

An Intercomparison of Current Measurements Using a Vector Measuring Current Meter, an Acoustic Doppler Current Profiler, and a Recently Developed Acoustic Current Meter

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ABSTRACT

Horizontal current measurements were obtained simultaneously with a vector measuring current meter (VMCM), an acoustic Doppler current profiler (ADCP), and the recently developed Falmouth Scientific, Inc., acoustic current meter (ACM) during a 110-day period from the Bermuda Testbed Mooring (BTM). The BTM site is located approximately 80 km southeast of Bermuda at 31°44'N, 64°10'W in waters of about 4550-m depth. The ACM is a relatively small, lightweight instrument, which can be deployed relatively close to the ocean surface or bottom as well as at intermediate depths. Prior to the present study, in situ data and knowledge concerning the ACM performance were quite limited. Zonal, meridional, and horizontal current speed data were obtained and time series were computed for each instrument. Several analyses were done to evaluate and intercompare instrument performance. The ACM results compared favorably with those of the VMCM and ADCP for 36-h filtered data. The ADCP typically recorded the largest horizontal current speed and the ACM typically recorded the smallest values. The strongest correlation was seen between the VMCM and ADCP data; however, the lowest correlation for all intercomparisons (by component and speed) was $r = 0.95$ with most values of $r = 0.98$ or greater. Directional error/bias is a primary factor in limiting current component measurement accuracy. In particular, the ACM direction was up to 20°–30° offset from those of the other two instruments. After rotating or “correcting” the ACM components with respect to the VMCM direction, ACM mean current component differences with respect to the other instruments’ values were less than about 2 cm s^{-1} . Based upon the spectral analysis, both the ACM and VMCM have better performance characteristics than the ADCP in the higher-frequency portion of the spectral domain. The authors’ analysis indicates that the three different systems provide generally similar results in terms of coherence and phase with significant departures occurring only with respect to the ADCP at frequencies greater than 0.01 cph. The present study indicates that the ACM provides another viable means of obtaining accurate current measurements.

1. Introduction

Ocean current measurements can be achieved from a variety of types of current meters [see review by Dickey et al. (1998a)]. The vector measuring current meter (VMCM; Weller and Davis 1980) and the acoustic Doppler current profiler (ADCP; Pinkel 1980; Gordon 1996) are two instruments that have been extensively used by oceanographers during the past decade. In particular, these instruments have proven to be reliable instruments for obtaining quality ocean current data from moorings for scientific studies (Halpern et al. 1981; Beardsley 1987; Irish et al. 1995; Dickey et al. 1998a).

A three-dimensional ACM was recently developed by Falmouth Scientific, Inc. (FSI 1997a,b). The motivation

for the development of the ACM was to provide an inherently low-cost, power efficient (less than 100 mW), rugged, user-friendly, small, and lightweight instrument that offers excellent performance. The ACM was originally calibrated and tested in the FSI laboratory (FSI 1997a,b). However, very limited in situ performance data from the ACM existed prior to its deployment on the Bermuda Testbed Mooring (BTM; Dickey et al. 1998b) in 1996. The focus of the present report is on horizontal velocity components rather than the vertical component because 1) the primary anticipated application of the instrument is for horizontal current observations, 2) there is no common standard for vertical current intercomparisons, and 3) there were no critical measurements of mooring dynamics.

The BTM is located approximately 80 km southeast of Bermuda at 31°44'N, 64°10'W in water about 4550 m deep. The mooring has been deployed since June 1994 and provides opportunities for interdisciplinary instrument development and testing, especially for those instruments designed for high temporal resolution, long-

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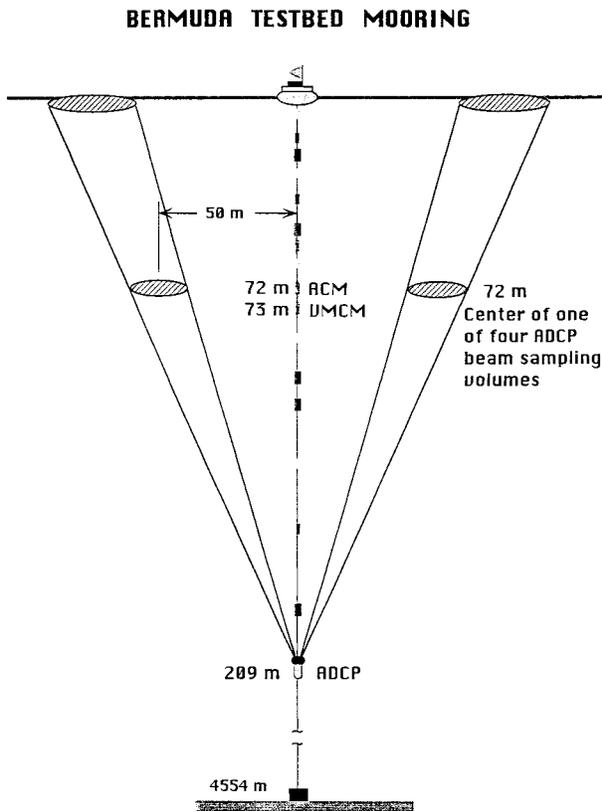


FIG. 1. Schematic diagram of the BTM showing the location of the ACM, VMCM, and ADCP on the mooring; and the location of the center of an ADCP beam-sampling volume, which represents the bin, used in the intercomparison.

term data collection (Dickey et al. 1998b). The mooring configuration is shown in Fig. 1. An RD Instruments upward-looking 150-kHz Blue Water broadband ADCP (RDI 1995) was located at a depth of 209 m and provided data in the range bin of interest, centered at a depth of 72 m. A Weller-Davis type VMCM (Weller and Davis 1980) was included as part of a multivariable moored system (see Dickey 1991; Dickey et al. 1991) and positioned at a depth of 73 m. The FSI ACM was located at a depth of 72 m.

Current measurements were made during a 110-day period from 24 August to 13 December 1996 with the VMCM, ADCP, and ACM. The motivation was to test the endurance and performance of the ACM and to evaluate the quality of ACM data as compared with the VMCM and ADCP data. The close proximity on the mooring of the VMCM and the ACM along with the use of the relevant ADCP bin minimized instrumental variances associated with vertical shear of currents. However, each instrument has an inherently unique sampling volume. Comparison of the VMCM data with the ADCP data was a natural extension of this study.



FIG. 2. Photograph of the FSI 3D-ACM.

2. Instrumentation

Brief descriptions of the three current measurement systems used for this study are provided below.

a. VMCM

The VMCM employs biaxial propellers and has undergone extensive tests and calibrations (Weller and Davis 1980; Halpern et al. 1981; Winant et al. 1994; Irish et al. 1995). It is a well-characterized mechanical current meter and has been used for benchmarking other current meters (e.g., Dickey et al. 1998a). The two sets of orthogonal cosine response propeller sensors directly measure components of horizontal velocity, and direction is determined with a flux-gate compass (estimated resolution of 1.4° and accuracy of $\pm 5^\circ$) to allow rotation of components into geographical coordinates.

The instrument continuously records the number of revolutions for each propeller during a selected sampling interval. A sampling interval of 3.75 min was used for this study. The average horizontal water displacement as determined from the number of propeller turns is calculated for each sampling interval and is then divided by the sampling interval time to determine the velocity. The propeller rotations are counted every one-quarter revolution, and the propeller revolves about 2.5 times per meter of fluid motion. This results in 10 counts per meter of flow past the sensor.

The geometric sampling volume of the VMCM is estimated to be roughly 0.025 m^3 using the propeller diameter (0.21 m) and the separation distance between the axles of each propeller (0.38 m). The VMCM has a threshold flow rate of about 1 cm s^{-1} . The VMCM was designed so that flow interference by the instrument body is minimal. The VMCM effectively averages over the higher frequency scales and optimizes a linear response ($\pm 1\%$ from 2 to 400 cm s^{-1}) between the sensor

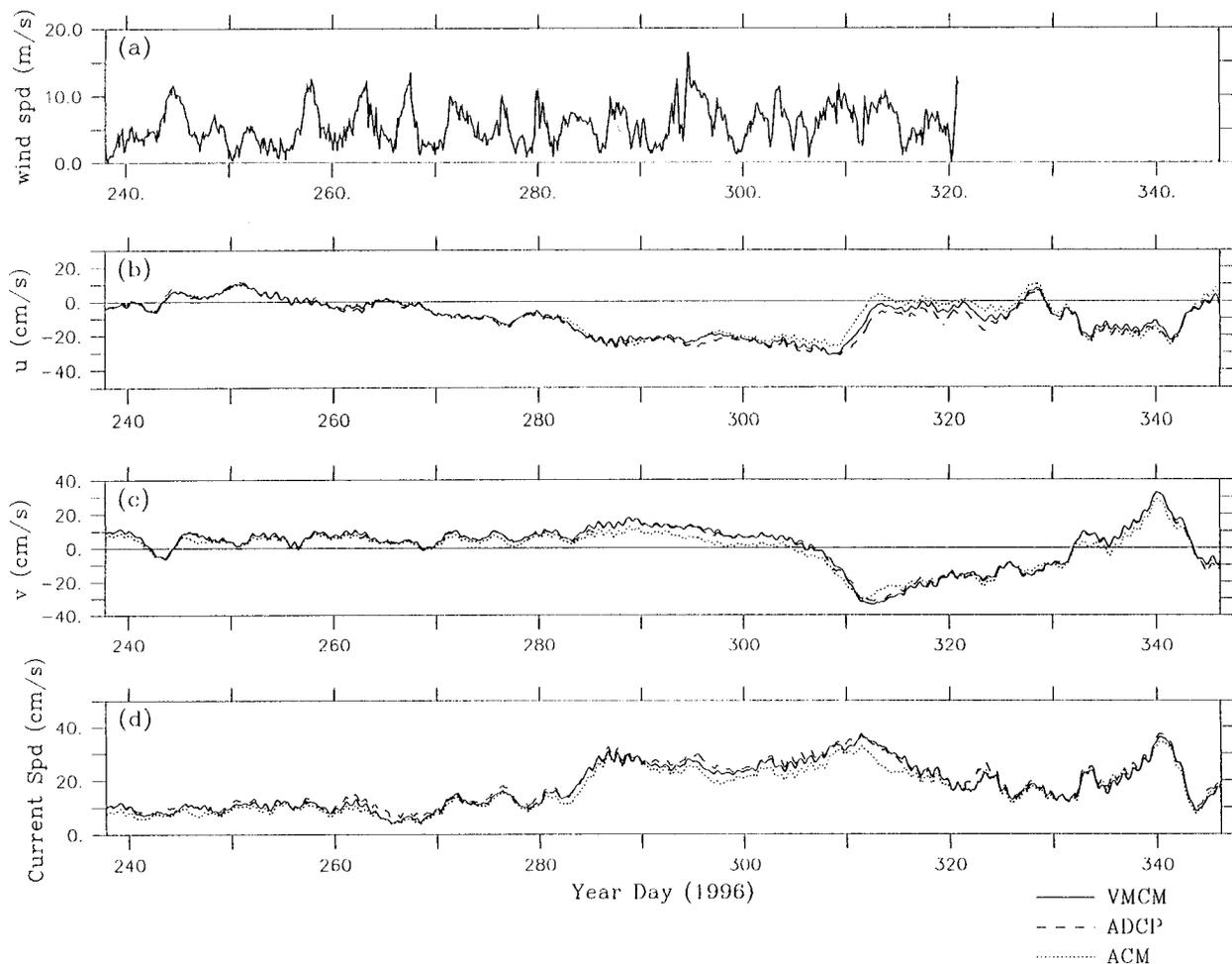


FIG. 3. (a) Time series of surface winds using 2-h averaged data. (b) Time series data obtained with the VMCM (solid line), ADCP (dashed line), and ACM (dotted line) using 36-h filtered data for zonal current time series. (c) Same as (b) except for meridional current time series. (d) Same as (b) except for current speed time series.

output and the averaged vector component. It has excellent cosine response ($\pm 1\%$) and works well in both steady and unsteady flows with minimal rectification error. The propeller speed goes through zero on flow reversal. A drawback of a large sensor is that the relatively large sampling volume can be perturbed to an extent by the sensor itself (i.e., the propeller can create a wake, which it may reencounter). This can result in a misrepresentative measurement of the flow and consequent error.

b. ADCP

ADCPs have been tested and proven to be effective oceanographic tools (e.g., Delcroix et al. 1992; Lien et al. 1994; Winant et al. 1994; Irish et al. 1995). ADCPs measure profiles of horizontal currents with vertical resolution that are difficult to attain with conventional current meters, thus they are effectively taking the place of many current meters. Recent technical developments

have improved ADCP velocity precision (estimated to be $\pm 4 \text{ cm s}^{-1}$; RDI 1995) and accuracy ($\pm 0.2\%$ of velocity or $\pm 0.2 \text{ cm s}^{-1}$; RDI 1995) to the point where they equal or exceed those attainable with most conventional mechanical current meters (Irish et al. 1995; Dickey et al. 1998a). The ADCP computes north, east, and vertical velocity components using full compass and tilt corrections. According to manufacturer's specifications, compass resolution is 0.2° and accuracy is $\pm 5^\circ$ (RDI 1995). The most significant difficulty with velocity component measurements by ADCPs, as well as most Eulerian devices, appears to be compass error.

Using the ADCP, the fluid velocity is estimated by detecting the Doppler frequency shift of the acoustic backscatter generated by sound-scattering bodies in the water. During typical operation, an acoustic transducer emits a pulse of acoustic energy along a beam insonifying a volume of fluid determined by the beamwidth, the pulse duration, and the distance from the transducers. As the time after transmission increases, the re-

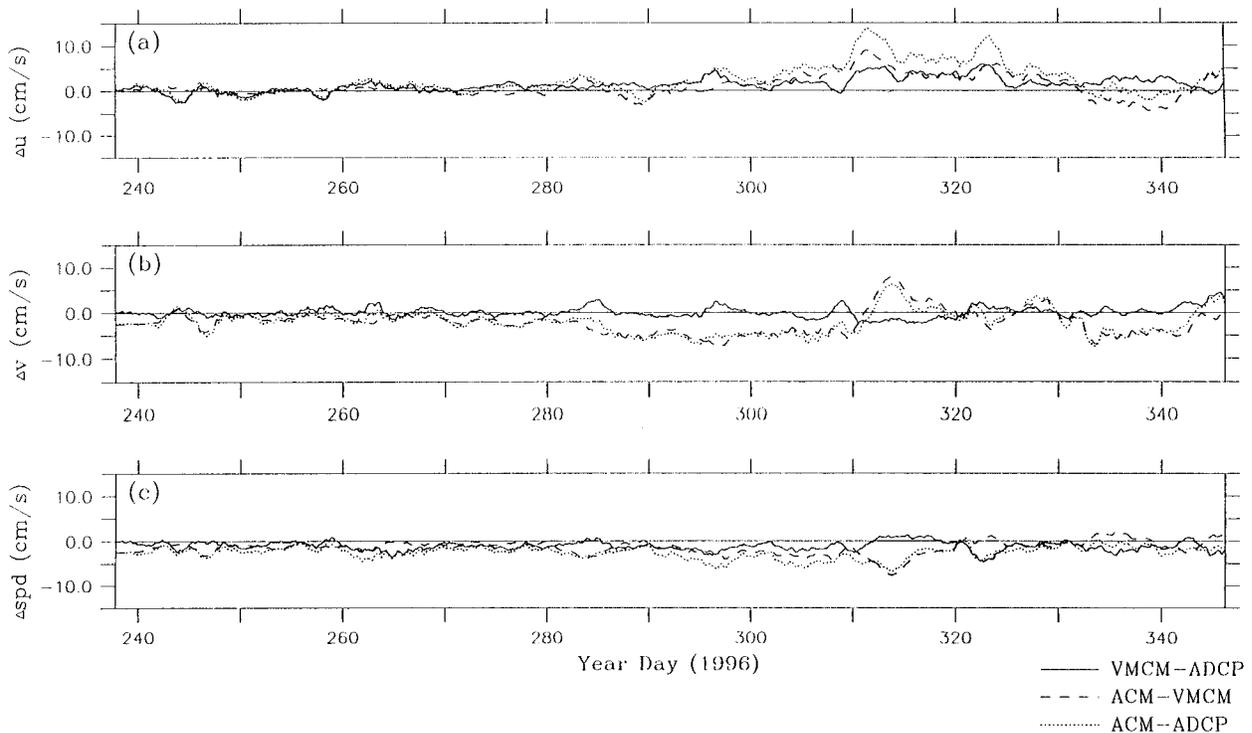


FIG. 4. Time series of the differences of the VMCM - ADCP (solid line), ACM - VMCM (dashed line), and ACM - ADCP (dotted line) using 36-h filtered data. (a) Zonal current time series differences. (b) Meridional current time series differences. (c) Current speed time series differences.

turned signal comes from successively more distant sample volumes known as range bins. Backscattered energy from each range bin arrives at the transducer with a Doppler shift proportional to the average speed of many scatterers within the sampled volume. The velocity estimation requires the assumption that the scatterers are moving passively with and effectively tracking the surrounding fluid and that horizontal homogeneity exists (Gordon 1996). The ADCP measures average velocity over the depth of each bin.

For the present study, the ADCP transmitted at 36-s intervals for 12 transmissions during a 7.5-min sampling interval. The averaging bin size was 3 m. Our ADCP also employed the broadband technique, which takes advantage of the full signal bandwidth available for measuring velocity and allows for pulse coding (e.g., Brumley et al. 1991; Trevorrow and Farmer 1992). The broadband method gives high resolution along the profile with little reduction of velocity precision.

The four ADCP transducers were aligned in the Janus configuration (Gordon 1996), which is good for rejecting errors in horizontal velocity caused by tilting. The transducers were aligned at 20° from vertical and the acoustic transmission beam spreads at approximately 4° . This results in a 7.5-m-diameter bin for each beam at the 72-m depth (horizontal surface area of 44.2 m^2). The surface area multiplied by the bin depth results in the fundamental measurement of sampling volume for

each beam of 133 m^3 (data from the four beams are processed). The sampling volumes for the observation depth bins were located about 50 m horizontally from the VMCM and ACM on the mooring as a result of the 20° angle of each of the transducers (Fig. 1).

c. ACM

The FSI ACM (Fig. 2) is a new product; however, it is based on a previous design by Brown (1992). The ACM is designed to collect high precision current velocity data in three dimensions (FSI 1997a,b). It measures velocity magnitude and direction along four acoustic paths (approximate pathlengths of 0.15 m), three orthogonal magnetic vectors, and two orthogonal gravity vectors for tilt (FSI 1997a). The transducers are spaced 0.11 m vertically apart and cover approximately a 0.023 m^2 horizontal area. The sampling volume of the ACM is approximately 0.002 m^3 .

Because only one of the four paths will be significantly contaminated by the wake from the center support strut, three axes remain for the complete solution of the x , y , and z components of velocity. The microprocessor determines which axis is contaminated by flow interaction with the center strut and rejects the data from this axis. This procedure results in essentially uncontaminated flow.

The ACM current measurement is based on phase

TABLE 1. Means and 95% confidence (conf.) intervals of currents from ACM, VMCM, and ADCP. The ACM data with "corrected" direction (ACM_{cor}) are also presented.

	Zonal current		Meridional current		Current speed	
	Mean ($cm\ s^{-1}$)	95% conf. ($cm\ s^{-1}$)	Mean ($cm\ s^{-1}$)	95% conf. ($cm\ s^{-1}$)	Mean ($cm\ s^{-1}$)	95% conf. ($cm\ s^{-1}$)
ACM	-8.24	8.35	-0.38	8.73	16.50	7.54
ACM_{cor}	-8.60	8.83	1.53	9.56	16.50	7.54
VMCM	-9.27	9.29	1.73	9.52	17.95	8.05
ADCP	-10.64	9.51	1.64	9.56	19.02	8.15

shifts of the sound wave. The sound speed is either advanced in time when the mechanical sound wave travels in the same direction as the water movement or is retarded when the water is moving in the direction opposite that of the mechanical sound wave (FSI 1997a,b). The computation of velocity is based on the acoustic phase shift of the sound. The ACM transmits a 1-MHz continuous wave signal for 2 ms, first in one direction when the total phase shift including the receiver phase shift is measured, and then in the opposite direction when the total phase shift is measured again, using the same receiver. The current velocity is proportional to the difference in phase for the two directions. A simple low power circuit for measuring phase shift at the carrier frequency is employed. Since the same receiver is used for both directions, the errors due to the different phase shifts of two receivers (offset errors) in the phase sensitive detector are eliminated.

The ACM includes a direction sensor with no moving parts. The compass uses a combination of a very low power, nongimbaled three-axis flux-gate magnetometer along with a two-axis electrolytic type tilt sensor to determine the instrument orientation relative to the earth's magnetic and gravity field (FSI 1997a). The magnetometer is an adaptation of the "ring core" design described by Geyger (1962). The data from these sensors are processed in the microprocessor to determine tilt and magnetic direction. This is combined with the velocity sensor outputs to determine the horizontal and vertical components for vector averaging (FSI 1997a).

The ACM samples at 2 Hz. Individual velocity samples consist of four path measurements. Each path is measured during an 8-ms interval with all four paths

measured during a 32-ms period twice per second. The ACM has a selectable time over which the sampling averaging occurs. This study used a 5-min interval, over which the 2-Hz sampled data were vector averaged.

The following specifications were provided by the manufacturer (A. Fougere). Compass accuracy for the ACM is estimated to be $\pm 2.0^\circ$ for $40^\circ N$, $70^\circ W$ (dependence on position with respect to the earth's magnetic poles). Velocity threshold is about $\pm 0.03\ cm\ s^{-1}$ (rms value in still water tank). Velocity precision and resolution are reported to be $\pm 3\%$ of reading and $\pm 0.01\ cm\ s^{-1}$, respectively.

The ACM was initially tested and characterized in a tow tank. However, tow tanks cannot simulate natural flows observed in the ocean, nor mooring motion and frame effects (e.g., Dickey et al. 1998a). Hence, the present intercomparison study represents a critical evaluation of in situ performance of the FSI ACM under representative operating conditions.

3. Current data intercomparisons

Data obtained from 24 August (day 237) to 13 December (day 347) 1996 were used for the present intercomparisons. Zonal current, meridional current, and horizontal current speed values were obtained for each current measurement system. Since the three current measurement systems recorded data over different intervals (VMCM: 3.75 min; ADCP: 7.5 min; ACM: 5.0 min), averaging was required to allow intercomparisons. For the following discussion, 36-h filtered current data are utilized except for the specific sections focusing on the spectral analysis. The 36-h filtering scheme is commonly employed to emphasize subtidal motion.

All data were corrected for true north by using the magnetic declination factor (-16°) for the BTM location. The dynamic range of observed speeds was from roughly 2 to $40\ cm\ s^{-1}$ as indicated in Fig. 3 (based on the 36-h filtered data). The range of wind speeds measured by the meteorological system mounted on the BTM buoy ranged from about 2 to over $18\ m\ s^{-1}$ as shown in Fig. 3a (wind speed based on 2-h average data). It is evident that weather systems passed over the mooring about every 4–6 days.

As a preface to the intercomparison of the current time series, it is worth emphasizing that the ADCP sampling volume is much greater than and not superimposed

TABLE 2. Mean difference values calculated from time series statistics for the ACM – VMCM, ACM_{cor} – VMCM, ACM – ADCP, ACM_{cor} – ADCP, and VMCM – ADCP intercomparisons.

	Zonal current mean difference ($cm\ s^{-1}$)	Meridional current mean difference ($cm\ s^{-1}$)	Current speed mean difference ($cm\ s^{-1}$)
ACM – VMCM	1.03	-2.11	-1.45
ACM_{cor} – VMCM	0.67	-0.20	-1.45
ACM – ADCP	2.39	-2.02	-2.52
ACM_{cor} – ADCP	2.04	-0.11	-2.52
VMCM – ADCP	1.37	0.09	-1.06

TABLE 3. Regression statistics calculated from the regression plots of the ACM vs VMCM, ACM vs ADCP, and VMCM vs ADCP intercomparisons. Time series of 36-h filtered data are used.

	Zonal current				Meridional current				Current speed			
	<i>r</i>	<i>r</i> ₉₅	Slope	Zero offset (cm s ⁻¹)	<i>r</i>	<i>r</i> ₉₅	Slope	Zero offset (cm s ⁻¹)	<i>r</i>	<i>r</i> ₉₅	Slope	Zero offset (cm s ⁻¹)
ACM vs VMCM	0.97	0.88	0.94	-1.48	0.99	0.83	1.15	2.16	0.98	0.93	1.05	0.63
ACM vs ADCP	0.95	0.87	0.98	-2.58	0.98	0.82	1.12	2.06	0.99	0.93	1.06	1.55
VMCM vs ADCP	0.99	0.91	1.04	-0.97	1.00	0.81	0.98	-0.07	0.99	0.93	1.00	1.03

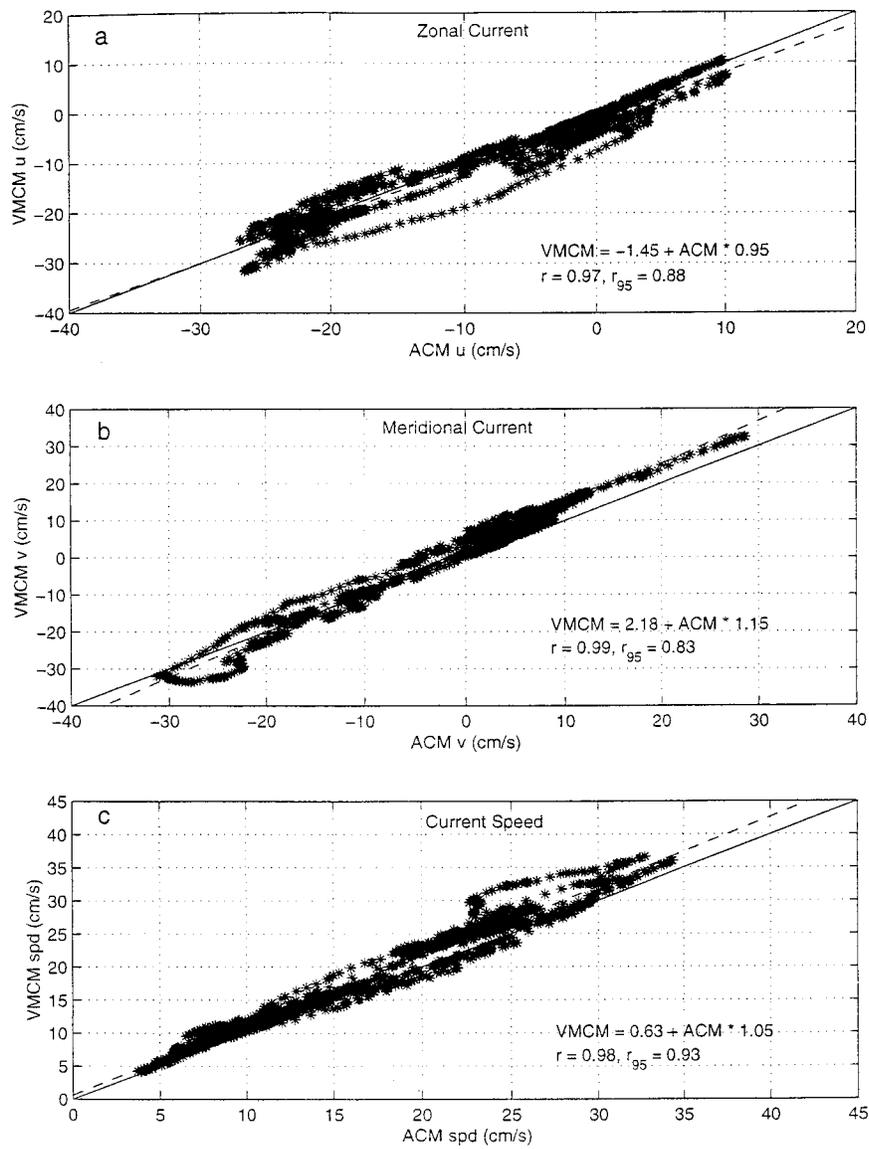


FIG. 5. ACM vs VMCM regression plots using 36-h filtered data. The solid line is the one-to-one ($r = 1$) line and the dotted line is the best-fit line. (a) Zonal current regression plot. (b) Meridional current regression plot. (c) Current speed regression plot.

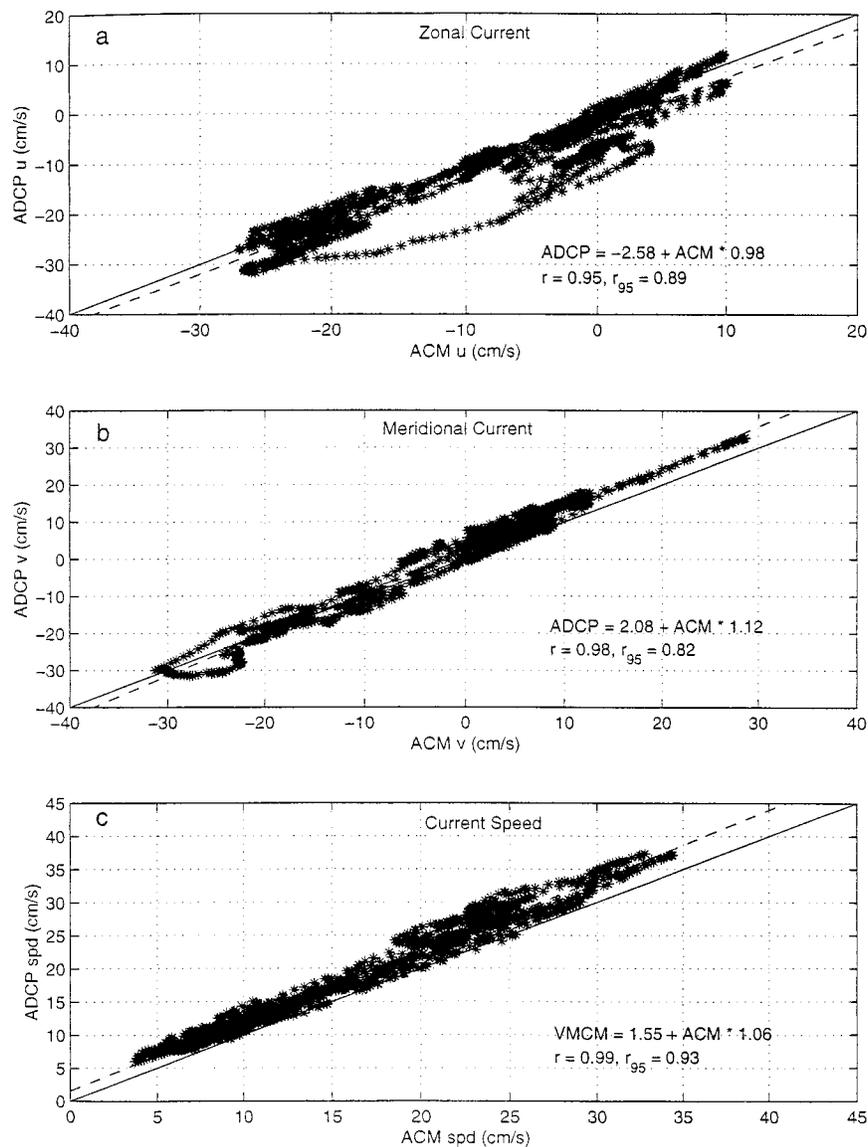


FIG. 6. ACM vs ADCP regression plots using 36-h filtered data. The solid line is the one-to-one ($r = 1$) line and the dotted line is the best-fit line. (a) Zonal current regression plot. (b) Meridional current regression plot. (c) Current speed regression plot.

with the VMCM and ACM sampling volumes. The ACM and VMCM measure currents at relatively localized points in space when compared to the ADCP measurement. Also, the VMCM sampling volume is greater than that of the ACM. Therefore, the three separate instruments should not be expected to return exactly the same values, and differences in sampling volumes likely cause some interinstrument discrepancies, particularly in the higher frequency range of currents.

a. Time series results

The zonal, meridional, and horizontal current speed time series (36-h filtered data) are illustrated in Figs.

3b, 3c, and 3d, respectively. The instruments show excellent agreement from the beginning of the time series to around day 280 and again after day 325. However, there are some noticeable differences from approximately day 280 to day 325. The percent differences are larger during the day 280–325 period and it is evident that the VMCM – ADCP differences are smaller than the ACM – VMCM or ACM – ADCP differences (Figs. 4a–c). There is no obvious reason for the poorer agreement during this period. The current speed time series show better agreement than the zonal and meridional current time series, which indicates that directional errors and/or biases may cause differences among the instruments. This point is discussed in detail below.

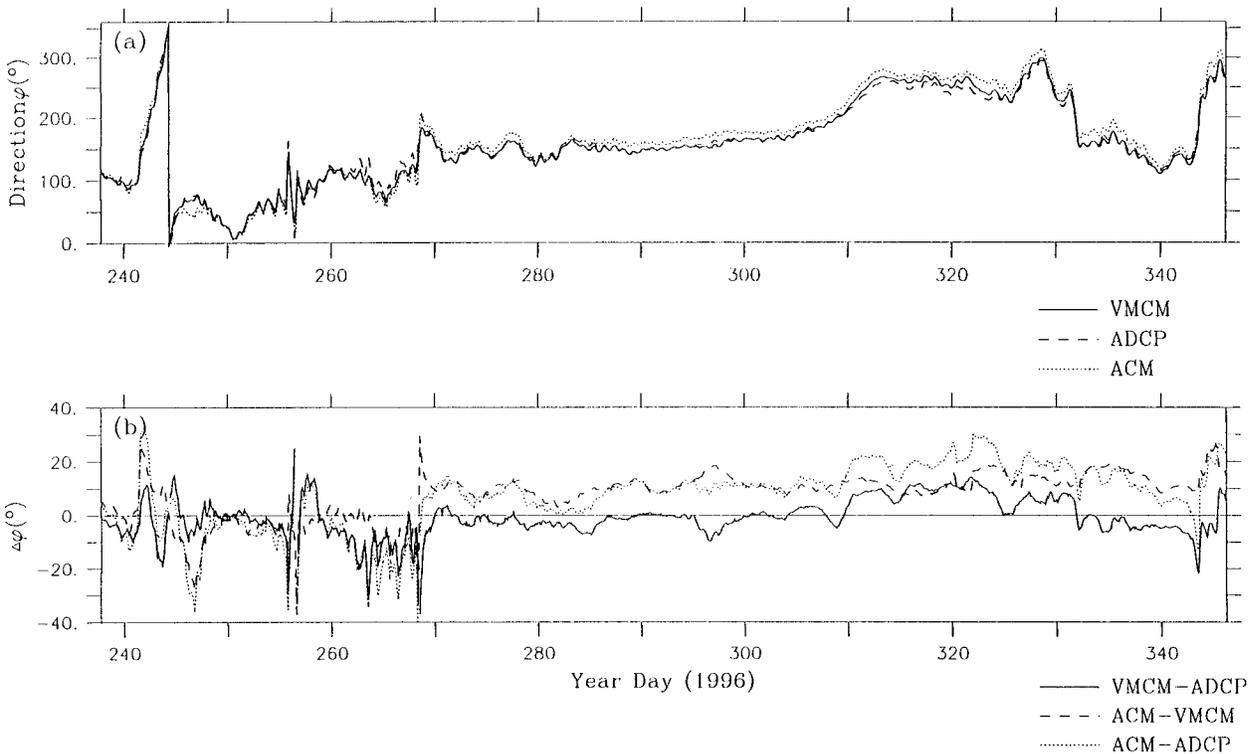


FIG. 7. (a) Time series of current direction based on 36-h filtered horizontal currents from the VMCM, ADCP, and ACM. (b) Time series of direction differences between each pair of current meters.

The zonal, meridional, and speed difference values for the ADCP and VMCM generally fall within $\pm 5 \text{ cm s}^{-1}$ with values typically falling between $\pm 2 \text{ cm s}^{-1}$. The smallest differences for each current parameter generally occur with this time series. The largest zonal differences exist between the ACM and ADCP time series with difference values as great as 14 cm s^{-1} . The ACM and VMCM zonal difference time series is similar to the ACM and ADCP difference time series with magnitude differences being slightly smaller throughout the time series. The differences between the ACM and ADCP time series of the meridional component are very similar with maximum difference values of about 7 cm s^{-1} . The same is true for the ACM and VMCM time series. However, they generally fluctuate well within $\pm 5 \text{ cm s}^{-1}$. The current speed difference for these two comparisons is also similar with the ACM - VMCM differences resulting in typically smaller values than for the ACM - ADCP differences. These values typically fall well within $\pm 4 \text{ cm s}^{-1}$.

It should be noted that some of the largest zonal differences between the ACM and VMCM and the ACM and ADCP time series occur when the ACM recorded positive zonal values and the VMCM and ADCP recorded negative zonal current values (e.g., day 313). This situation occurred a few times, before and after periods of extreme zonal current change episodes. This problem also affected a few meridional data points and

likely may be attributed to a combination of differences in direction and response.

Statistics for the VMCM, ADCP, and ACM time series and their differences (relating to Figs. 3 and 4) were calculated and are summarized in Tables 1 and 2. The 95% confidence intervals are somewhat smaller for the ACM than the other two instruments. Further comparative insights are provided by noting how closely each difference time series fluctuates about the zero value in Fig. 4.

b. Regression analysis

Linear, least-squares fits were computed for the intercomparison and statistics were tabulated. Table 3 contains r values, 95% significance levels for r (r_{95}), slopes, and offsets from zero values calculated from regression statistics for the ACM versus VMCM, ACM versus ADCP, and VMCM versus ADCP comparisons. The zonal, meridional, and speed values were calculated using 36-h filtering. The ACM versus VMCM zonal current, meridional current, and speed regression calculations resulted in r values of 0.97, 0.99, and 0.98, respectively, as shown in Fig. 5. The ACM versus ADCP zonal current, meridional current, and speed are correlated with r values of 0.95, 0.98, and 0.99, respectively, as shown in Fig. 6. All of these values are above the respective 95% significance levels.

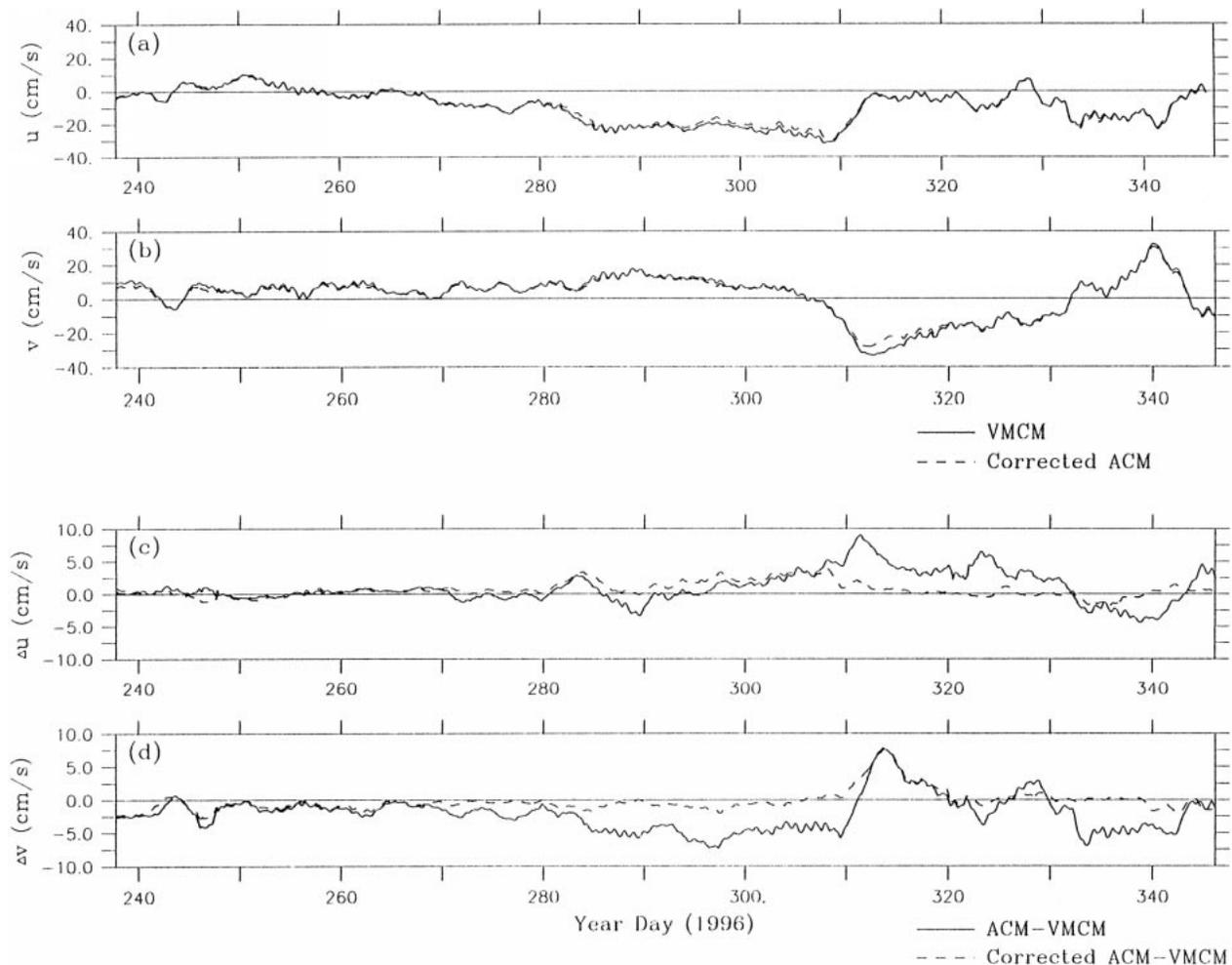


FIG. 8. Time series of VMCM currents and "corrected" ACM currents for (a) zonal and (b) meridional currents. Differences between time series shown in (a) and (b) are presented in (c) and (d).

The highest correlation of current data was obtained for the VMCM versus ADCP comparison. The current speed regression resulted in good correlation with an r of 0.99 (Table 3). The VMCM generally measured slightly smaller values than those obtained by the ADCP. This is consistent with an offset of 1.03 cm s^{-1} and may be relevant to the observation of Weller and Davis (1980), who indicated that the VMCM underspeeds slightly (up to $\sim 5\%$). The smallest mean differences (Table 2) among the comparisons for meridional current and current speed resulted from the VMCM versus ADCP analysis. However, these are not greatly different from the other comparisons. Our findings support previous reports, which show that the VMCM and ADCP provide similar data quality (Winant et al. 1994; Irish et al. 1995; Dickey et al. 1998a).

The r values for current speed were high (0.98–0.99) for all comparisons (Table 3). The mean zonal current differences were smallest for the ACM versus VMCM comparison. The meridional current regression plot

(Fig. 5b) shows a general pattern with the ACM recording smaller current magnitudes than the VMCM. This is also shown with the current speed plot (Fig. 5c). This is evident as the slope of the speed regression was close to 1 with a small positive VMCM offset value of 0.63 cm s^{-1} . The ACM versus ADCP comparison resulted in the lowest correlation for component currents from the regression statistics. The r values were generally the lowest of the three comparisons and the offsets were greatest. The zonal current regression plot of the ACM versus the ADCP (Fig. 6a) shows the poorest correlation of all the plots.

The time series of the speed data from the three instruments generally tracked better than either the zonal or meridional data (Fig. 3). As indicated earlier, direction determination biases and errors result in significant discrepancies between current component measurements (e.g., Irish et al. 1995). To focus on this problem, time series of direction, ϕ , for each current measurement system and the differences, $\Delta\phi$, between the systems

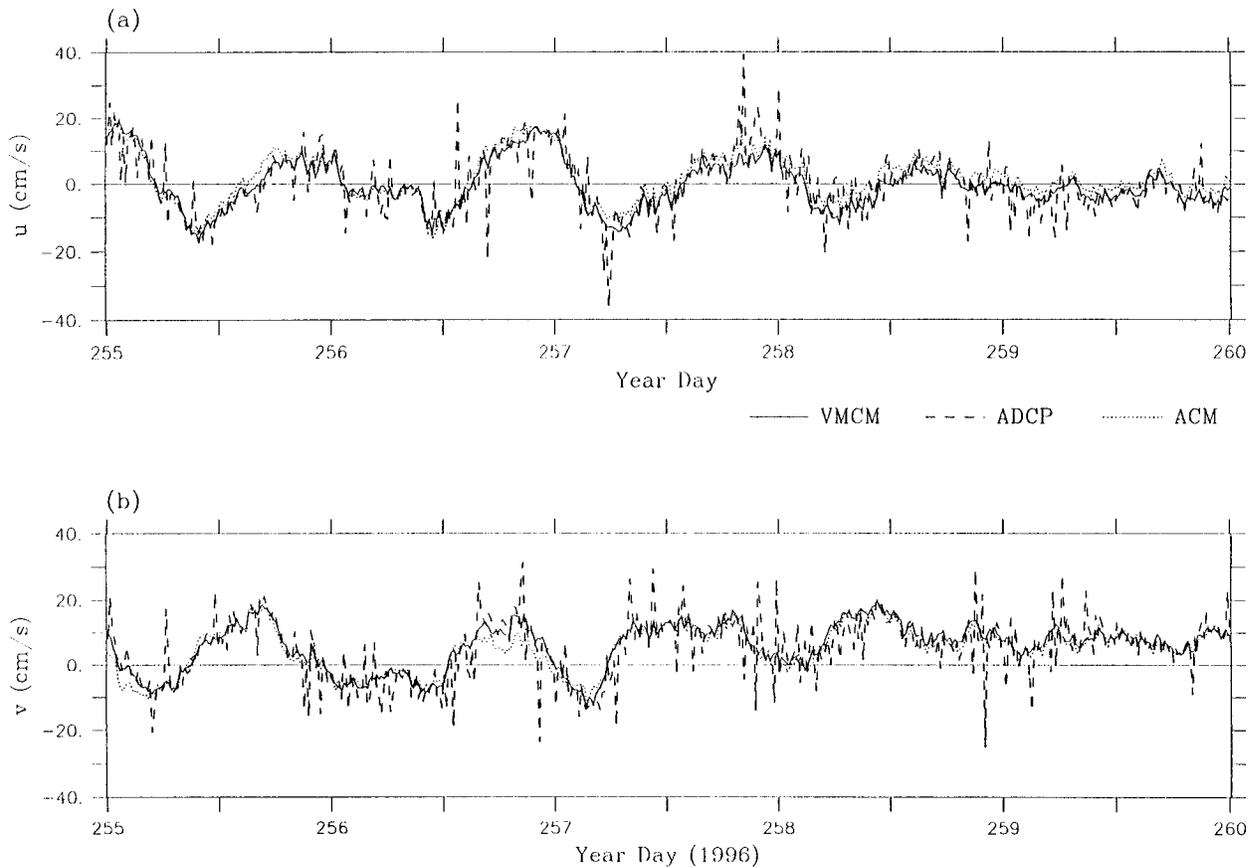


FIG. 9. Time series of 15-min averaged (a) zonal and (b) meridional currents for the VMCM, ADCP, and ACM for the period day 255–260.

are illustrated in Figs. 7a and 7b, respectively. The VMCM and ADCP obtained similar directional values (typically within $\pm 10^\circ$). However, considerably poorer agreement was found for the ACM versus ADCP and ACM versus VMCM comparison (up to 20° – 30°). By inspecting Fig. 7, it is evident that the VMCM and ADCP directions (and presumably compass measurements) are quite consistent, whereas the ACM direction is biased with respect to the other two. It should be noted that the deviations and biases are greater than expected according to manufacturer specifications given earlier.

To examine the importance of the directional differences on the component estimates by the ACM, an additional analysis was performed. In particular, the direction of the VMCM time series (i.e., solid line in Fig. 7a) was assumed to be correct. The ACM direction was then adjusted (rotated) or “corrected” with respect to the VMCM direction time series for consistency. Then the ACM’s zonal and meridional components were re-evaluated using the VMCM current direction and the original ACM current magnitude. The VMCM and “corrected” ACM zonal and meridional component time series and their differences are shown in Figs. 8a and 8b. For comparison, the differences between

VMCM currents and the “corrected” ACM component currents are shown in Figs. 8c and 8d. Considerable improvement in agreement is evident, especially during the period of day 280–325.

To summarize, it can be inferred that the ACM generally tends to result in the lowest current values. The ADCP measurements tend to be the greatest with the VMCM measurements falling in between (Fig. 3). With the exception of the noticeable difference in current values from day 280 to day 325, which was a period of relatively high currents, the three instruments appear to give similar current measurements as indicated by the statistical analyses. The primary factor causing differences in the velocity component time series is directional bias.

c. Spectral analysis

Thus far, the time series have been discussed in the context of relatively low-frequency variability (36-h filtered data). However, there is considerable information content in the higher frequency data with relevance to processes including internal gravity waves. A subset of the 15-min averaged time series (day 255–260) is shown in Fig. 9. This time series indicates that the three dif-

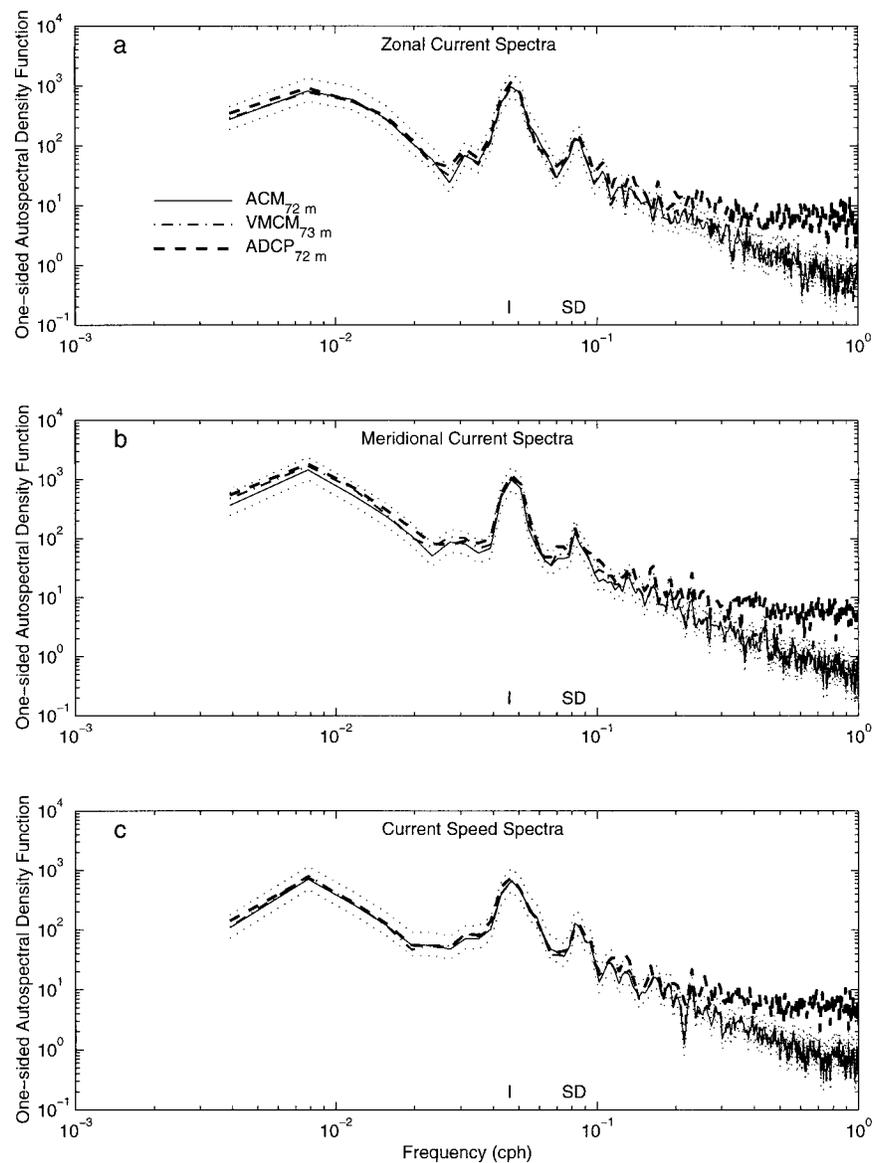


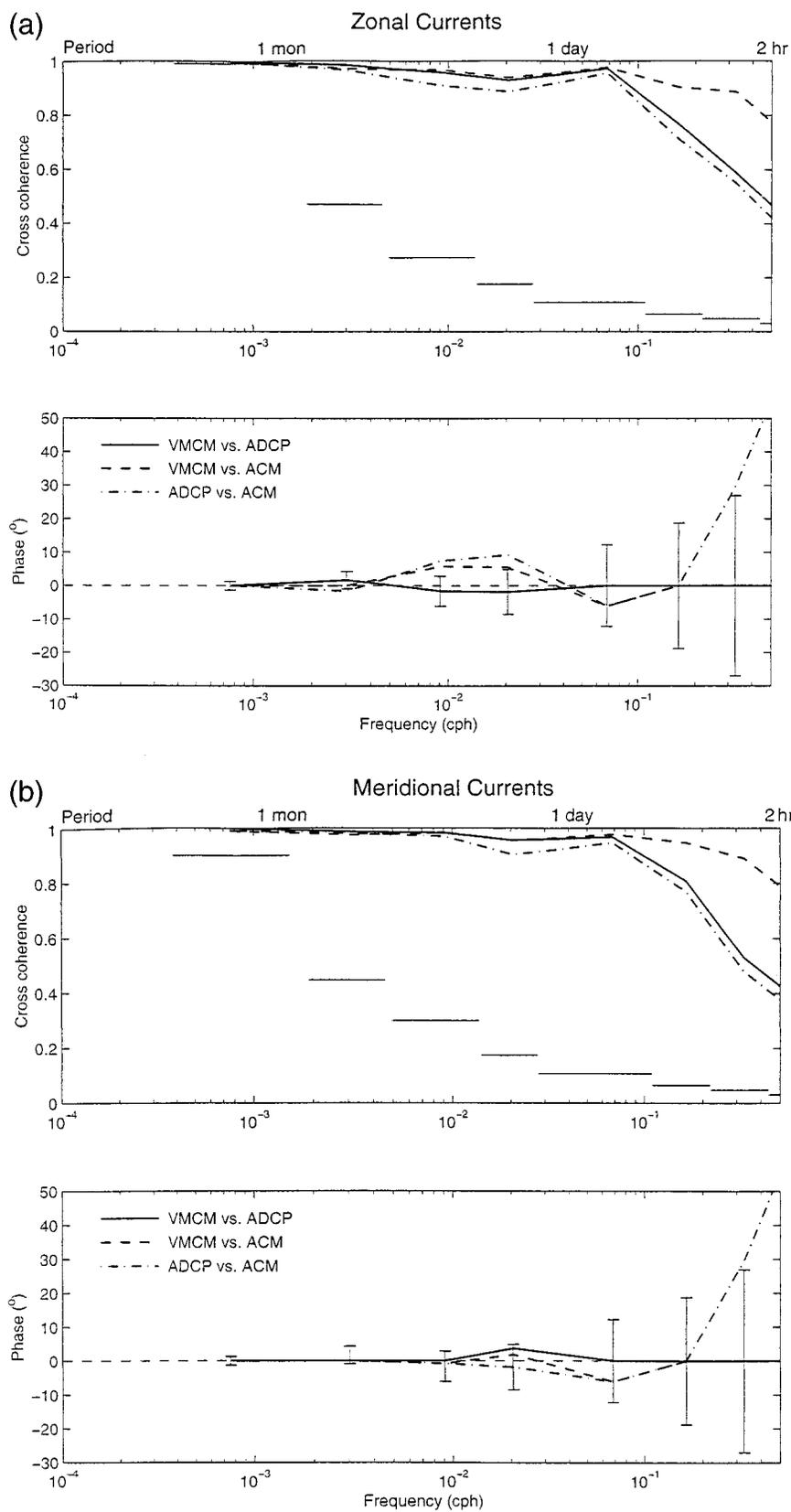
FIG. 10. Autospectrum plots of the ACM (darkest line), VMCM (intermediate gray line), and ADCP (lightest line) using 15-min-averaged data. The dotted lines indicate the 95% confidence interval for the ACM calculated from a chi-squared distribution. Here I is inertial period and SD is semidiurnal tidal period. (a) Zonal current spectra. (b) Meridional current spectra. (c) Current speed spectra.

ferent current measurement systems provide qualitatively similar currents in this time domain. Large “spikes” are seen in the ADCP data. The cause of these apparently spurious data is unknown at present, but could be related to instrument noise, differences in sampling methods, and signal contaminating environmental factors.

Autospectra were computed for the zonal current, meridional current, and horizontal current speed (Fig. 10) time series using 512-point fast Fourier transforms (FFTs). The spectra were computed using 15-min-averaged data. For each time series, the mean was removed

and each data segment was tapered with a Hanning window prior to computing the FFTs. Estimates of the autospectra were formed by averaging 20 individual spectral estimates (periodograms) together.

Spectra of the velocity records agree well at low frequencies (e.g., <0.2 cph). The ACM and VMCM autospectra continuously decrease in energy at about the same rate. At frequencies above 0.25 cph, the ADCP spectra level off compared to the ACM and VMCM. This is likely a result of the instrumental noise floor. This suggests that the ADCP was oversampled with respect to its inherent noise level (Irish et al. 1995).



An energy peak resides at the inertial period (0.045 cph) of the BTM site. A spectral peak can also be seen at the semidiurnal tidal frequency (0.08 cph). The dotted lines in Fig. 10 represent the 95% confidence interval for the ACM, which was calculated using a chi-square distribution. The VMCM values fall within this confidence interval for frequencies less than about 0.1 cph. The ADCP values fluctuate within this confidence interval at frequencies up to about 0.25 cph, after which the ADCP apparently begins to reach its noise floor. The spectral results also show general consistency among the three current meters except for the higher frequency domain.

Cross coherence and corresponding phase lag between each pair of current measurements were also computed for the zonal and meridional components (Figs. 11a and 11b) using the 15-min-averaged data (following Koopmans 1995). The calculations used the average of seven periodograms. The 95% significance level for coherence (horizontal bars for coherence) and 95% confidence intervals (vertical bars for phase) are also shown in Fig. 11. Cross coherence is always above the 95% significance level. At higher frequencies, the coherence between VMCM and ACM is greatest. This is consistent with the previous discussion concerning the apparent noise level problem with the ADCP at higher frequencies. The phase is usually within the 95% confidence interval except for the ADCP – ACM case. This analysis indicates that the three different systems provide generally similar results in terms of coherence and phase with significant departures occurring only with respect to the ADCP at frequencies greater than 0.01 cph.

4. Summary

Current measurements were obtained over 110 days in open ocean waters at the deep-water Bermuda Testbed Mooring site with a VMCM, an ADCP, and a newly developed FSI acoustic current meter (ACM). Advantages of the ACM include: small size, light in weight, and deployability near ocean surface and bottom as well as intermediate depths. The ACM had not been evaluated in situ, thus, the primary motivation of the study was to quantify ACM current measurements at sea and to compare them with measurements made with two other commonly used and well-tested current meters. A fair field intercomparison was enabled by making measurements at virtually the same depth over a broad range of physical forcing conditions.

Analyses of subtidal measurements (36-h filtered time

series data) showed that ACM currents compared favorably with those of the VMCM. The ADCP typically recorded the largest horizontal current speed magnitudes followed by the VMCM, and the ACM typically recorded the smallest values (means over entire experiment of 19.0, 18.0, and 16.5 cm s⁻¹, respectively). Excellent correlation was found for all instrument pairs by component and speed values with the lowest correlation of $r = 0.95$ and most values of $r = 0.98$ or greater. The major limiting parameter for determining current components was directional error/bias with ACM direction offsets of up to 20°–30° from those of the other two instruments. By “correcting” ACM components (using VMCM direction as true direction), the ACM experiment mean current component differed by less than 2 cm s⁻¹ from those of the other instruments. The ACM and VMCM both perform better in the high-frequency region of the energy spectra. The present research has demonstrated that the new ACM can be used to obtain reliable and accurate current measurements.

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FIG. 11. (top) Cross coherence amplitude and (bottom) phase lag in frequency domain for the 15-min-averaged currents from each pair of instruments: VMCM vs ADCP (solid), VMCM vs ACM (dashed), and ADCP vs ACM (dash-dot): (a) Zonal currents and (b) meridional currents. Positive phase indicates that the former of a pair leads the latter. (top) The 95% confidence levels are shown by horizontal lines. (bottom) The 95% confidence limits for phase lags are shown as vertical bars. Confidence information is shown only for the VMCM vs ADCP (lines are similar for other pairs).

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