Evaluation of Mean Velocity and Turbulence Measurements with ADCPs

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Abstract: To test the ability of acoustic Doppler current profilers (ADCPs) to measure turbulence, profiles measured with two pulse-to-pulse coherent ADCPs in a laboratory flume were compared to profiles measured with an acoustic Doppler velocimeter, and time series measured in the acoustic beam of the ADCPs were examined. A four-beam ADCP was used at a downstream station, while a three-beam ADCP was used at a downstream station and an upstream station. At the downstream station, where the turbulence intensity was low, both ADCPs reproduced the mean velocity profile well away from the flume boundaries; errors near the boundaries were due to transducer ringing, flow disturbance, and sidelobe interference. At the upstream station, where the turbulence intensity was higher, errors in the mean velocity were large. The four-beam ADCP measured the Reynolds stress profile accurately away from the bottom boundary, and these measurements can be used to estimate shear velocity. Estimates of Reynolds stress with a three-beam ADCP and turbulent kinetic energy with both ADCPs cannot be computed without further assumptions, and they are affected by flow inhomogeneity. Neither ADCP measured integral time scales to within 60%.

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Introduction

Turbulence strongly affects many hydraulic processes, including mixing, transport, scour, and energy dissipation. Turbulence measurements often require large amounts of time and labor because of instruments and the corresponding measurement techniques. Acoustic Doppler current profilers (ADCPs) provide time series of velocity profiles quickly and easily, and they have been used in various turbulence measurements since at least 1990. ADCPs require no calibration, and they allow essentially non-intrusive measurements. However, the ability of commercially available ADCPs to measure turbulence has not been previously evaluated with laboratory tests. We describe results of laboratory experiments in which measurements with commercially available ADCPs were compared with measurements with an acoustic Doppler velocimeter (ADV).

Hinze (1975) identified several requirements for measuring turbulence. Along with not disturbing the flow, vibrating, or introducing drift into the measurement, the instrument must have adequate temporal response, a sensing volume smaller than the smallest scales of the flow, and the ability to measure fluctuations that only are a few percent of the mean flow. The temporal resolution of an ADCP depends on the physical response time, processing time in the electronics, and measurement frequency. The response time is limited by the acoustic pulse travel time. Data recording rates for commercially available ADCPs typically do not exceed 10 Hz, and many ADCPs cannot record faster than 1 Hz. Cheng et al. (2000) found that a sampling frequency of slightly higher than 1 Hz could not resolve the full range of flow scales in an estuary. Also, some ADCPs report the average of several profiles, and as a result, the temporal resolution of the instrument is reduced further.

The spatial scales that the ADCP can resolve are limited by the bin size (or the vertical resolution of the profile), the beam diameter, and the resolution of velocity components from beam velocities. The volume of the smallest eddies for most riverine flows is on the order of 1 mm^3 or less (Nezu and Nakagawa 1993), while the measurement volume of one-dimensional radial ADCP velocities typically is on the order of 100 cm^3 or more. Some quantities, such as Reynolds stress and turbulent kinetic energy, depend primarily on the large scales of the flow (e.g., Bradshaw 1971) and may not require the small scales to be resolved. However, the current generation of commercially available ADCPs cannot measure quantities that depend on the smallest scales of the flow.

The ability of the ADCP to measure small fluctuations depends on Doppler noise, which results from errors in measuring the frequency change or phase shift of the reflected pulse. These errors can be caused by variations originating from sound scattering off particles in the flow (SonTek 1996, p. 8). Many factors contribute to Doppler noise: the processing scheme (incoherent or coherent), operational mode, bin size, and pulse design (coding, length, and strength). Flow conditions such as shear and turbulence also affect the noise level of ADCPs, especially coherent

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profilers, because they affect the form of the reflected pulse. In pulse-coherent systems measurement errors can be due to decorrelation of sequential pings caused by rapid changes in the flow (e.g., turbulence). These flow changes result in increased measurement error or loss of data.

ADCP measurements are also affected by ringing, flow disturbance, and sidelobe interference. After transmitting a ping, the transducers continue to vibrate for a short time, and velocities cannot be measured over the distance that the sound travels while the transducers become quiescent enough to record the backscattered acoustic energy accurately. To exclude regions of the flow affected by ringing, a blanking distance is specified. Velocity measurements can also be affected by disturbance of the flow caused by the presence of the instrument in the water (Gartner and Ganju 2002). Although ADCPs measure nonintrusively, the instrument's transducers must be submerged to transmit acoustic pulses properly into the water column. This submergence disturbs the flow near the instrument, although this flow disturbance is typically assumed to fall only within the blanking distance. Sidelobe interference affects parts of the profile near boundaries. The fraction of the distance from transducer to the affected boundary is $(1-\cos\theta)$, where θ=angle between the beam and the vertical. Any bins within or partially within this part of the profile will be affected. Sidelobe interference biases velocities towards the boundary velocity, or in the case of a stationary boundary, towards zero (Appell et al. 1991).

An important limitation for turbulence measurements arises because the three velocity components are computed by combining velocities measured along acoustic beams oriented in different directions. In a turbulent flow, instantaneous velocities in one beam will differ from those in another beam. Gargett (1994) illustrated the effects of this inhomogeneity by comparing vertical velocity measured directly with a single vertical beam with that resolved from a slant-beam pair. The direct and resolved velocities became less correlated as the distance from the instrument (and, therefore, beam spread) increased. Although the instantaneous velocities are not homogeneous, researchers have assumed the statistics to be homogeneous (e.g., Lohrmann et al. 1990; Stacey et al. 1999). Lu and Lueck (1999a) showed that homogeneity of the first moments holds for 95% of the mean velocity estimates when the averaging time exceeds 55 integral time scales, and Lu and Lueck (1999b) suggested that a criterion similar to that for first moments holds for higher moments.

The assumption of homogeneity of the beam statistics allows Reynolds stress to be computed in some conditions, but turbulent kinetic energy (TKE) calculations still require extra assumptions. Because the variances of the beam velocities involve the six turbulent stresses (normal and tangential) in general, six beams would be needed to compute Reynolds stress and TKE. Stacey et al. (1999) used an ADCP with beams in the x–y and x–z planes to measure the Reynolds stresses $-\overline{u'w'}$ and $-\overline{v'w'}$; to estimate TKE, they assumed a value for the large-scale anisotropy (e.g., $\overline{v'^2}/\overline{u'^2}$) to close the systems of equations that involve five of the six turbulent stresses. For a three-beam instrument, more assumptions are required: For example, Kawanisi (2004) computed Reynolds stress and TKE with a three-beam ADCP by approximating the velocity variation between the beams with a linear function of distance. Marsden and Ingram (2004) developed a similar approach for correcting velocities measured with a four-beam system.

We extend the previous work in which the ability of ADCPs to measure turbulence was evaluated. Various laboratory measurements of turbulence have been made with specialized ADCPs. A few field measurements with commercially available ADCPs have been compared to point measurements: Hardcastle (1995) and Gartner and Cheng (1996) compared ADCP measurements to four-point electromagnetic current meter measurements, and Hardcastle (1997) compared ADCP measurements to an ADV point measurement near the ADCP. Lacy and Sherwood (2004) compared mean velocities from an acoustic Doppler profiler and an ADV in a tidal flow. We extend these previous tests by comparing profiles of mean velocity and turbulence quantities measured with ADCPs with those measured using an ADV and by comparing velocity time series measured in the acoustic beam of the ADCPs with those measured using an ADV. In the following sections, we describe the laboratory methods and calculations, discuss the results, and summarize the main conclusions.

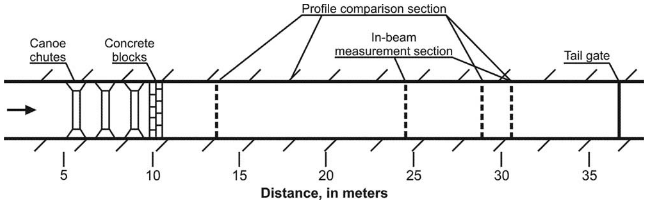

Fig. 1. Schematic plan view of the flume showing structures and measurement locations. Profiles were compared at 13.7, 29.0, and 30.5 m downstream of the flume entrance. In-beam measurements for the four-beam ADCP occurred at the 30.5 m station, and in-beam measurements for the three-beam ADCP occurred 24.4 m downstream of the entrance.

Methods

Experimental Facility

Measurements were made from a fixed platform in a recirculating, tilting flume (Fig. 1). The flume is approximately 48 m long, 1.8 m wide, and 1.2 m deep. Of the overall flume length, approximately 33 m makes up the main channel. The flume has a smooth bottom of painted steel and Plexiglas sidewalls. The water was seeded with powdered kaolin to increase acoustic scattering. All measurements were made at a channel slope of 0°. Throughout the measurements, a physical model of a series of canoe chutes was present in the upstream portion of the flume. During most of the measurements, a grid of concrete blocks was used to generate turbulence, break up large structures, and decrease asymmetry of velocities in the flume. The concrete blocks were placed directly downstream of the canoe chutes in three rows, extending above the water surface. Measurements were made from 3 to 21 m downstream from these blocks and structures to represent different turbulence conditions (Fig. 1). The discharge was approximately 0.3 m^3/s, and the water depth ranged from 0.85 to 0.89 m.

Measurements

Two acoustic Doppler current profilers were tested in this study: a 1.5 MHz Nortek high-resolution acoustic Doppler profiler and a 600 kHz RD Instruments Rio Grande acoustic Doppler current profiler. (Use of firm names in this paper is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.) Specifications of the instruments are shown in Table 1. Pulse coherent ADCPs were used because they can

Table 1. Instrument and Measurement Parameters and Specifications

Description	Three-beam ADCP	Four-beam ADCP	ADV
Instrument frequency	1,500 kHz	600 kHz	10 MHz
Number of beams	3	4	3
Beam angle θ from vertical	25°	20°	30°[a]
Angle 2α between beams in horizontal plane	120°	90°	120°
Coherent/incoherent	Coherent/incoherent	Coherent/incoherent	Coherent
Mode used	Coherent: high resolution	Coherent: Mode 5	Range ±30 cm/s
Blanking distance used	5 cm	0 cm	Not applicable
Minimum bin size recommended for general profiling	3 cm	10 cm	9 mm[b]
Minimum bin size used	3 cm	5 cm	Not applicable
Maximum velocity measurable for profiling range (0.9 m)	1.29 m/s	0.5 m/s[c]	Not applicable
Maximum pinging frequency	8 Hz	5 Hz[d]	250 Hz
Maximum recording frequency	0.4 Hz	5 Hz	25 Hz
Side lobe area	9.4%	6%	Not applicable
Manufacturer specified standard deviation	Not specified	0.8 cm/s[e]	1% of range

[a] Transmitting transducer at 0°; receiving transducer at 30°.

[b] Sampling volume fixed.

[c] For coherent profiling in Mode 5.

[d] Higher pinging rates can be achieved by averaging pings.

[e] This value corresponds to a 10 cm bin.

profile in shallow water with small bin sizes and low single-ping standard deviation. The transducer faces of both instruments were submerged from 5 to 10 cm.

The 1.5 MHz Nortek ADCP (hereafter, "three-beam ADCP") is a three-beam pulse coherent system designed for high-resolution measurements, typically, near a boundary. The horizontal angle between the beams was 120°, and each beam was oriented 25° from the vertical. The instrument is equipped with special firmware and a high-resolution pulse coherent mode. In high-resolution mode, the instrument is operated from a fixed platform. Each profile recorded by the instrument is, at minimum, an average of approximately 20 pings. The maximum pinging rate achieved in the laboratory was approximately 6–10 Hz; thus, the maximum recording rate was 0.33–0.5 Hz. Data were processed internally by the instrument and transmitted digitally in real time to the serial port of a personal computer.

Data from the three-beam ADCP contained a few large spikes, possibly a result of acoustic contamination specific to the laboratory (Nortek 1998). Spikes, in which velocities could jump from 20 to 200 cm/s, occurred most often in a bin near the boundary. Velocities outside a range of mean velocity ±3 times standard deviation were identified as spikes and removed from the data to compute statistics such as turbulence intensities. The spikes were not removed to calculate quantities, such as correlation and autocorrelation, that require a continuous time series of samples evenly spaced in time.

The 600 kHz four-beam RD Instruments Rio Grande ADCP (hereafter, "four-beam ADCP") was designed for measurements in rivers and shallow water. The four acoustic beams are oriented in two perpendicular planes of beam pairs, or the Janus configuration (Gordon 1996), and they were 20° from the vertical. Several operational modes are available, including incoherent and pulse coherent. All measurements for this study were made in Mode 5, a pulse coherent mode. All data collected with the four-beam ADCP were single ping, and the maximum pinging and recording rates were 5 Hz. RD Instruments specifies a blanking distance of 25 cm for their 600-kHz instruments, but we used zero blanking distance because (a) the transmit pulse length was short (Gary Murdock, RD Instruments, personal communication); (b) the concentration of scattering material in the water was high; and (c) an appropriate blanking distance could be determined during postprocessing. Data were processed internally by the instrument and transmitted digitally in real time to a personal computer.

Reference measurements were acquired at 25 Hz with a 10 MHz SonTek ADV, which has a 1.4 cm^3 ellipsoidal sampling volume located 5 cm from the probe tip. Voulgaris and Trowbridge (1998) performed a laboratory evaluation of ADVs for turbulence measurements. Their results, based on ground truthing ADV measurements with laser Doppler velocimeter measurements and theory, indicate that ADVs measure mean velocities and Reynolds stress $-\overline{u'w'}$ within 1% of the ground truth value. The ADV resolves the vertical velocity variance well, but sensor noise can affect the variance of the horizontal velocity components. Noise was removed by finding the spectral level of the plateau at high wavenumbers in the energy spectra (Voulgaris and Trowbridge 1998) and subtracting the product of the spectral level and the Nyquist frequency from the variance of the time series.

Two main types of measurements were made: profiles for evaluating flow statistics and in-beam measurements for time-series analysis. The measurements are summarized in Table 2, which also indicates the experiments in which the concrete blocks were present. Profiles of mean velocity, Reynolds stress, and turbulent kinetic energy measured with the three-beam and four-beam ADCP were compared to profiles of ADV point measurements. Profiles at a given location were measured with the ADCP first for the durations described below. The ADCP was removed, and a profile was measured with the ADV.

Instantaneous velocities were evaluated using in-beam measurements within the ADCP's sampling volume (Fig. 2). Simultaneous measurements in the same volume of water were possible because of the differences in instrument frequency and the nonintrusive nature of both the ADCPs and ADV. The ADV sampling volume was carefully positioned in the downstream beam of the ADCP, and measurements were made in several bins along the

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Table 2. Experimental Conditions

ADCP	Type	Distance from entrance (m)	Blocks present	I_u (%)	$\lvert dU/dx \rvert$ (10^{-3} s^{-1})[a]	r_x/ℓ
Four-beam ADCP	Profile	30.5	No	6–16	0.2	1.0
Four-beam ADCP	In-beam	30.5	No	6–16	0.2	1.0
Three-beam ADCP	Profile	29.0	Yes	10–14	0.6	0.8
Three-beam ADCP	Profile	13.7	Yes	20–32	2.6	2.6
Three-beam ADCP	In-beam	24.4	Yes	—	—	—

Note: In all runs, the discharge was approximately 0.3 m^3/s, and the water depth ranged from 0.85 to 0.89 m.

[a] Value is an average over the middle half of the profile.

beam. This radially projected velocity was then compared directly to the radial beam velocity recorded by the instrument; all data were averaged to achieve a recording rate of 0.4 Hz. The radial beam velocity is the most basic and direct velocity measurement made by the ADCP, and it is not affected by instantaneous inhomogeneity between beams.

ADCP measurements were recorded for at least 15 min and ADV measurements were recorded for 6 min. These durations were designed to capture many of the large scales of the flow and thereby approximate as closely as possible the asymptote of the cumulative average of the turbulence statistics. The integral time scale, which characterizes the time scale of the largest eddies, was computed from an autocorrelation (Tennekes and Lumley 1972) to be approximately 1.5–2 s. Thus, a 6-min duration sampled more than 100 large-scale structures. The flow was checked for stationarity using a 70-min time series, and no overall temporal trends were observed.

Calculations

Both ADCPs were oriented with at least one beam parallel to the flume sides (Fig. 2) to reduce contamination from acoustic reflections and to isolate streamwise velocity measurements from spanwise velocity measurements where possible. Beams 3 and 4 of the four-beam ADCP and Beam 1 of the three-beam ADCP were oriented in the streamwise-vertical plane. Resolved velocities were computed from radial beam velocities V, which are positive towards the transducer for the four-beam ADCP and negative towards the transducer for the three-beam ADCP. For time series analysis, the streamwise and vertical components of the ADV reference measurement from an in-beam time series were projected along the direction of the beam of the ADCP using

$$V = \pm u \cos\theta \mp w \sin\theta \tag{1}$$

where the upper sign is used for the three-beam ADCP and the lower sign is used for the four-beam ADCP.

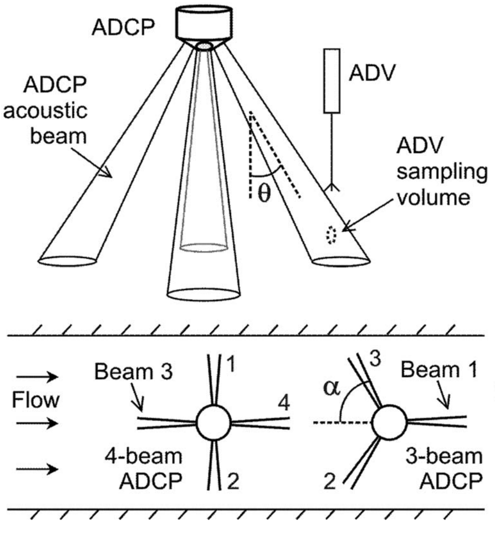

Fig. 2. Schematic of a four-beam ADCP and beam orientation for the two ADCPs. The placement of the ADV during in-beam tests is shown in the upper part of the figure.

Because the beams of the ADCP sample in different locations, homogeneity between the instantaneous velocity signals is unlikely. We follow Stacey et al. (1999) and assume homogeneity in the mean and variance of the velocity signal. Thus, the mean streamwise velocity can be computed from the four-beam ADCP measurements as

$$\bar{u} = \frac{\overline{V_3} - \overline{V_4}}{2\sin\theta} \tag{2}$$

and the three-beam ADCP measurements as

$$\bar{u} = \frac{2\overline{V_1} - \overline{V_2} - \overline{V_3}}{2\sin\theta(1+\cos\alpha)} \tag{3}$$

where α=half of the angle between the beams in a horizontal plane (Fig. 2) and an overbar denotes a time average value. Considering the variances of the four-beam ADCP beam velocities allows the Reynolds stress $-\overline{u'w'}$, where primes denote fluctuations from the time average, to be computed as

$$-\overline{u'w'} = -\frac{\overline{V_3'^2} - \overline{V_4'^2}}{4\sin\theta\cos\theta} \tag{4}$$

Reynolds stress cannot be computed from the three-beam ADCP without additional assumptions. Kawanisi (2004) expanded the beam velocities in a Taylor series about the center of the beam spread; his approach applied to our case (with θ=25° and α=60°) yields

$$\begin{aligned} -\overline{u'w'} = {} & -(\overline{u'w'})_{\mathrm{er}} + 0.58(\overline{V_1'^2} - \overline{V_2'V_3'}) \\ & - 0.29(\overline{V_2'^2} + \overline{V_3'^2} - \overline{V_1'V_2'} - \overline{V_1'V_3'}) \end{aligned} \tag{5}$$

where $(\overline{u'w'})_{\mathrm{er}}$ is an error term that depends on the beam spread and degree of inhomogeneity. [Errors in Eqs. (21) and (22) of Kawanisi (2004) are corrected in Eqs. (5) and (8) here (K. Kawanisi, personal communication).]

The turbulent kinetic energy $q^2/2 = (\overline{u'^2} + \overline{v'^2} + \overline{w'^2})/2$ cannot be computed with data from either ADCP without additional assumptions. Defining $\zeta = \overline{w'^2}/q^2$ and

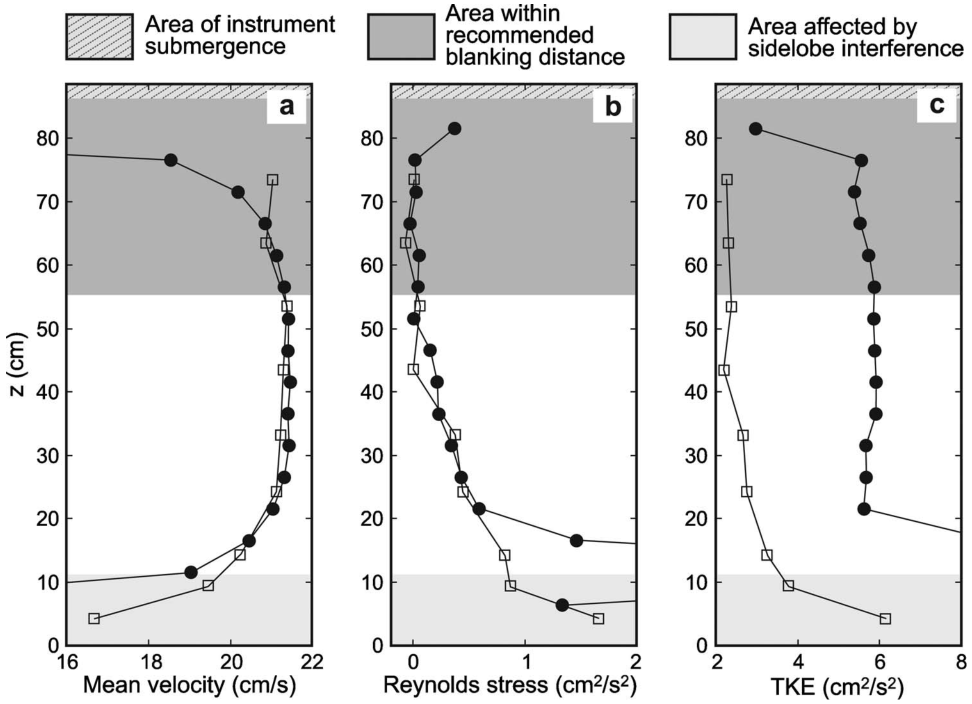

Fig. 3. Comparison between the four-beam ADCP (circles) and the ADV (squares) at the 30.5 m station: (a) mean velocity; (b) Reynolds stress; and (c) TKE estimated from Eq. (7) with $\zeta = 0.17$

$$S^2 = \frac{1}{4\sin^2\theta}\sum_{i=1}^{4}\overline{V_i'^2} = \tfrac{1}{2}(\overline{u'^2}+\overline{v'^2}) + \overline{w'^2}\cot^2\theta \qquad (6)$$

for the four-beam ADCP (e.g., Lohrmann et al. 1990) allows the TKE to be expressed as

$$\frac{q^2}{2} = \frac{S^2}{1+\zeta(2\cot^2\theta - 1)} \qquad (7)$$

Computing TKE with Eq. (7) requires a value of ζ to be assumed. Lohrmann et al. (1990) argued that $\overline{w'^2} < (\overline{u'^2}+\overline{v'^2})/2$, and thus that isotropy ($\zeta = 1/3$) would be a limiting case. For their measurements in a tidal, unstratified channel flow, Stacey et al. (1999) used measurements of Nezu and Nakagawa (1993), which yield $\zeta = 0.17$. [The numerical values in Eqs. (12a) and (12b) of Stacey et al. (1999) should be switched (M. Stacey, personal communication).] TKE can also be computed if instantaneous homogeneity is assumed. For the three-beam ADCP the TKE can be computed using

$$\frac{q^2}{2} = (\mathrm{TKE})_{\mathrm{er}3} + 1.312(\overline{V_1'^2}+\overline{V_2'^2}+\overline{V_3'^2}) - 1.109(\overline{V_1'V_2'}+\overline{V_1'V_3'}+\overline{V_2'V_3'}) \qquad (8)$$

while for the four-beam ADCP, the TKE can be computed using

$$\frac{q^2}{2} = (\mathrm{TKE})_{\mathrm{er}4} + \tfrac{1}{2}\left(1+\tfrac{1}{4}\tan^2\theta\right)S^2 + \frac{1}{16\cos^2\theta}[\overline{V_1'V_3'}+\overline{V_1'V_4'}+\overline{V_2'V_3'}+\overline{V_2'V_4'} + (1+4\cot^2\theta)(\overline{V_1'V_2'}+\overline{V_3'V_4'})] \qquad (9)$$

where $(\mathrm{TKE})_{\mathrm{er}3}$ and $(\mathrm{TKE})_{\mathrm{er}4}$ are error terms for the three-beam and four-beam systems, respectively.

Results and Discussion

The ability of each ADCP to reproduce profiles of mean velocity and turbulence quantities, including the Reynolds stress and turbulent kinetic energy, measured by the ADV is discussed, and then the results of in-beam measurements are presented. The results from the four-beam ADCP are not compared to the results of the three-beam ADCP because the ADCPs measured in different conditions (e.g., Table 2).

Four-Beam ADCP

The four-beam ADCP reproduced the mean velocity profile well [Fig. 3(a)]. At this downstream position in the flume, where the turbulence intensity $I_u = (\overline{u'^2})^{1/2}/\bar{u}$ was less than 0.16, the error was smaller than 3% in much of the interior of the flow. Measurement errors were larger near the instrument and bottom boundary of the flume. Near the instrument, measurements showed evidence of acoustic contamination from transducer ringing and flow disturbance caused by the ADCP head. A low bias affected the upper 15 cm of the four-beam ADCP profile [Fig. 3(a)]; we expect flow disturbance to contribute most of the bias, but because this portion is within the specified blank for general profiling, the bias could also be due to contamination resulting from ringing. While sidelobe interference should affect 6% of the profiling range of the four-beam ADCP, velocities were biased low in approximately the lower 15% of the profile. This effect should not be disregarded as a laboratory anomaly—it is important to consider sidelobe interference in the field, especially in boundary layer calculations—but the biases outside of the sidelobe area near the boundary could be a result of strong, directional acoustic reflections and lingering echoes unique to the laboratory. The limited profiling range also could contribute to this result (i.e., one bin represents a large portion of the water column). Low biases near the boundary may be difficult to detect because a decrease in velocity is expected; without an independent measurement for comparison, superimposed error could go unnoticed.

The four-beam ADCP measured the Reynolds stress profile accurately away from the bottom boundary [Fig. 3(b)]. The values from the four-beam ADCP and the ADV matched well in the upper 75% of the profile; in particular, effects of transducer ringing and flow disturbance from the instrument head appeared to be small. Near the flume bottom, however, the four-beam ADCP overestimated the Reynolds stress, even out of the area affected by sidelobe interference. Turbulence quantities measured with an ADCP should be less accurate closer to the solid boundary because the large eddies become smaller. For example, in the logarithmic region of the boundary layer, turbulence theory states that the large eddy size is κz, where $\kappa=0.4$ is von Kármán's constant. However, we estimate that the length scale of the large eddies was always larger than the horizontal dimension of the four-beam ADCP bin in our experiments.

Accurate profiles of Reynolds stress can be used to compute the shear velocity u_*, which is important in many hydraulics problems. For steady, uniform, turbulent flow, the Reynolds stress is given by

$$-\overline{u'w'} = u_*^2\left(1-\frac{z}{H}\right) \tag{10}$$

where H=water depth. Thus, the shear velocity can be estimated by fitting Eq. (10) to the Reynolds stress profiles. Reynolds stresses near the boundaries deviate from the linear profile that would be observed in uniform flow, but using the slope of the Reynolds stress profiles for z between 20 and 80 cm gives shear velocities of 0.94 and 0.93 cm/s for the ADV and four-beam ADCP with R^2 of 0.72 and 0.83, respectively. These estimates of shear velocity agree well, and they are about 24% lower than the shear velocity ($u_*=1.22$ cm/s) estimated from a logarithmic velocity profile fit over $0<z/H<0.2$.

The four-beam ADCP overestimated the turbulent kinetic energy [Fig. 3(c)]. The TKE estimated with Eq. (7) and $\zeta=0.17$ was more than a factor of 2 larger than the TKE measured with the ADV, and the TKE estimated with Eq. (9), assuming instantaneous homogeneity, was more than a factor of 4 higher (not shown). The value of ζ used in Eq. (7) comes from the exponential profiles suggested by Nezu and Nakagawa (1993) for open-channel flow. The TKE profile measured with the ADV qualitatively followed an exponential profile, but the depth-averaged value of ζ computed from the ADV was 0.24. Larger values of ζ would improve the agreement between the four-beam ADCP and ADV, but a value greater than the isotropic limit of 1/3 would be needed to achieve perfect agreement.

Several effects, including sidewall contamination and Doppler noise, could cause the TKE to be overestimated. Beams 1 and 2 of the four-beam ADCP, from which the transverse velocity v was determined, were perpendicular to the sidewalls. However, the beams were more than 0.6 m from the sidewalls; furthermore, the agreement between $-\overline{v'w'}$ measured with the ADCP and the ADV suggests effects of sidewalls are small. Stacey et al. (1999) showed that Doppler noise, modeled as Gaussian white noise in each beam, can cause a high bias in estimators related to TKE; they estimated the noise variance from histograms of quantities related to TKE and subtracted the noise from TKE estimates. The use of the four-beam ADCP's Mode 5 in our experiments complicates noise removal because in the high-resolution modes noise is correlated with the mean velocity (Stacey et al. 1999). Thus, in selecting the mode of operation, one should consider the trade-off between higher resolution and increased bias in TKE profiles.

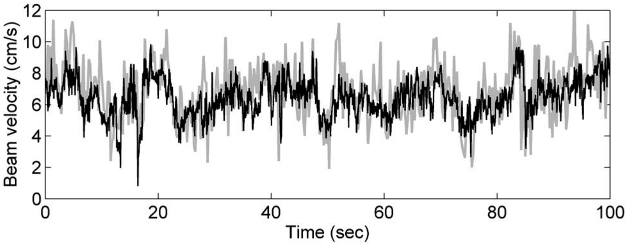

Fig. 4. Simultaneous colocated time series of radial velocity. The black line represents data from the ADV, and the gray line represents data from the four-beam ADCP.

Our second main set of measurements involved comparing ADCP radial velocities to ADV measurements in the ADCP beam. Qualitatively, the four-beam ADCP captured the trend of the ADV velocities over most of the record (Fig. 4), but the amplitude of the profiler's signal was larger, as the TKE results suggest it should be [Fig. 3(c)]. Quantitatively, the instantaneous accuracy of the ADCP can be measured with the correlation coefficient, defined for two time series, a and b, as $\rho_{\mathrm{ab}}=\overline{a'b'}/\sqrt{\overline{a'^2}}\sqrt{\overline{b'^2}}$; a correlation coefficient of 1 indicates perfect agreement between the two time series (assuming no average bias). The correlation between ADCP velocities and subsampled and averaged ADV velocities for a short time series was fair; four-beam ADCP correlation coefficients had an average of about 75% with values from individual records ranging from 67 to 84%. Correlation coefficients computed for the single-ping recording rate of the ADCP (time interval 0.2 s) were much lower, typically, 45–50%. Gartner and Cheng (1996) compared velocities from an ADCP and an electromagnetic current meter separated by about 50 m and found good correlation ($R^2>0.94$) between the records. Integral time scales (Tennekes and Lumley 1972) were compared by integrating the autocorrelation to the first zero crossing; the autocorrelation was calculated from ADCP beam velocities and ADV velocities resolved along the ADCP beam. The four-beam ADCP underestimated the integral scale measured with the ADV by a factor of 2–4.

Three-Beam ADCP

Results for the three-beam ADCP are shown at a downstream station (Fig. 5) and an upstream station (Fig. 6). The upstream station represents a challenge for an ADCP because the flow is more turbulent and instantaneous inhomogeneity is less likely to hold (Table 2). Values of I_u are 2–3 times higher than downstream, and values of dU/dx, which helps to quantify the uniformity of the flow, averaged over the center half of the profile are about four times higher upstream. Upstream the streamwise beam separation r_x is 2.6 times the integral scale ℓ on average, while downstream the beams span less than one large eddy. Therefore, the three-beam ADCP results should be less accurate upstream than downstream.

The three-beam ADCP reproduced the mean velocity profile well at the station farther downstream [Fig. 5(a)]. Over most of the profile, the error was less than 2%. In the highly turbulent conditions ($I_u>0.2$) 3–4 m downstream from the concrete blocks, measurement accuracy declined [Fig. 6(a)]; velocities measured with the three-beam ADCP were as much as 17% lower than velocities measured with the ADV. As Voulgaris and Trowbridge

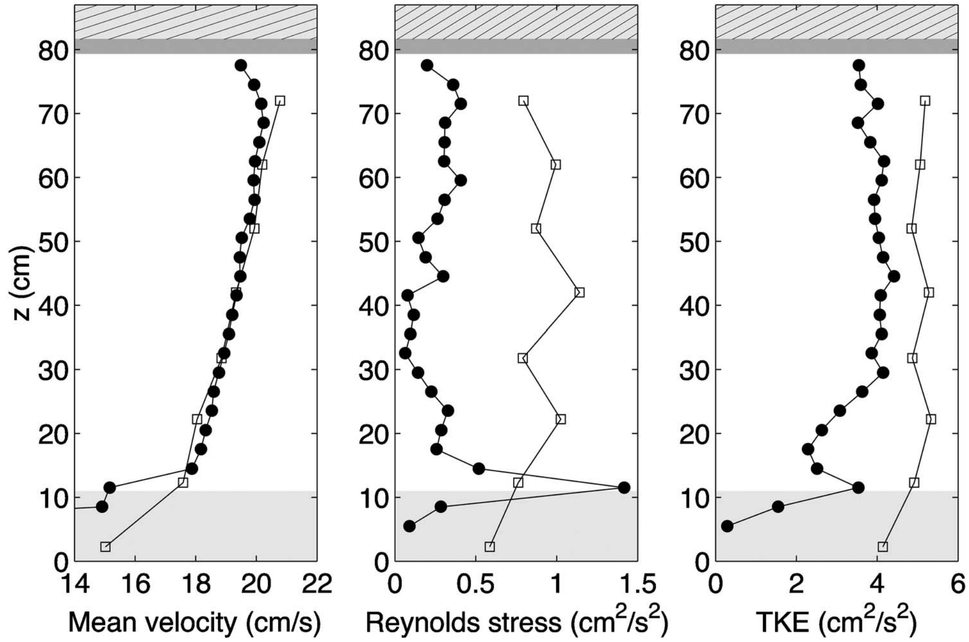

Fig. 5. Comparison between mean velocity profiles measured with the three-beam ADCP (circles) and ADV (squares) at the 29.0 m station: (a) mean velocity; (b) Reynolds stress; and (c) TKE. Shading is explained in Fig. 3.

(1998) discuss, turbulence within the sample volume contributes to Doppler bandwidth broadening, which leads to errors in the radial velocity measured with any coherent Doppler acoustic system; the spectral broadening increases with increasing size of the sampling volume and increasing dissipation of TKE. Larger errors occurred near the boundaries. Although Nortek specifies the minimum blanking distance for the three-beam ADCP as 5 cm, velocities within 10–15 cm of the transducers were biased low. Velocities in the area affected by sidelobe interference were also biased low.

Reynolds stresses from the three-beam ADCP, which were estimated by using Eq. (5) and ignoring the error term, underestimated the values from the ADV [Figs. 5(b) and 6(b)]. The concrete blocks changed both the shape and magnitude of the Reynolds stress profile. Reynolds stress profiles with the blocks differed greatly from the theoretical profile [Eq. (10)], and the values were large in the three-beam ADCP tests. At both stations, the profiles estimated with the three-beam ADCP qualitatively reproduced the trend with depth measured with the ADV. However, farther downstream from the concrete blocks, the three-

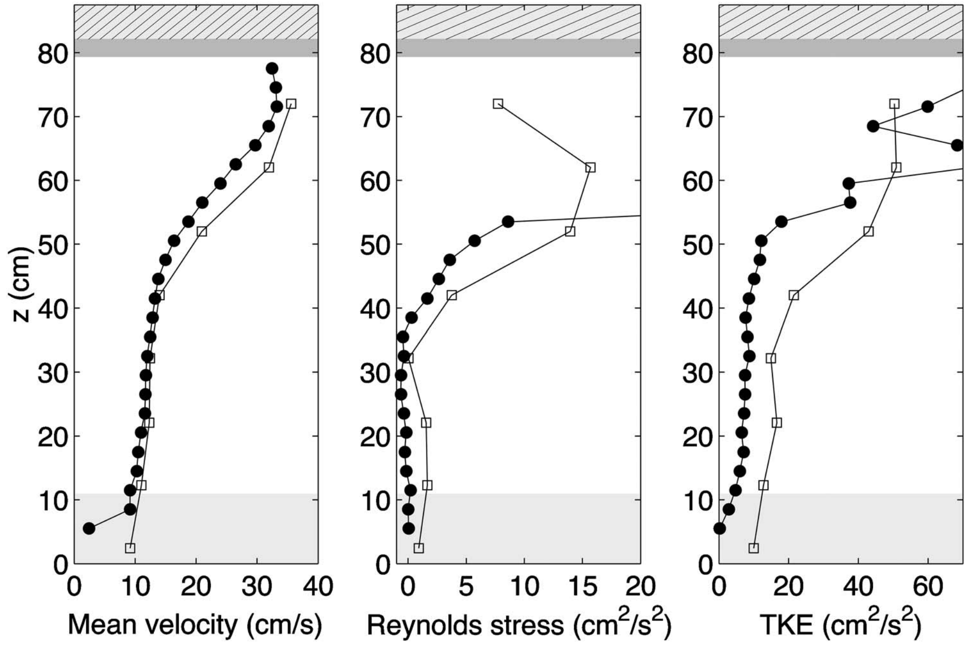

Fig. 6. Comparison between mean velocity profiles measured with the three-beam ADCP (circles) and ADV (squares) at the 13.7 m station: (a) mean velocity; (b) Reynolds stress; and (c) TKE. Shading is explained in Fig. 3.

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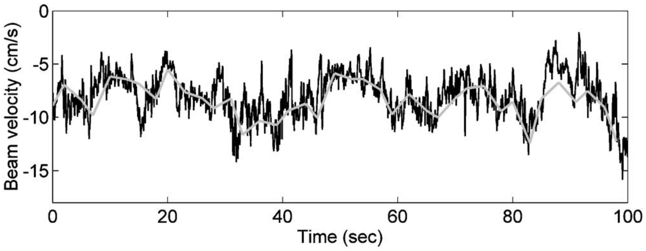

Fig. 7. Simultaneous colocated time series of radial velocity. The black line represents data from the ADV, and the gray line represents data from the three-beam ADCP.

beam ADCP values were low by up to 90% except for one point [Fig. 5(b)], and closer to the concrete blocks, the three-beam ADCP values were off by at least 55% and much more in the upper part of the profile [Fig. 6(b)].

Kawanisi (2004) discussed two sources of bias or error in three-beam ADCP measurements of turbulence: the finite time over which samples are averaged and flow inhomogeneity. He estimated that the former caused a low bias of 20% in his experiments, while the latter caused an error in Reynolds stress of about 5%. While Kawanisi's (2004) field comparison between an ADV and the three-beam ADCP showed no consistent bias, our laboratory results show that the three-beam ADCP almost always underestimated the Reynolds stress. One might expect the ratio of the integral length scale and the beam spread to indicate the importance of inhomogeneity effects; as the beams span more of the large eddies, the assumption of flow homogeneity should worsen. In our experiments, the integral length scale is larger than the beam spread in the top 20 cm of the water column, and it is comparable to or less than the beam spread in the bottom 50 cm. Our measurements do satisfy the criterion that Lu and Lueck (1999a) found for homogeneity of the first moments and Lu and Lueck (1999b) suggested for homogeneity of higher moments: The ADCP's sampling time captures between 190 and 1200 integral time scales.

TKE computed from three-beam ADCP measurements using Eq. (8) and assuming instantaneous homogeneity underestimated the TKE measured with the ADV [Figs. 5(c) and 6(c)]. As with the Reynolds stress, the TKE in the three-beam ADCP tests was large, and neither profile followed that given by Nezu and Nakagawa (1993). While the three-beam ADCP estimates followed the qualitative trend over most of the depth, the values at the station far downstream of the concrete blocks were lower by 20–45% [Fig. 5(c)], and the values at the station closer to the blocks were lower by 20–70% [Fig. 6(c)]. Part of the underestimation is due to the averaging of pings: When the time series from the ADV is subsampled at 8 Hz and 20 "pings" are averaged, the resulting TKE is less than that estimated from the ADCP measurements over most of the profile.

Qualitatively, the three-beam ADCP captured some of the large-scale (or low frequency) features of the time series (Fig. 7). Three-beam ADCP measurements were acquired at a much smaller rate than the ADV measurements (0.4 Hz compared to 25 Hz), but velocities measured with the profiler followed the same large-scale trends as those measured by the ADV. The three-beam ADCP captured flow structures with frequency of 0.2 Hz or less in many cases—for example, the large structure from approximately 45 to 60 s; in other parts of the time series, the profiler velocities fell below the ADV velocities (e.g., 85–95 s), and the low temporal resolution was apparent throughout the record. The three-beam ADCP in-beam measurements had an average correlation coefficient of 82%, with values from individual records ranging from 75 to 88%, and the three-beam ADCP overestimated the integral time scale by 60–80%.

Summary and Conclusions

Laboratory experiments were conducted to evaluate acoustic Doppler current profilers for measuring mean velocities and turbulence. Measurements with two commercially available acoustic Doppler current profilers—one with three beams and one with four beams—were compared to measurements with an acoustic Doppler velocimeter. Mean velocities, Reynolds stresses, turbulent kinetic energy, and in-beam time series were measured in a flow approximately 0.87 m deep with a maximum mean velocity from 20 to 30 cm/s.

The four-beam ADCP reproduced the profiles of mean velocity and Reynolds stress well. Near the instrument, errors were due to transducer ringing and flow disturbance, while near the bottom, errors were due to sidelobe interference. The four-beam ADCP measured the Reynolds stress profile accurately away from the bottom boundary, and shear velocities estimated by extrapolating the Reynolds stress profiles from the ADV and four-beam ADCP to the bottom agreed well. While the four-beam Janus configuration leads to accurate measurements of Reynolds stresses, further assumptions are needed to compute turbulent kinetic energy with the four-beam ADCP. The TKE measurements illustrate the tradeoffs involved in selecting the operating mode: While Mode 5 of the four-beam ADCP offers high resolution, the correlation between the mean velocity and noise does not allow the TKE measurements to be corrected. Measurements in a beam of the ADCP showed that four-beam ADCP velocities match those of the ADV with an average correlation coefficient of 75%, while estimates of the integral time scale are lower than those from the ADV by a factor of 2–4.

The three-beam ADCP reproduced the profile of mean velocity well in places with weaker turbulence, and the assumptions required to compute turbulence quantities with a three-beam system affected the estimates of the Reynolds stress and TKE. The mean velocities from the three-beam ADCP agreed best with the ADV measurements farther downstream from the concrete blocks. Reynolds stresses and TKE estimated from the three-beam ADCP fell below values computed from the ADV measurements. The average correlation coefficient for in-beam measurements with the three-beam ADCP was 82%, and three-beam ADCP estimates of the integral time scale were higher by 60–80%.

These laboratory experiments may represent a stringent test of the ability of ADCPs to measure mean velocities and turbulence. Because length and time scales of the turbulence in the laboratory flume will be smaller than those in a river or estuary, ADCPs may resolve the turbulence better in the field. Of course, since both the length scales and the beam spread increase, flow inhomogeneity will still affect the measurements. Further field tests of ADCPs in rivers would be worthwhile.

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Notation

The following symbols are used in this paper:

H = water depth;
$I_u = (\overline{u'^2})^{1/2}/\bar{u}$, streamwise turbulence intensity;
ℓ = longitudinal integral scale;
$q^2/2$ = turbulent kinetic energy (TKE);
r_x = beam separation in the streamwise direction;
$S^2 = \Sigma_{i=1}^{4}\overline{V_i'^2}/(4\sin^2\theta)$;
T = integral time scale;
u = streamwise velocity;
u_* = shear velocity;
v = transverse velocity;
V = radial ADCP beam velocity;
w = vertical velocity;
z = vertical distance from the flume bottom;
α = half-angle between ADCP beams in a horizontal plane;
$\zeta = \overline{w'^2}/q^2$, isotropy factor;
θ = angle between ADCP beam and vertical.
ρ_{ab} = correlation coefficient between two time series, a and b;
$\bar{\phi}$ = time-averaged value of ϕ; and
$\phi' = \phi\text{-}\bar{\phi}$, fluctuating value of ϕ.

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