1} and the mean variability was 25 cm s^{-1} .

Experiment III consisted of a VACM/VMCM doublet placed at 110°W at 120 m in weakly stratified water. The mean zonal current at 120 m was about 20% less than the corresponding value at 98 m; the record-length mean meridional components at 120 and 98 m were equal to within 1 cm s^{-1} .

In experiment IV, which occurred at 160 m depth at 140°W , the mean zonal current was midway between the values at 120 and 98 m. The mean v speeds in experiments II, III and IV were virtually the same. The range of the mean variability of the current during experiments II, III and IV was $14\text{--}19 \text{ cm s}^{-1}$.

These experiments occurred in regions of very large vertical mean shears. From 13 to 50 m, the mean depth-averaged shear was 0.021 s^{-1} , and between 75 and 98 m and 98 and 150 m the mean shears were 0.005 and 0.006 s^{-1} , respectively. At 160 m the mean shear was about 0.007 s^{-1} . Thus, with a 1-m separation between the VACM and VMCM sensors, the natural variation of the mean flow field induces a velocity difference between the instruments in each doublet, which would be about 2 cm s^{-1} near the surface (experiment I) and 0.5 , 0.6 , and 0.7 cm s^{-1} during experiments II, III, and IV, respectively. Because of small-scale shear of about 0.03 s^{-1} associated with internal waves and turbulence (Gregg et al., 1985), the shears (and consequently the flow differences) occurring at each doublet would most likely be larger than the mean depth-averaged values.

In summary, large speeds (average = 65.3 cm s^{-1}) and shears (average = 0.01 s^{-1}) occurred during the intercomparison tests. Currents were unsteady in direction at 13–14 m and very steady at 98, 120 and 160

m. Surface wave orbital velocities were nonexistent at the depths of experiments II, III and IV, and in experiment I they were small to moderate compared to the current.

5. Results

a. Experiment I: 13 m VACM and 14 m VMCM

Throughout the observational period the daily averaged VACM and VMCM u and v speeds were very similar, except in mid-May when the largest differences ($\approx 25 \text{ cm s}^{-1}$) occurred in the v -component and were concurrent with zonal speeds greater than 150 cm s^{-1} (Halpern, 1986). While the VACM record-length vector mean u -component was five times larger than the VMCM value (Table 1), the standard deviations differed by only 7%. A similar result was found for the vector mean v speeds: the VACM mean value was ten times larger than the VMCM data (Table 1), yet the standard deviations differed by less than 13%. The record-length VACM mean 15-min averaged speed was 11% greater than the VMCM (Table 1).

Throughout the frequency range the VACM KED spectral estimates were slightly greater than the VMCM measurements (Fig. 2A), suggesting that the VACM overresponds and/or the VMCM underresponds to velocity fluctuations. At frequencies less than 1 cycle per hour (cph), the maximum ($\approx 25\%$) discrepancy of spectral levels occurred in the v speeds at the lowest resolvable spectral frequency ($1.3 \times 10^{-3} \text{ cph}$ or ≈ 1 month time scale); however, because of the corresponding spectral levels of the VACM and VMCM u -component, which were equivalent and nearly ten times greater, the speed spectral level difference was

TABLE 1. Statistical summary of 15-min vector-averaged current measurements recorded by VACM and VMCM dyads during four intercomparison tests. Dates: A = 24 April–1 November 1983 (191.3 days); B = 18 April–15 October 1984 (180.5 days); C = 27 April–24 October 1984 (180.0 days). Locations: X1 = $00^\circ 03'\text{N}$, $109^\circ 10'\text{W}$ (buoy T34); X2 = $00^\circ 03'\text{N}$, $109^\circ 51'\text{W}$ (buoy T42); X3 = $00^\circ 05'\text{S}$, $140^\circ 15'\text{W}$ (buoy T43). Nominal positions of X1 and X2 are 0° , 110°W and of X3 is 0° , 140°W . The S/N = current meter serial number. Velocity components: east–west = u (positive eastward); north–south = v (positive northward); speed = $s = [(u^2 + v^2)^{1/2}]$. Standard deviations of u , v and s are u_{SD} , v_{SD} and s_{SD} . The $f_{50\%NL}$ is the frequency of the 50% noise level. The muf is the maximum usable frequency. The frequency of the semidiurnal tidal current is $f = M_2$. The record-length rms deviation was calculated with 15-min and daily averaged data.

Experi- ment	Current meter (depth, type, S/N)	Date	Loca- tion	Mean value			Standard deviation			muf	$f_{50\%NL}$ (cph)	rms deviation				rms ($f = M_2$) amplitude	
				u	v (cm s ⁻¹)	s	u_{SD}	v_{SD} (cm s ⁻¹)	s_{SD}			u		v		u	v (cm s ⁻¹)
												15 min	24 hr	15 min	24 hr		
I	13 m, VACM, V363 14 m, VMCM, 2203	A	X1	-4.1	5.2	69.2	71.1	32.6	37.0	1.3	1.3	7.9	7.6	10.0	9.7	1.50	0.98
				-0.8	0.5	61.8	65.5	28.4	35.7							1.41	0.87
II	98 m, VACM, V242 99 m, VMCM, 3505	A	XI	71.0	-3.5	73.4	18.6	17.4	17.8	>2.0	1.5	4.1	3.9	4.1	3.9	1.57	0.86
				67.5	-0.0	69.7	18.7	17.1	18.3							1.61	0.88
III	120 m, VACM, V242 121 m, VMCM, 3505	B	X2	57.6	-2.9	60.2	19.9	15.7	18.4	>2.0	1.3	4.5	4.4	6.0	5.9	1.91	1.17
				53.7	2.4	56.2	20.4	15.0	19.3							1.92	1.08
IV	160 m, VACM, V460 161 m, VMCM, 2203	C	X3	66.5	-2.6	67.8	12.8	12.9	12.6	>2.0	>2.0	3.9	3.7	2.5	2.3	1.42	1.25
				63.0	-1.5	64.3	13.4	12.6	13.3							1.52	1.24

FIG. 2. Kinetic energy density spectra of VACM (solid line) and VMCM (dashed line) measurements recorded 1 m apart at (a) 13–14 m, (b) 98–99 m, (c) 120–121 m, and (d) 160–161 m. The 95% represents the 95% confidence levels determined from the chi-square distribution applicable to each curve.

reduced to about 15%. At frequencies less than 1.3 cph, the VACM and VMCM KED spectral estimates were equivalent within 95% confidence limits, though the differences were not purely random because the VACM values were consistently larger than the VMCM values. The muf was about 1.3 cph. Above 1.3 cph (to the 2 cph Nyquist frequency, defined as 1 cycle per 2 times the sampling interval and which is the high frequency limit of spectral coverage), the average spectral level of the VACM speeds (rms amplitude $\approx 1.2 \text{ cm s}^{-1}$) was about 50% greater than the VMCM data. The VACM KED spectra contained a distinct spectral flattening (i.e., a less rapid decrease of spectral estimates with increasing frequency) above about 1.5 cph. The continuing decrease in the spectral values of the VMCM data at frequencies greater than 1.5 cph indicated that

during this experiment the VMCM spectrum was a better approximation to the true spectrum in this frequency band, presumably because the VMCM was the more effective vector averager.

Throughout the frequency range the coherences of the Cartesian velocity components were statistically significant at the 95% confidence level and the phase differences were essentially zero (Fig. 3A). For time scales greater than the semidiurnal period, the coherence was extremely high (>0.95) and the noise level was nearly zero. The frequency of the 50% noise level was about 1.3 cph.

b. Experiment II: 98 m VACM and 99 m VMCM

The VACM mean values were larger than VMCM measurements: u speeds differed by 3.5 cm s^{-1} or 5%, and v speeds also differed by 3.5 cm s^{-1} (the mean VMCM v speed was 0.0 cm s^{-1}). Unlike the mid-May situation at 13–14 m, there was no instance of substantial difference between daily averaged values. The mean variability recorded by the different instruments was virtually equal: the u standard deviations (Table 1) agreed to within 1%, similarly for v .

Throughout the entire frequency range 0.0011–2.0 cph, KED spectral estimates (Fig. 2B) computed from the VACM and VMCM records were virtually identical, indicating that the muf was greater than 2 cph. No evidence of a spectral flattening was seen (except perhaps above 1.7 cph on both series). Agreement between these spectra at frequencies below the muf was better than between the MILE 92 m VACM and 94 m VMCM spectra and the JASIN 79 m VACM and 85 m VMCM (Halpern et al., 1981), where VACM and VMCM spectral estimates differed by about 100% and where in each case the muf was about 2 cph.

Throughout the entire frequency range the velocity fluctuations were statistically coherent within 95% confidence limits, with 1.5 cph being the frequency of the 50% noise level and with zero phase difference below 0.5 cph (Fig. 3B). The change of phase difference with frequency above 0.5 cph was time dependent. Monthly estimates of coherence displayed a pattern of nonzero phase differences after about the third month and this pattern was most prominent during the sixth month; the coherence magnitude also decreased from the first through the last month. For frequencies at and below the semidiurnal tidal frequency, the month-to-month complex coherency function was unchanged ($C \approx 0.98$ and phase difference $\approx 0^\circ$).

c. Experiment III: 120 m VACM and 121 m VMCM

The VACM record-length mean zonal current was 3.9 cm s^{-1} or 7% greater than the VMCM data (Table 1). The mean meridional speeds (Table 1) had different

FIG. 3. Coherence and phase difference between closely spaced VACM and VMCM pairs at (a) 13–14 m, (b) 98–99 m, (c) 120–121 m, and (d) 160–161 m. The three horizontal lines on the coherence magnitude plot represents the 95% confidence limits (Thompson, 1979). A positive phase difference corresponds to fluctuations occurring earlier at the VACM than the VMCM.

directions, illustrating the difficulty of measuring small mean v flows in the presence of 1) strong u speeds where the ratio of the mean zonal to meridional components was about 20, 2) large u and v fluctuations, and 3) instrument direction uncertainties. The VACM and VMCM u and v standard deviations (Table 1) differed by less than 3 and 5%, respectively. The KED spectral values (Fig. 2C) were equivalent to within 95% confidence limits. While the muf seemed to be higher than 2 cph, the VACM and VMCM u spectral estimates above about 1.7 cph increased with higher frequencies. The two series were 95% statistically coherent throughout the frequency range with a 50% noise level at about 1.3 cph and zero phase difference below 0.5 cph (Fig. 3C). During the first month of measurements the phase differences were zero throughout the range. A departure from zero phase difference at frequencies greater than 0.5 cph became noticeable in the third month, and was substantial in the sixth month. The uniform change of the complex coherency function phase difference above

0.5 cph to nonzero values seemed to be related to a particular VACM-VMCM doublet, which, by coincidence, was identical in experiments II and III. Fouling by marine organisms was virtually nonexistent at these depths. It is tempting to speculate that the phase difference behavior was caused by a slowing of the VACM clock relative to the VMCM clock because the VACM lagged the VMCM data. By the end of the 180–190 day experiments the VACM's ± 1 sec per day time base could yield a 3 min delay, which was similar to the ≈ 4 min delay inferred from the near-Nyquist frequency phase differences in Figs. 3B and C. Unfortunately, the current meter clocks were not adequately checked upon recovery to verify this speculation.

d. Experiment IV: 160 m VACM and 161 m VMCM

Because the VACM and VMCM differences were expected to be largest at our deepest comparison test (Gould et al., 1974; Halpern et al., 1981), the quality

FIG. 4. Daily averaged 160 m VACM and 161 m VMCM u (upper panel) and v (lower panel) velocity components at 0° , 140°W .

of the 160–161 m time series is shown in Fig. 4. The VACM recorded a higher mean u value by 3.5 cm s^{-1} or 5%; the mean v speeds were within 1.2 cm s^{-1} (Table 1). The standard deviations of u (and v) differed by less than 1 cm s^{-1} or 5% (Table 1). This excellent agreement is highlighted by the KED spectral estimates (Fig. 2D), which are virtually identical throughout the entire frequency range. Above about 1.7 cph the VACM and VMCM u spectral estimates no longer decreased with increasing frequency but remained constant; the v spectra did not contain this feature. Apparently the muf was greater than 2 cph. Throughout the entire frequency range the coherence was 95% statistically significant with zero phase difference (Fig. 3D). The phase difference patterns during the first and sixth months of measurements were very similar. The frequency of the 50% noise level was above 2 cph, which was the Nyquist frequency of the test.

e. Summary

Table 1 presents a statistical summary of the current measurements from the four experiments. A VACM typically, but not always, recorded higher speeds than a VMCM. The average VACM record-length mean values of u and v were about 1.6 cm s^{-1} larger, which

because of the ambient vertical shear is reduced to about $0\text{--}1 \text{ cm s}^{-1}$, or about 2% of the average mean value. The average record-length VACM u and v standard deviation was about 1.2 cm s^{-1} higher, or 4.5%, of the average VMCM standard deviation value. The record-length rms deviations between the 15-min or 24-h averaged values were nearly twice as large for the 13–14 m doublet compared to the three other doublets. The average deviation between VACM and VMCM estimates of the rms amplitude of the semidiurnal tidal current components, which were 95% statistically significant during each test, was 0.01 cm s^{-1} or 1.0% of the average u and v rms amplitude. Examination of Table 1 shows that while mean differences throughout each observational period were small, the best agreement was found at the deepest intercomparison depth and largest differences occurred near the surface.

Comparison of the spectra indicated clearly that the VACM and VMCM rms amplitude of current fluctuations with time scales from $\sim 1000 \text{ h}$ to 1 h were very similar. The rms amplitude differences are perhaps a more useful measure of similarity. The average ($\pm$ standard deviation) rms amplitude differences (rad) were computed from the spectral estimates shown in Fig. 2. Of all the rad values, only two were greater than 1 cm s^{-1} . These were associated with the two lowest frequency spectral estimates of the 13 m VACM and 14 m VMCM doublet and were equal to 5.4 cm s^{-1} at 0.00121 cph (829 hours) and 2.2 cm s^{-1} at 0.00340 cph (294 hours). The smallness of all other spectral differences (Table 2) indicates that these VACM and VMCM measurements made beneath a surface-following buoy were comparable to tenths of millimeters per second, especially below the depth of direct surface wave influence.

Better agreement occurred between VACM and VMCM deep spectra than near the surface. Near the surface, the lower spectral energies and the continuing decrease in the spectral levels at high frequencies of the VMCM data (Fig. 2A) indicated that during the experiment the VMCM spectrum may better approximate the true spectrum of currents. It is doubtful whether a perfect current meter would record the true

TABLE 2. Decadal frequency distribution of average $\pm$ standard deviation of rms amplitude differences (rad) between VACM and VMCM data. The number of spectral estimates is n .

Time scale (h)	n	13–14 m	98–99 m	120–121 m	160–161 m
(cm s ⁻¹)					
829–100	5	1.89 ± 1.88	0.05 ± 0.20		
785–100	4			-0.03 ± 0.08	-0.04 ± 0.10
100–10	41	0.09 ± 0.08	-0.00 ± 0.04		
100–10	39			0.01 ± 0.03	-0.02 ± 0.04
10–1	94	0.03 ± 0.02	-0.01 ± 0.01		
10–1	89			0.01 ± 0.01	-0.01 ± 0.01
1–0.5	50	0.06 ± 0.01	-0.00 ± 0.00		
1–0.5	48			0.01 ± 0.01	0.00 ± 0.00

FIG. 5. Distribution of monthly averaged least-square orthogonal regression line coefficients computed between 15-min vector-averaged VACM and VMCM values of (a) speed and (b) direction as a function of monthly averaged speed. The long- and short-dashed lines represent the coefficients' mean and standard deviation values, respectively.

spectrum of currents (Von Zweck and Saunders, 1981). Because the energy levels at high frequencies can be a direct measure of the noise introduced into the record by aliasing, resolution of measurement, mooring and surface wave motions, and other errors, the lower energy of the 14 m VMCM indicated that it contained a lesser amount of spurious currents than the VACM.

Least-square orthogonal regression lines, which minimize the sums of the squares of the perpendicular deviations from the regression line, were computed for 30-day nonoverlapping, consecutive segments of 15-min vector-averaged VACM-VMCM pairs of speed and direction values. The monthly averaged regression line coefficients are shown in Fig. 5. For the 24 months of data (i.e., four experiments of 6 months duration each) the average ($\pm$ standard deviation) orthogonal regression lines were

$$\begin{aligned} \text{VMCM}(\text{cm s}^{-1}) = & [-5.4(\pm 3.1)(\text{cm s}^{-1})] \\ & + [1.013(\pm 0.062) \text{VACM}(\text{cm s}^{-1})] \end{aligned}$$

and

$$\begin{aligned} \text{VMCM}(\text{degrees}) = & [-2.9(\pm 5.7)(\text{degrees})] \\ & + [1.017(\pm 0.035) \text{VACM}(\text{degrees})]. \end{aligned}$$

Within the 30–130 cm s^{-1} range of the monthly averaged speeds, the typical 15-min VACM speed was 4–5 cm s^{-1} higher than the corresponding VMCM value, or 3–4 cm s^{-1} higher if the influence of the natural shear is considered. The average difference between the 15-min VACM and VMCM speeds was $\approx 4\%$ of the monthly mean speeds recorded during the four experiments. The regression line coefficients were essentially independent of the monthly averaged speed (Fig. 5). Largest differences between VACM and VMCM regressed data occurred in experiment I: the VACM was greater by 4 cm s^{-1} at 30 cm s^{-1} and by as much as 12 cm s^{-1} at 130 cm s^{-1} . The speed regression lines associated with experiments II, III and IV were nearly identical, with the VACM-VMCM difference decreasing from 4 cm s^{-1} at 30 cm s^{-1} to less than 2 cm s^{-1} at 130 cm s^{-1} . The 15-min vector-averaged direction pairs computed from the measured u and v data were, on the average, equivalent to within 3° ; below 170° the VACM direction was slightly larger and above 170° the opposite was found. The average correlation coefficient between speed or direction pairs was 0.98, indicating that nearly all of the variance of the 15-min VACM data can be explained by a linear relationship between the VACM and VMCM records and that the

amount of scatter about each speed or direction regression line was very small.

6. Conclusions

During the April–October periods in 1983 and 1984, four experiments were carried out to evaluate the similarity of upper ocean VACM and VMCM measurements and to examine how deep can reliable VACM measurements be made beneath surface-following buoys moored in deep water on the equator in the Pacific Ocean. Each experiment consisted of a VACM placed 1 m above a VMCM. Experiments II, III and IV demonstrated that VACM and VMCM sensitivities to surface wave and mooring motions were essentially equivalent, while experiment I at 13–14 m depth showed that a VACM was slightly more affected by these high frequency motions than a VMCM. One explanation for the nearly perfect 1:1 correspondence between VACM and VMCM data recorded in experiments II, III, and IV was that at these depths the surface wave and swell generated water velocities were negligible ($<1 \text{ cm s}^{-1}$) compared to the ambient current speeds. In experiment I, the $5\text{--}15 \text{ cm s}^{-1}$ velocities produced by the surface wave field apparently influenced the VACM to a slightly greater extent than the VMCM. In the middle latitude tests described by Halpern et al. (1981), the signal-to-noise ratio decreased rapidly with depth producing increased VACM-VMCM differences with depth.

Acknowledgments. I am extremely grateful to Andrew Shepherd (Pacific Marine Environmental Laboratory, PMEL) and Douglas Fenton (SeaMarTec, Inc.) for maintaining the current meters and moorings, Paul Freitag (PMEL) for processing the data, and Jean Newman (University of Washington) for preparing many of the diagrams and statistical data. This paper is a contribution to the U.S. TOGA Project Office, NOAA's EPOCS (ERL Grant 8K2A2002) and NSF's TROPIC HEAT (OCE-8521510) programs; financial

and logistical support from these programs to acquire and analyze these data is gratefully appreciated.

REFERENCES

- Brenner, N. M., 1967: Three Fortran programs that perform the Cooley–Tukey transform. Tech. Note 1967-2, Lincoln Laboratory, M.I.T., Bedford, MA, 29 pp.
- Every, M. J., R. King and D. S. Weaver, 1982: Vortex-excited vibrations of cylinders and cables and their suppression. *Ocean Eng.* **9**, 135–157.
- Gould, W. J., W. M. Schmitz and C. Wunsch, 1974: Preliminary field results for a Mid Ocean Dynamics Experiment (MODE-0). *Deep-Sea Res.* **21**, 911–932.
- Gregg, M. C., H. Peters, J. C. Wesson, N. S. Oakey and T. J. Shay, 1985: Intensive measurements of turbulence and shear in the Equatorial Undercurrent. *Nature*, **318**, 140–144.
- Halpern, D., 1986: Preliminary results of four VACM-VMCM dyads in the upper ocean of the equatorial Pacific. *Proceedings of the IEEE Third Working Conference on Current Measurements*, W. Woodward, Ed., Institute of Electrical and Electronics Engineers, New York, NY, 13–18.
- , R. A. Weller, M. G. Briscoe, R. E. Davis and J. R. McCullough, 1981: Intercomparison tests of moored current measurements in the upper ocean. *J. Geophys. Res.* **86**, 419–428.
- Kalvaitis, A. N., 1974: Effects of vertical motion of vector-averaging (Savonius rotor) and electromagnetic type current meters. Technical Memorandum NOAA-TM-NOS-NOIC-3, NOAA, Rockville, MD, 32 pp.
- McCullough, J. R., 1975: Vector-averaging current meter speed calibration and recording technique. Tech. Rep. 75-44, WHOI, Woods Hole, MA, 35 pp.
- Saunders, P. M., 1980: Overspeeding of a Savonius rotor. *Deep-Sea Res.* **27**, 755–759.
- Savonius, S. J., 1931: The S-rotor and its applications. *Mech. Eng.* **53**, 333–338.
- Sverdrup, H. U., M. W. Johnson and R. H. Fleming, 1942: *The Oceans: Their Physics, Chemistry and General Biology*, Prentice-Hall, 1060 pp.
- Thompson, R. O. R. Y., 1979: Coherence significance levels. *J. Atmos. Sci.* **36**, 2020–2021.
- Von Zweck, O. H., and K. D. Saunders, 1981: Contamination of current records by mooring motion. *J. Geophys. Res.* **86**, 2071–2072.
- Weller, R., and R. E. Davis, 1980: A vector-measuring current meter. *Deep Sea Res.* **27**, 565–582.
- Wyrki, K., and G. Meyers, 1976: The trade wind field over the Pacific Ocean. *J. Appl. Meteor.*, **15**, 698–704.