LIMNOLOGY
and
OCEANOGRAPHY: METHODS

Limnol. Oceanogr.: Methods 5, 2007, 23–33

The accuracy of acoustic Doppler velocimetry measurements in turbulent boundary layer flows over a smooth bed

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Abstract

An evaluation of acoustic Doppler velocimetry (ADV) in the near-bed region of turbulent boundary layer flows is presented. Acoustic instruments have large sampling volumes compared with the smallest scales of motion in turbulent flows. This limits the accuracy of the technique, especially when making measurements close to the bed or in flows where large spatial gradients are present. These limitations are quantified by comparing ADV results to laser Doppler velocimetry (LDV) measurements from the same flow, and to direct numerical simulations of similar flows. A SonTek 16 MHz ADVField system was used in the evaluation. Measurements were made in a turbulent boundary layer over a smooth bed in a laboratory flume. The instrument was evaluated in both a fast and slow flow case with free stream velocities similar to those found in many natural environments. Additionally, results from an assessment of ADV sample volume size and position are reported. Mean velocities were within 5% accuracy down to 0.7 cm from the bed for the fast flow case and 1 cm for the slow flow case. ADV-derived Reynolds stresses matched well with those from LDV to within 1-2 cm of the bed, however turbulence intensities were found to deviate markedly up to 3-4 cm from the bed in some cases. In general, errors are largest close to the bed, but extend further away from the bed than reported in previous studies.

Acoustic Doppler velocimetry (ADV) is a popular technique for quantifying turbulent fluid flows in aquatic, marine, and laboratory environments. The technique relies on the Doppler shift principle to measure the velocity of suspended scattering particles that are assumed to move passively with the flow. Descriptions of ADV principles of operation are given by Lohrmann et al. (1994), Sontek (1997), and Voulgaris and Trowbridge (1998). The velocimeter employed in this evaluation is a SonTek 16 MHz MicroADV with the ADVField signal processing hardware enclosed in a splash-proof housing. This is a newer generation instrument that is advertised as having better spatial and temporal characteristics than the original SonTek 10 MHz and 5 MHz Ocean probes. These attributes make the 16 MHz model ideal for laboratory and turbulence measurements; however all of the models are available with ADVField processors enabling the probe to be used in the field. Acoustic instruments have a sampling volume (located at the intersection of the transmitting and receiving beams) that is large compared to the smallest scales of motion in turbulent flows. This limits the resolution and signal-to-noise (SNR) performance of the instrument, particularly in flows with small-scale turbulence and large velocity gradients. Thus, the ADV technique is subject to certain limitations in different flow regions and conditions. In this study, we evaluate ADV system performance by using the instrument to measure controlled laboratory flows. ADV results are compared to laser Doppler velocimetry (LDV) measurements in the same flow and to direct numerical simulations (DNS) of similar flows. The mean flow rates are designed to mimic those typically found in natural marine and aquatic systems so as to provide a useful guide for users interested in field and laboratory study.

Acoustic Doppler velocimetry—ADV is often used in studies of turbulent processes in limnology (e.g., Cornelisen and Thomas 2004; Tritico and Hotchkiss 2005; Venditti and Bauer 2005), oceanography (e.g., Yahel et al. 2002; Talke and Stacey 2003; Butt et al. 2004), and benthic ecology (e.g., Eckman et al. 1990; Friedrichs et al. 2000). The technique has been employed in a range of flow conditions, including natural stream environments (Lane et al. 1998; Mutz 2000; Carollo et al. 2002), estuaries (Kim et al. 2000), natural and artificial wave environments (Osborne et al. 1997; Doering and Baryla 2002), and artificial channels (Cheng and Chiew 1998; Car-

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Acknowledgments
This research was supported by the National Science Foundation (Grant IOB-0131553). The project benefited greatly from background research conducted by Erin Carlson. We are also grateful for the thoughtful comments of three anonymous reviewers.

bonneau and Bergeron 2000; Nikora and Goring 2000; Lawless and Robert 2001). ADV is typically used to measure mean velocities, the strength of the velocity fluctuations away from the mean (turbulence intensities), and temporal correlations between the directional components of these fluctuations (turbulent Reynolds stresses).

Laser Doppler velocimetry—The LDV technique (see Adrian and Thompson 1993; Albrecht et al. 2003) is similar to ADV in that it relies on the Doppler shift principle to measure the velocity of suspended scattering particles in the flow. However, laser Doppler instruments have smaller sampling volumes than acoustic Doppler instruments due to the fact that light waves are much shorter in wavelength than sound waves. LDV is a commonly used technique for the characterization of boundary layer turbulence, primarily because the measurement volume is nonintrusive and small relative to the scales of motion in turbulent flows. This allows the user to make highly spatially and temporally resolved measurements throughout the boundary layer, including the near-bed region. While generally not practical for field use, LDV is used extensively to examine turbulent flow in laboratory flumes (e.g., Nezu and Rodi 1986; Crimaldi et al. 2002).

This study adds to a collection of work from researchers reporting on the accuracy and performance characteristics of ADV systems. Early evaluations of ADV directly compared the technique with results from LDV (Kraus et al 1994; Lohrmann et al 1994), although this was a mostly qualitative assessment of its performance. While these comparisons generally showed favorable agreement, the techniques were not tested in challenging conditions, such as in the near-bed region, and there was no objective comparison with known flow statistics. A similar study conducted by Voulgaris and Trowbridge (1998) produced a "ground-truth" estimate of true flow characteristics in a water flume. The estimate was derived from both ADV (10 MHz model) and LDV measurements and was used as a baseline of comparison for the instruments. The ADV measurements compared favorably with the "ground-truth" estimate, however the LDV measurements differed significantly. Most of the data were above 10 mm from the bed, although one experiment set that did include data points as close as 3 mm to the bed suffered from a failure of the LDV instrument and, therefore, direct comparison and ground-truthing was unavailable. Finelli et al. (1999) extended the evaluation of ADV to the near-bed region by comparing the technique to hot-film velocimetry. It was shown that accurate knowledge of the sample volume size and location is necessary for making measurements near the bed. Good agreement between the two instruments (within 5%) was found above 10 mm from the bed, however, below this point ADV velocities were as much as 80% lower. Similar to other reports on accuracy of ADV, the comparison gave an evaluation relative to another measurement technique without an objective method of independent evaluation. Furthermore, turbulent fluctuations were not included in the hot-film velocimetry results. The authors expressed the need for further research to be done in evaluating performance within 1 cm of the bed.

In this paper, we present direct comparisons of ADV and LDV data in the same flow. We also provide DNS results of comparable flows by Spalart (1988). While the DNS cannot capture all the finer details of our laboratory flow, the agreement between the theoretical predictions and our LDV measurements is shown to generally be excellent. This provides additional confidence for the LDV results to be used as an independent baseline in evaluating ADV performance. The aim of the study is to provide an evaluation of ADV at flow rates typical of what might be found in natural environments, including an evaluation of data from the near-bed region. An independent evaluation of measurement volume size and location was also performed, which allowed for precise alignment between the ADV sampling volume, the bed of the flume, and the LDV. The results of this paper will help researchers to understand the accuracy of acoustic Doppler systems, especially within a turbulent boundary layer.

Error sources—Before proceeding to our study, we first review error sources related to the ADV technique. ADV is subject to several sources of error related to the size of the measurement volume and the nature of the acoustic system. Firstly, positioning errors of the sampling volume can result in interpretation errors in both turbulence statistics and mean velocities when measuring flows in the near-bed region. Finelli et al. (1999) developed a method for mapping the vertical size and position of the sample volume by systematically moving the instrument vertically over an acoustic target and quantifying the signal response. The results of the mapping procedure found the sample volume to be significantly larger (12.5-15.8 mm, depending on setup) than reported by the manufacturer, and their determination of the sample volume position differed from that reported by about 4 mm. These discrepancies are especially problematic when making measurements near the bed where large gradients are present. Another source of error in ADV measurements is Doppler noise, which is intrinsic to the technique and can add a significant positive bias to the velocity power spectrum (Lohrmann et al. 1994). This "white noise" can be identified as an added noise floor in the high frequency region of the spectrum. Typically, Doppler noise does not bias the mean velocity measurements or the Reynolds stresses (as long as the noise is uncorrelated between the channels upon which the statistic is based and the signal strength is equal between the receiving beams). However, the effects do change the unidirectional statistics associated with the fluctuating time series (e.g., turbulence intensities). Increased spatial averaging can reduce this type of noise, however the corresponding loss in resolution may offset any improvements in accuracy. Thus, the instrument is typically set up with a nominal sample volume size that represents an optimization between an acceptable noise level and the ability to resolve pertinent spatial scales. Voulgaris and Trowbridge (1998) compared two methods of removing noise from ADV data in post-processing. The first method was spectral analysis, removing the noise tail in the power spectrum. The second method used the results of the ground-truthing technique but was potentially biased high due to inclusion of errors related to the ADV and LDV techniques. Voulgaris and Trowbridge (1998) also identify errors resulting from limitations in the ability of the system to resolve the Doppler shift of the acoustic pulse and errors due to mean velocity shear within the sample volume.

Materials and procedures

Laboratory facility—The experiments were performed in a recirculating water flume at the University of Colorado. The flume test section features a glass bed and walls and is 15 m in length and 1.25 m across. A stainless steel rod that trips the turbulent boundary layer is mounted 0.30 m downstream from the beginning of the test section. At the end of the test section, different size weir plates are used to adjust the running depth of the flow. Two digitally controlled pumps ensure accurate and repeatable flow conditions.

Acoustic Doppler velocimeter—The SonTek 16 MHz MicroADV system used in this study has a 40-cm down-looking three-dimensional (3D) stem. The manufacturer specifies a nominal sample volume height of 9 mm and a distance of 50 mm from the transmitter to the center of the sample volume. The system components include the probe, signal processing hardware, and communication and power cables. The processing module is available as either the ADVLab model (PC card) or the ADVField model (splash-proof housing or submersible canister). Any probe of a given frequency can be used with a processing module of that frequency, provided that the cables and connectors are compatible (SonTek 1997). The system was operated at a 10 Hz sampling rate using firmware version 8.04. The ADV cannot resolve frequencies above 4 or 5 Hz as seen by a flattening at the noise floor of turbulence spectra (Carlson 2003). Sampling at 10 Hz captures all signal content up to 5 Hz. Sampling at a higher frequency than 10 Hz would not provide any improvement in resolution, and would merely provide redundant data that were not statistically independent from the 10 Hz data. The instrument has five user-selectable velocity range settings. At each measurement point in a profile, we used the minimum velocity range such that the mean velocity and fluctuations recorded by the instrument were within the bounds of that range.

Laser Doppler velocimeter—The LDV is a Dantec Dynamics 2-component fiber optic system with a 112 mm diameter probe, and uses a BSA F60 processor running Flow Software version 4.0. The probe has an 800 mm focal length with an expansion ratio of 1.5, producing a measurement volume 0.080 mm in diameter and 1.17 mm in length. The longer dimension is aligned horizontally, perpendicular to the mean flow direction. The LDV probe contains both transmitting and receiving optics, and operates in backscatter mode. It is mounted on a 3D automated traverse that is controlled through the BSA software. The LDV is driven with 700 mW of argon-ion laser power.

Procedure—LDV velocity measurements rely on light scattered from a measuring volume formed by the intersection of two or more laser beams. The intersecting beams create a pattern of interference fringes, and the calibration of the instrument is based on the spacing of the fringes. The spacing depends only on the laser wavelength, which is known, and the beam crossing angle, which can be accurately measured. We calibrated the LDV by calculating the beam crossing angle from measurements of the beam spacing at a given distance from the intersection at the measurement volume. Error associated with this calibration was less than 1%.

The manufacturer tested the ADV alignment prior to data acquisition. The instrument output was also calibrated to match mean free stream velocities reported by our LDV at a mean flow rate of 14.5 cm/s. SonTek made this adjustment by redefining the transformation matrix in the configuration file, and it represented a change of less than 5% relative to the original factory settings. The configuration file is loaded by the HorizonADV software and is used for transforming the raw measurements into an orthogonal coordinate system. The size and location of the sample volume was determined using the mapping procedure detailed by Finelli et al. (1999). To do this, the instrument is systematically lowered over a fine crosshair while measuring the signal response. The resulting SNR ratio reported by the instrument varies as a Gaussian with crosshair position; the peak of the Gaussian corresponds to the sample volume center. This information was used to calibrate a vertical scale and align the ADV and LDV sampling volumes for comparative measurements. ADV and LDV measurement locations are always referenced from the center of their sample volumes (i.e., a measurement location of 2 cm indicates that the center of the sample volume is located 2 cm from the bed).

The flow tests were conducted at two flow settings for comparison with Spalart's (1988) data at $Re_\theta = 670$ and $Re_\theta = 1410$. Table 1 contains the setup parameters and flow conditions for each recorded data set. Twenty-minute sample records from each point in the flow were used to produce profiles of velocity and calculate turbulence statistics. The LDV profiles consisted of 29 points spaced logarithmically from 0.50 mm to 250 mm above the bed. The ADV profiles consisted of 21

Table 1. Flume conditions and flow parameters for the slow and fast flow cases during operation of each instrument

	Slow flow		Fast flow	
	LDV	ADV	LDV	ADV
Static water depth (cm)	26	26	28.3	28.3
Water temperature (°C)	21.75	18.5	22	21.5
U_{free} (cm/s)	6.7	6.9	14.6	14.9
U*	0.34	0.34	0.68	0.68
$Re_{ø}$	730	860	1500	1600

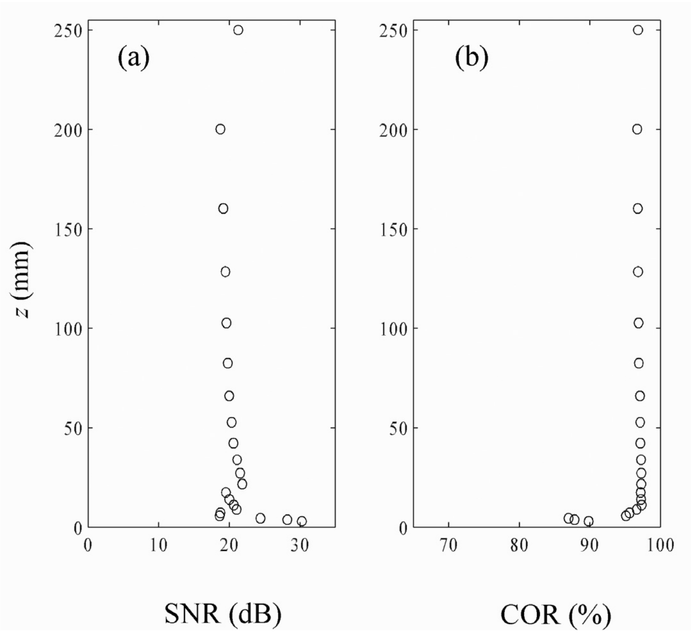

Fig. 1. Profiles of (a) signal-to-noise ratio (SNR) and (b) correlation (COR) for the $Re_\theta = 670$ flow case. Profiles represent an average over the sampling period from the 3 transmit beams of the ADV.

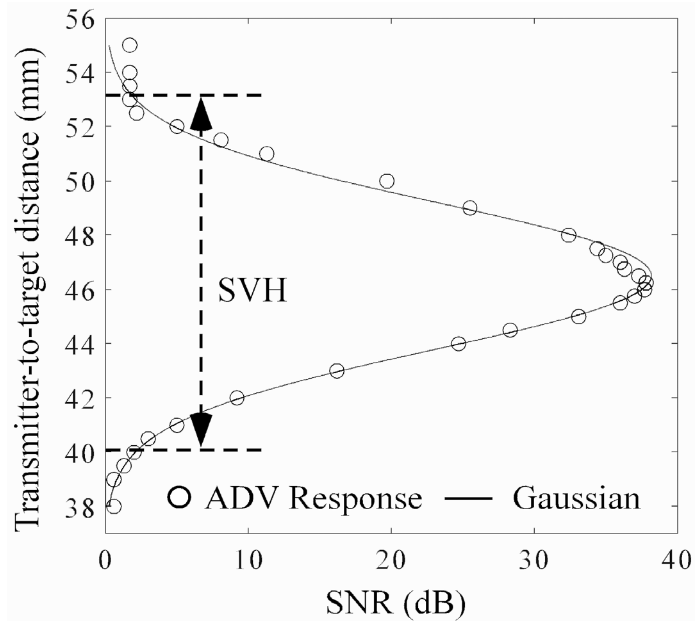

Fig. 2. Sample volume mapping. Vertical axis is the distance from the ADV transmitter to the crosshairs and horizontal axis is the signal response from the instrument. Symbols are SNR data from the ADV, and the line is a least-squares Gaussian fit to the data. The results indicate a sample volume with a height (SVH) of 1.3 cm and centered 4.6 cm from the transmitter (edges defined at e^{-3} of the peak signal response).

points spaced logarithmically from 3 mm to 240 mm above the bed. The sampling time (and by extension, the averaging period) is designed to be sufficient in extent to ensure sufficient statistical convergence. The ADV and LDV were operated independently because they have different particle seeding requirements for optimum performance. The seeding particles used for the ADV are larger than those for the LDV, and their presence in the flume causes the LDV to report lower peak turbulence statistics. The flow depends only on temperature, flow depth, and pump settings, the latter two of which we have precise control over. Temperature effects are very minimal and are removed in the nondimensionalization scheme by using a temperature-dependent value for the kinematic viscosity, ν. Although the profiles were not taken simultaneously, the facility provides extremely stable flow conditions over time and highly repeatable statistics.

There are narrow vertical regions within an ADV profile where anomalous readings may occur due to acoustic interference with the bed. This occurs when the time for the first acoustic pulse to travel from the transmitter to the boundary and back to the transmitter is equal to the pulse lag plus the time for the second pulse to travel from the transmitter to the sample volume and back to the transmitter (Carlson 2003). We avoided sampling in the regions where these interferences can occur.

Data quality was monitored through SNR and correlation (COR), which the ADV provides as feedback in real-time as well as in recorded data. In Fig. 1, we present typical profiles of SNR and COR, plotted against *z* (mm), the measurement height above the bed. The profiles are averaged over the sampling period and across the three transmit beams. Although not presented here, we found the individual response of the three beams to be quite similar.

Assessment

Sample volume mapping—Sample volume mapping addresses two issues related to positioning of ADV systems: (a) quantifying the location of the sample volume in relation to the transmitter and (b) quantifying the vertical extent of the sample volume. The procedure provides an independent method of determining the size and position. The vertical extent of the sample volume is identified as the region where the signal strength is large relative to background noise (Sontek 1997). Fig. 2 displays the signal response as a function of sample volume position. We chose to define the edges of the sample volume at e^{-3} of the peak signal, as this results in a conservatively large estimate of the vertical extent. For comparative purposes, e^{-3} corresponds to bounds at 5% of the peak signal whereas e^{-2} corresponds to bounds at 14% of the peak signal. From the mapping procedure, we found the ADV sample volume to be 1.3 cm in vertical extent and centered 4.4 cm from the probe tip. This compares with nominal measurements of 0.9 cm and 5 cm reported by the manufacturer, respectively. With a 1.3 cm measuring volume, an instrument height of 0.7 cm would place the lower edge of the sampling volume just above the bed surface. Finelli et al. (1999) describe similar discrepancies between the mapped sample volume size

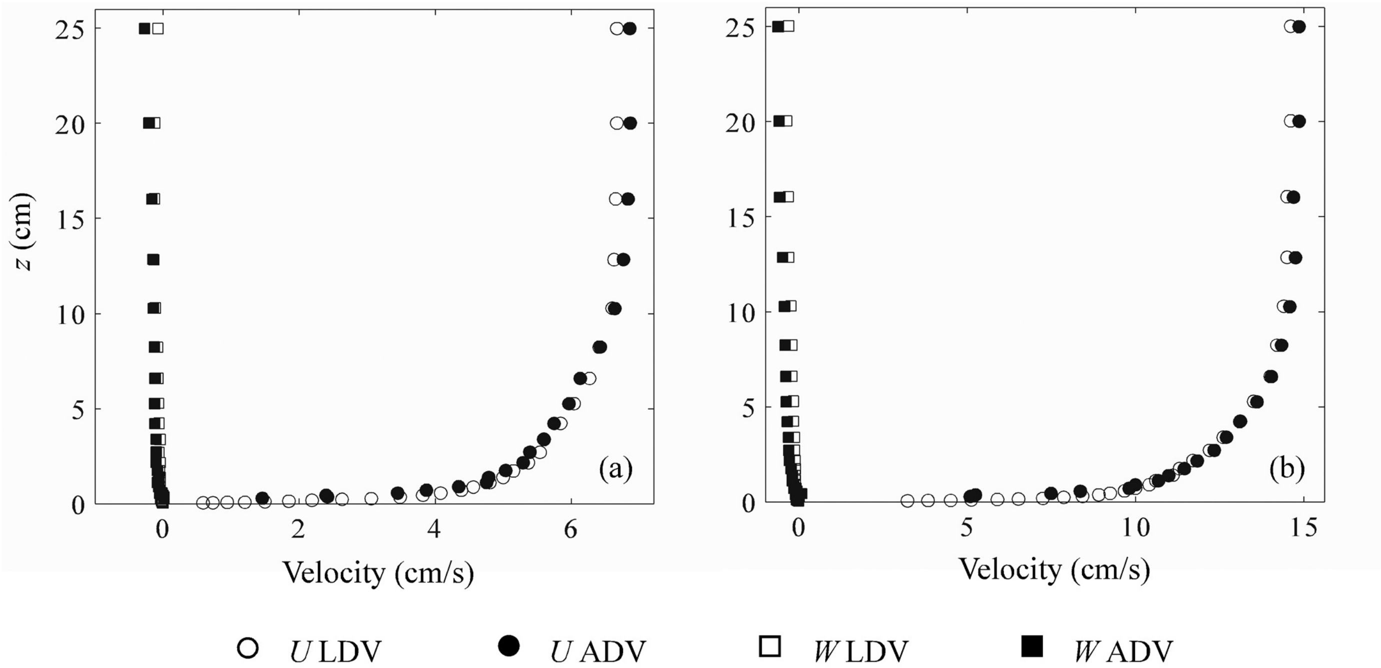

Fig. 3. Dimensional velocity profiles in the streamwise and vertical components for (a) Re_θ = 670 and (b) Re_θ = 1410 flow cases.

and what the instrument reports. Error in vertical placement of the sample volume due to user error is estimated to be within 0.02 cm.

Results

The velocity signal is decomposed according to $\tilde{U} = U + u(t)$, where U is the mean velocity and $u(t)$ is the fluctuating component. The mean velocity is also described nondimensionally as $U^+ = U/u_\tau$, where the shear velocity, u_τ, is a measure of shear stress at the bed. It is obtained by fitting the mean velocity profile to the law-of-the-wall, as shown in Fig. 4. The shear velocity used in nondimensionalized statistics was derived from the LDV data; however the difference between LDV-derived and ADV-derived shear stress values was less than 1% for the slow flow case and 3% for the fast flow case. Vertical location is specified in terms of the nondimensional wall unit z^+, defined as $z^+ = zu_\tau/\nu$, where z is the distance from the bed to the center of the sample volume and ν is the kinematic viscosity. Fig. 3 contains dimensional velocity data and Figs. 4-6 contain nondimensional velocity, variance, and Reynolds stress profiles. The figures compare ADV data (closed symbols) with LDV data (open symbols). Also shown in the figures are DNS results (solid line) by Spalart (1988). The LDV data are used as the baseline because it is considered to be the best estimate of true flow characteristics in the flume, because the technique does not suffer from the same spatial averaging problems that are inherent to the ADV technique. Streamwise and vertical turbulence intensities $\overline{u^2}$ and $\overline{w^2}$, and the Reynolds stress correlation $\overline{uw}$, are normalized by u_τ^2, the square of the shear velocity. The statistics are plotted versus z^+ on the left axis and z on the right axis. Results are shown for Re_θ = 670 (Figs. 3a-6a) and Re_θ = 1410 (Figs. 3b-6b) flow cases. For the Re_θ = 670 flow case, the ADV mean velocities were within 5% of the LDV mean velocities when the center of the sample volume was at or above about 1 cm from the bed (Fig. 3a and Fig. 4a). For the Re_θ = 1410 flow case, 5% accuracy was achieved above about 0.7 cm from the bed (Fig. 3b and 4b). This vertical location is consistent with our mapping results. A 0.7 cm sampling height would place the bottom of the measurement volume (1.3 cm total vertical extent) just above the bed of the flume. However, for the Re_θ = 670 flow case, the ADV results began to lose accuracy above where the sample volume would be expected to interfere with the bed. ADV measurements of mean velocity can be biased due to averaging spatial gradients, interfering with the static bed, or some combination of the two. One explanation for the discrepancy is the changing shape of the velocity boundary layer as Reynolds number varies. As the shape of the profile changes within the sample volume, spatial averaging could lead to accuracy differences in the velocity calculation. Voulgaris and Trowbridge (1998) investigated this effect by comparing an area-integrated velocity to the instrument's arithmetic average and found it to be only on the order of 0.1%, significantly less than the discrepancy reported by our ADV. They attributed velocity underestimation to problems in aligning the sample volumes of the LDV and ADV. This is a reasonable conclusion given that they did not conduct a sample volume mapping to verify the size and location of the sample volume. However, we experienced

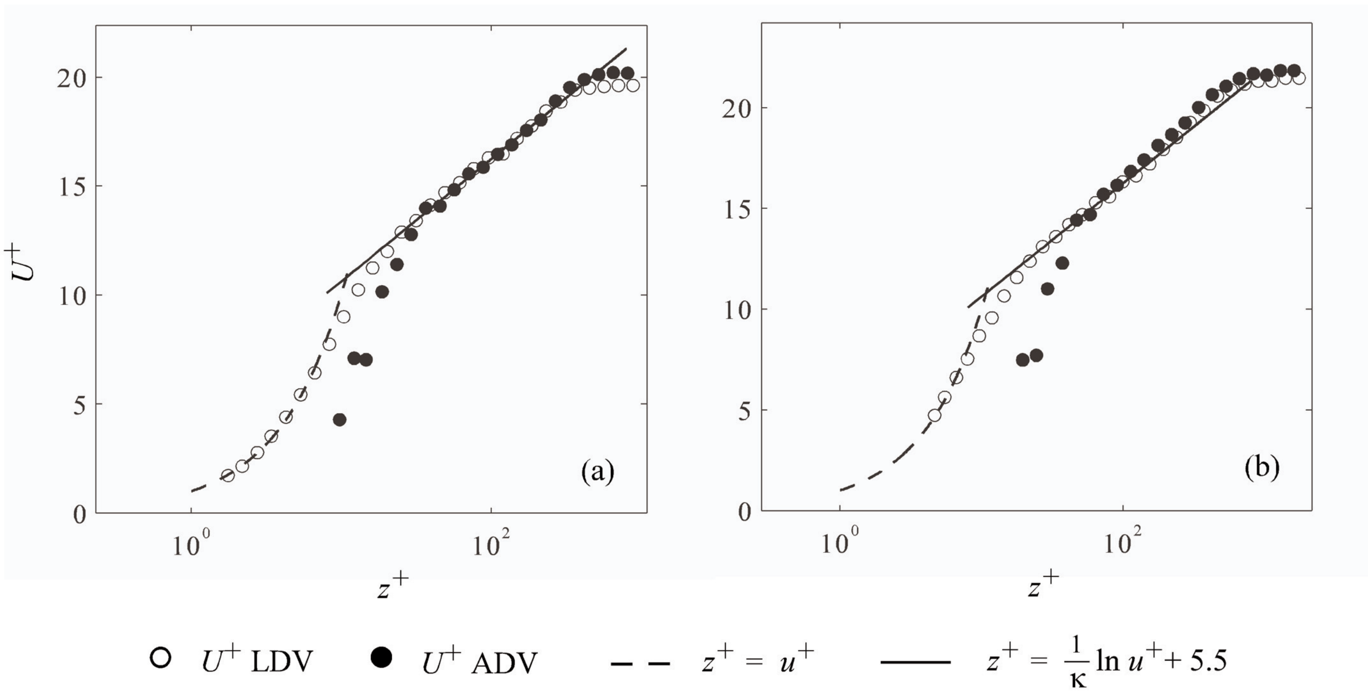

Fig. 4. Nondimensional streamwise velocity profiles for (a) $Re_\theta = 670$ and (b) $Re_\theta = 1410$ flow cases. The smooth line is direct numerical simulation by Spalart (1988).

this underestimation of velocity despite having accurately positioned the instruments. The second potential source of error in mean velocity measurement is interference with the bed. At 0.3 cm, the lowest point at which we took data, 25% of the sample volume is below the bed surface. Correspondingly, mean velocities measured closest to the bed suffer from significant bias and are underestimated by a factor of two. If the mapping procedure correctly predicts the vertical extent of

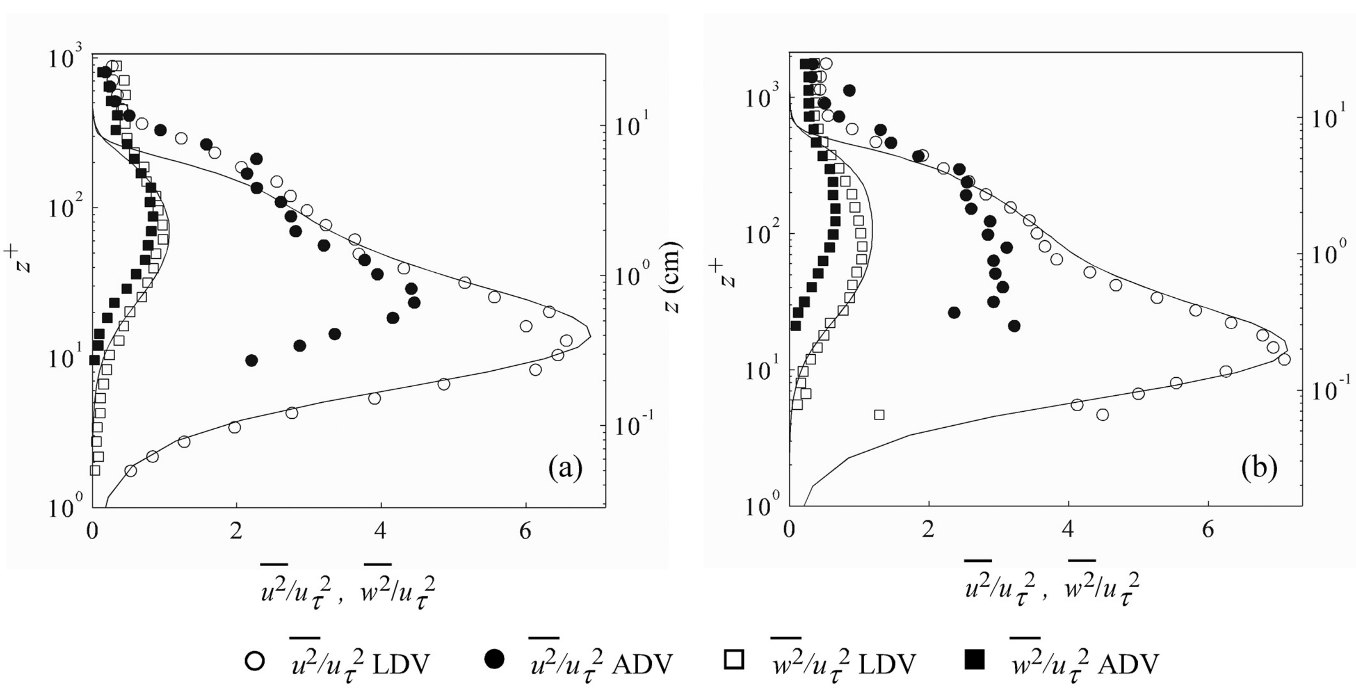

Fig. 5. Nondimensional turbulence intensities for (a) $Re_\theta = 670$ and (b) $Re_\theta = 1410$ flow cases. The statistic is nondimensionalized by the shear velocity, u_τ^2, and is plotted against dimensionless z^+ on the left axis ($z^+ = zu_\tau/\nu$) and dimensional z on the right axis (cm). The smooth line is direct numerical simulation (DNS) by Spalart (1988).

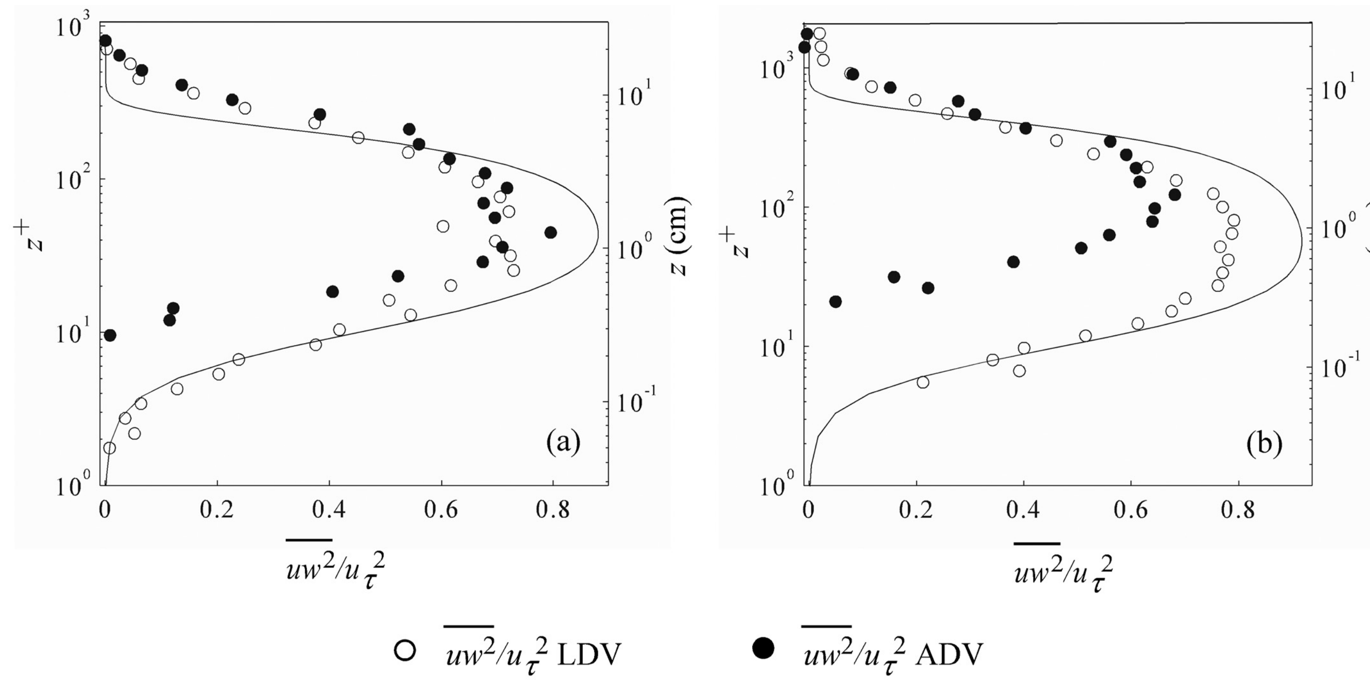

Fig. 6. Nondimensional Reynolds stress for (a) $Re_\theta = 670$ and (b) $Re_\theta = 1410$ flow cases. The statistic is nondimensionalized by the shear velocity squared, u_τ^2, and is plotted against dimensionless z^+ on the left axis ($z^+ = zu_\tau/\nu$) and dimensional z on the right axis (cm). The smooth line is DNS by Spalart (1988).

the sample volume, then measurements taken above 0.7 cm should be free from this bias. It is conceivable, however, that the signal response from a large static object such as the wall is more pervasive (and therefore extends further) than predicted by a much smaller acoustic target. Finelli et al. (1999) reported that the mean velocities were accurate to within 1 cm of the bed for mean freestream flows of approximately 20 cm/s and 40 cm/s. They then provided some simple calculations showing that velocity underestimation within 1 cm of the bed is greater than what would be predicted based on spatial resolution. It is likely that the full extent of errors in mean velocity measurements is due to some combination of factors related to the sample volume size.

In addition to mean velocities, statistics such as turbulence intensities and Reynolds stresses are commonly calculated using ADV velocity records. In Fig. 5, we present streamwise ($\overline{u^2}$) and vertical ($\overline{w^2}$) turbulence intensities, normalized by the shear velocity squared, u_τ^2, and plotted in terms of wall units (z^+, left-hand axes) and dimensional distance from the wall (z, right-hand axes). The LDV data are generally in close agreement with the DNS results for both flow cases. The flow statistics in the flume (as quantified by the LDV) deviate from the DNS results in places due to details of the flow in our flume. In particular, the flow in the flume has a weakly turbulent freestream (with nonzero turbulence intensities), whereas the DNS results have a laminar freestream (with turbulence intensities asymptoting to zero). So, whereas the DNS results are useful for verifying that the flow in the flume has a well-behaved boundary layer, the actual details of the local flow statistics in the flume are best quantified by the LDV results. The turbulence intensities calculated from ADV data follow three broad generalizations: (1) they are artificially low, (2) the error increases close to the bed, and (3) the magnitude of the errors (and the distance from the wall at which they appear) is larger for the faster flow case. These generalizations are all consistent with data averaged within a large sample volume, which (1) spatially averages some energy out of the flow, (2) is biased by the presence of a solid boundary close to the sample volume, and (3) averages mean spatial gradients, which are more severe in faster flows. Near-bed errors in ADV measurements are well known and have been reported elsewhere. However, the distance from the wall to which the errors persist is surprising, especially in the faster flow case. In this case, the turbulence intensities deviate markedly from the LDV results as far as 3 to 4 cm from the wall. In addition, the vertical location of the peak streamwise intensity value is significantly overestimated by the ADV. This is due to the ADV measurement volume interfering with the bed at locations where the LDV and Spalart report the highest streamwise turbulence levels. The interference causes values at these locations to be greatly underreported due to incursion of the static bed into the sample volume. The ADV is more accurate in estimating the vertical location of the peak intensity in the w-direction due to the vertical structure

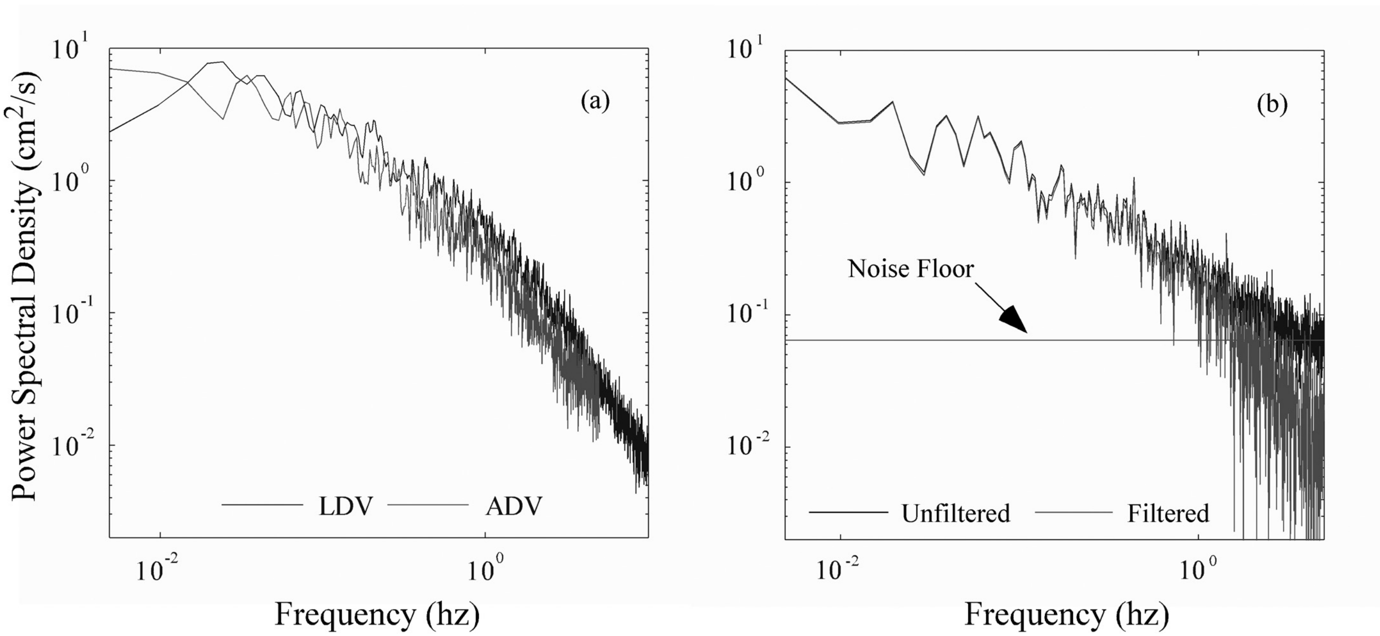

Fig. 7. Power spectral density (PSD) for the streamwise (Re_θ = 1410) flow component of (a) the LDV and ADV at z = 0.7 cm above bed and for (b) the ADV with noise floor demarcated by a solid black line.

of the boundary layer. The presence of the solid boundary means that turbulent fluctuations in the vertical direction peak at larger distances from the bed. ADV measurements can be made at the higher locations without suffering from interference between the sample volume and the bed. Voulgaris and Trowbridge (1998) also reported better accuracy in the vertical direction.

Fig. 6 contains Reynolds stresses ($\overline{uw}$) calculated with ADV data, again compared with LDV data and DNS results for both the Re_θ = 670 (Fig. 6a) and Re_θ= 1410 (Fig. 6b) flow cases. The LDV data show that the Reynolds stresses in the flume are similar to that predicted by the DNS results, with the exception of larger values in the freestream, and smaller values near the Reynolds stress peak. When comparing the Reynolds stresses calculated from the ADV data with those from the LDV, the agreement is seen to be very good for distances from the wall greater than 1 to 2 cm. Below that location, the ADV Reynolds stresses are underpredicted, and the error is larger closer to the wall and for the faster flow case.

Spectral analysis—Accurate experimental estimation of turbulence statistics relies on adequate spatial and temporal resolution in the measurement technique, combined with a sufficiently high SNR ratio. Although turbulence statistics are typically calculated in the time domain for the sake of convenience, an evaluation of the spatial, temporal, and noise characteristics of data from a particular technique can be more conveniently examined in the frequency domain. Time series data are easily converted into the frequency domain using Fourier techniques, whereby the frequency (or, alternatively, wavelength) content of a particular statistic can be determined. The power spectral density (PSD) calculation (e.g., Bendat and Piersol 1984) converts the time history of a statistic into frequency space, showing how contributions to the variance are distributed with respect to their frequency (or wavelength) content. Typically, the PSD is normalized such that it integrates to the variance of the input signal. From the spectral perspective, spatial and temporal characteristics of the instrument resolution are more readily observed, as are telltale signatures of noise content. A typical turbulence spectrum rolls off at high frequencies due to viscous dissipation at small spatial scales. White noise, on the other hand, is characterized by a flat spectrum. A noisy turbulence spectrum, therefore, is often characterized by a flattening of the spectra at high frequency in the region where the SNR ratio of the instrument response is very low. Power spectral densities of the streamwise and vertical components of the fast flow case, measured at a height of 0.7 cm above the bed are displayed in Figs. 7 and 8, respectively. Plotted in Figs. 7a and 8a are a comparison between the ADV (gray line) and LDV (black line) data. Figs. 7b and 8b demonstrate the identification of the ADV noise floor with a horizontal line. For the present flow conditions and instrument configurations, the ADV was able to resolve signal up to about 4-5 Hz. In this case, an ADV sampling rate of 10 Hz is sufficiently high to capture all signal fluctuations resolved by the instrument. This noise is inherent to the instrument and contributes to the variance reported. Thus, theoretically the true signal is the signal reported from the instrument minus the noise signal.

We implemented a correction algorithm discussed in Lemmin and Lhermitte (1999) and employed by Voulgaris and Trowbridge (1998). The method involves subtracting off the high frequency noise floor in the PSD and was invoked over a

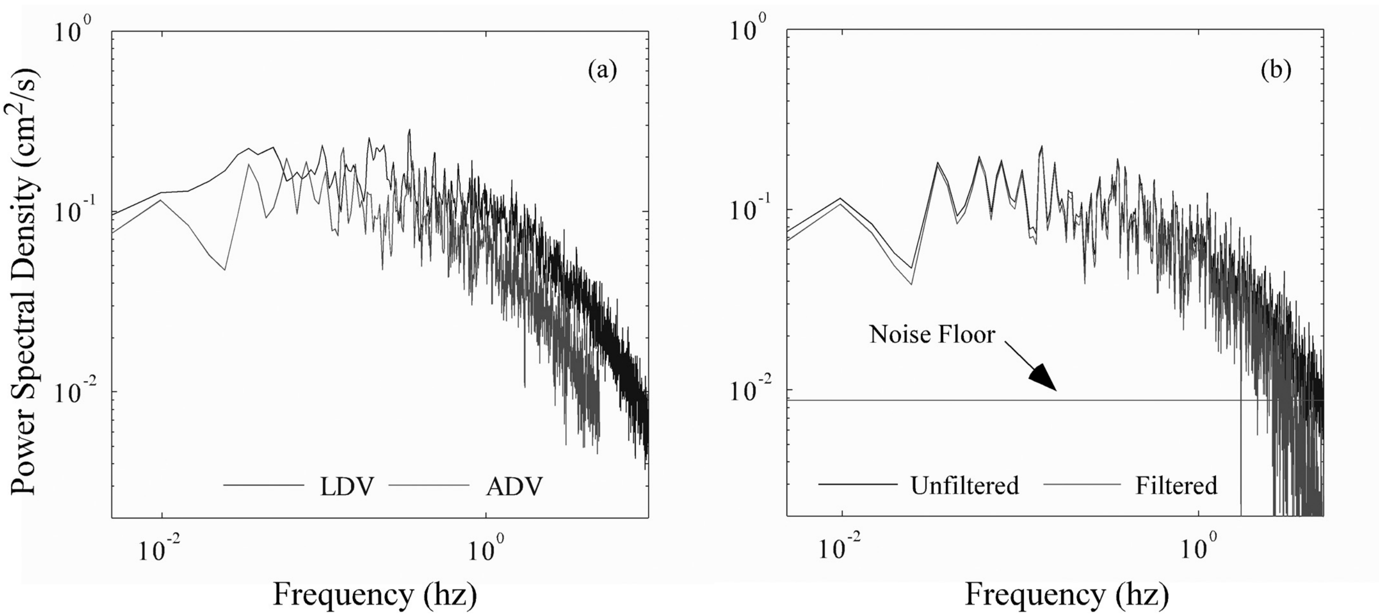

Fig. 8. PSD for the vertical (Re_θ = 1410) flow component of (a) the LDV and ADV at z = 0.7 cm above bed and for (b) the ADV with noise floor demarcated by a solid black line.

subset of data from both instruments. The effect of this filtering depends on the magnitude of the noise floor relative to the signal at that location. The LDV signal has a very small noise component and therefore filtering does not have a significant effect on the LDV data. The effect of filtering ADV data are more considerable due to the higher noise levels inherent to acoustic instruments. A greater portion of the instrument response is noise and the effect of removing it is to reduce the energy content in the data reported from the instrument. The unfiltered ADV data already underreports turbulence levels in the flow prior to filtering, which means that removal of noise brings the data farther from the LDV and Spalart data. Presented in Fig. 9 are filtered (solid circles) and unfiltered (open circles) ADV variances plotted with LDV data (open squares) for comparison. The variance profiles in Fig. 9 correspond to the streamwise component of the Re_θ = 1410 flow case and are calculated in the spectral domain. The figure shows that the error in the ADV results is even greater if the contributions to the variance from the instrument noise are removed.

Spectral comparison between LDV and ADV data indicates that the large sample volume is not solely responsible for underreported turbulence statistics. The energy cascade model predicts a range of eddy sizes from large, low frequency turbulent motions progressing down to small, high frequency motions at the Kolmogorov microscale. Thus, in a spectral representation of flow characteristics, there is a relationship between frequency and eddy size. The ADV technique cannot be expected to resolve scales of motions that are on the order of the sample volume size and smaller. If the ADV were only underreporting energy at scales smaller than the sample volume, then the PSD would drop off at a frequency corresponding to a length-scale on the order of the sample volume size. However, the magnitude of the ADV PSD is smaller than that of the LDV over the full frequency range of the plot (excepting only the lowest frequencies). Therefore, energy is being

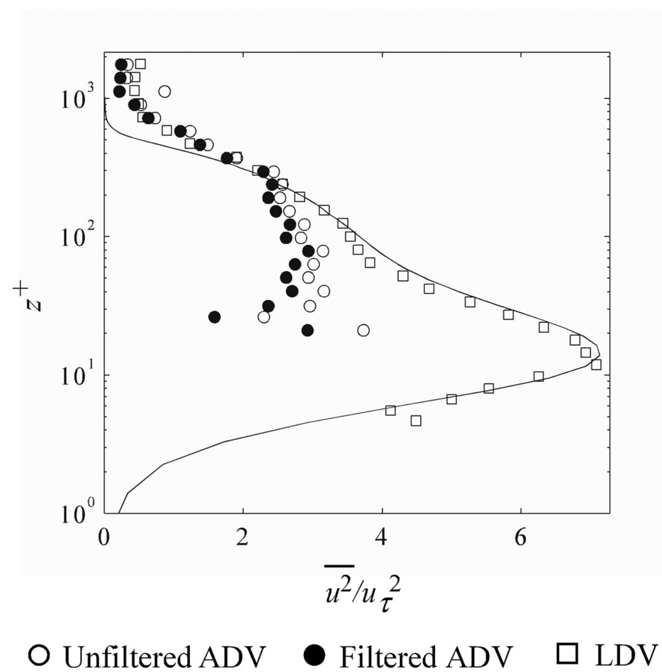

Fig. 9. Filtered and unfiltered ADV turbulence intensities compared with LDV and Spalart data for the Re_θ = 1410 flow case. The statistic is nondimensionalized by the shear velocity squared, u_τ^2, and is plotted against dimensionless z^+ on the left axis ($z^+ = zu_\tau/\nu$) and dimensional z on the right axis (cm). The line is DNS by Spalart (1988).

underreported over a wide range of spatial scales, even those much larger than the sample volume.

Discussion

ADV performance is evaluated by comparing results with an independent measure of known flow statistics. We found that, in general, ADV employed in turbulent boundary layers is not as accurate as previously reported, and the region where inaccurate results are obtained extends farther from the bed than previously reported. We also give results from ADV sample volume mapping in which we found the measurement volume to be larger and located differently than specified by the manufacturer. This finding is consistent with previous studies. The results from the mapping procedure provide the means for accurate placement of the measuring region. However, locating the lower edge of the sample volume above the bed is not a sufficient condition to guarantee accurate results. At 0.7 cm above the bed, the ADV measured mean velocities to within 5% accuracy only for the Re = 1410 flow case. For the Re = 670 flow case, 5% accuracy was achieved only to within 1 cm of the bed. Results for turbulence statistics show that ADV inaccuracies can extend much farther from the bed, up to about 4 cm in some cases. Because the nature of these inaccuracies is to underreport statistics, the high noise level inherent to ADV contributes to the signal in a way that makes reported turbulence statistics appear better than they would without the addition of noise to the signal. Therefore, we conclude that noise filtering is not a beneficial or worthwhile approach to improving accuracy of results from the ADV technique.

Comments and recommendations

The ADV technique is limited largely due to a sample volume that is (1) larger than the smallest scales of motion in most turbulent flows and (2) large compared to the distances from the bed where near-wall measurements are commonly required. Furthermore, ADV measurements can be biased at distances from the bed that are outside the theoretical and experimental extent of the sample volume. Interference between the bed and sample volume causes the SNR reported by the instrument to increase in proportion to the amount of interference, which can give users a false level of confidence in results. This point underscores the importance of conducting sample volume mapping before data acquisition. Mean velocities can be accurately measured to within 1 cm of the bed. ADV users should exercise caution, however, when reporting turbulence statistics. These results indicate that the accuracy within the 1 to 3 cm range is somewhat dependent on the flow itself. For slower flows, turbulence statistics may be accurate to as close as 1 cm from the bed, however for faster flows the same level of accuracy may only be possible 3 to 4 cm from the bed. Further research is needed to provide an objective evaluation of ADV performance while taking measurements in turbulent flows with a rough substrate, as this will add additional complexity in aligning the ADV and interpreting results.

References

Albrecht, H.- E., M. Borys, N. Damaschke, and C. Tropea. 2003. Laser Doppler and phase Doppler measurement techniques. Springer.

Adrian, R. J., and B. J. Thompson. 1993. Selected papers on laser Doppler velocimetry. SPIE Optical Engineering Press.

Bendat, J. S., and A. G. Piersol. 1984. Random data: analysis and measurement procedures, 2nd ed. John Wiley & Sons.

Butt, T., P. Russell, J. Puleo, J. Miles, and G. Masselink. 2004. The influence of bore turbulence on sediment transport in the swash and inner surf zones. Cont. Shelf. Res. 24(7-8): 757-771.

Carbonneau, P. E., and N. E. Bergeron. 2000. The effect of bedload transport on mean and turbulent flow properties. Geomorph. 35:267-278.

Carlson, E. M. 2003. An evaluation of acoustic Dopper-velocimetry in laboratory flumes and natural streams. Master thesis. Univ. of Colorado at Boulder.

Carollo, F. G., V. Ferro, and D. Termini. 2002. Flow velocity measurements in vegetated channels. J. Hydr. Eng. 128: 664-673.

Cheng, N. S., and Y. M. Chiew. 1998. Turbulent open-channel flow with upward seepage. J. Hydr. Res. 36:415-431.

Cornelisen, C. D., and F. I. M. Thomas. 2004. Ammonium and nitrate uptake by leaves of the seagrass *Thalassia testudinum*: impact of hydrodynamic regime and epiphyte cover on uptake rates. J. Mar. Sys. 49(1-4):177-194.

Crimaldi, J. P., M. B. Wiley, and J. R. Koseff. 2002. The relationship between mean and instantaneous structure in turbulent passive scalar plumes. J. Turb. 3(014):2-24.

Doering, J. C., and A. J. Baryla. 2002. An investigation of the velocity field under regular and irregular waves over a sand beach. Coast. Eng. 44:275-300.

Eckman, J. E., W. B. Savidge, and T. F. Gross. 1990. Relationship between duration of cyprid attachment and drag forces associated with detachment of *Balanus amphitrite* cyprids. Mar. Biol. 107:111-118.

Finelli, C. M., D. D. Hart, D. M. Fonseca. 1999. Evaluating the spatial resolution of an acoustic Doppler velocimeter and the consequences for measuring near-bed flows. Limnol. Oceanogr. 44:1793-1801.

Friedrichs, M., G. Graf, and B. Springer. 2000. Skimming flow induced over a simulated polychaete tube lawn at low population densities. Marine Ecology Progress Series. 192:219-228.

Kim, S. C., C. T. Friedrichs, J. P. Y. Maa, and L. D. Wright. 2000. Estimating bottom stress in tidal boundary layer from acoustic Doppler velocimeter data. J. Hydr. Eng. 126:399-406.

Kraus, N. C., A. Lohrmann, and R. Cabrera. 1994. New acoustic meter for measuring 3D laboratory flows. J. Hydr. Eng. 120(3):406-412.

Lane, S. N., K. F. Bradbrook, S. W. B. Caudwell, and K. S. Richards. 1998. Mixing processes at river confluences: field informed numerical modeling, p. 345-350. *In* J. H. W. Lee, A. W. Jayawardena, and Z. Y. Wang [eds.], Environmental hydraulics. Balkema.

Lawless, M., and A. Robert. 2001. Scales of boundary resistance in coarse-grained channels: turbulent velocity profiles and implications. Geomorph. 39:221-238.

Lemmin, U., and R. Lhermitte. 1999. Discussion: ADV measurements of turbulence: can we improve their interpretation? J. Hydr. Eng. 125(9):987-988.

Lohrmann, A., R. Cabrera, and N. C. Kraus. 1994. Acoustic-Doppler velocimeter (ADV) for laboratory use, p. 351-365. *In* Proc. conf. on fundamentals and advancements in hydraulic measurements and experimentation. American Society of Civil Engineers.

Mutz, M. 2000. Influences of woody debris on flow patterns and channel morphology in a low energy, sand-bed stream reach. Int. Rev. Hydrobiol. 85:107-121.

Nezu, I., and W. Rodi. 1986. Open channel flow measurements with a laser Doppler anemometer. J. Hydraul. Eng.. 112: 335-355.

Nikora, V. I., and D. G. Goring. 2000. Flow turbulence over fixed and weakly mobile gravel beds. J. Hydr. Eng. 126(9):679-690.

Osborne, P. D., K. Black, P. V. Villard, and S. Douglass. 1997. Field measurements of 3-D velocity structure and suspended sediments under locally generated waves and swell. Pacific Coasts and Ports 1997. 564.

SonTek. 1997. Sontek ADVField acoustic Doppler velocimeter: technical documentation. version 4.0. San Diego, CA: SanTek.

Spalart, P. R. 1988. Direct simulation of a turbulent boundary layer up to $R_\theta = 1410$. J. Fluid Mech. 187:61-98.

Talke, S. A., and M. T. Stacey. 2003. The influence of oceanic swell on flows over an estuarine intertidal mudflat in San Francisco Bay. Est. Coast. Shelf Sci. 58(3):541-554.

Tritico, H. M., and R. H. Hotchkiss. 2005. Unobstructed and obstructed turbulent flow in gravel bed rivers. J. Hydr Eng. 131(8):635-645.

Venditti, J. G., and B. O. Bauer. 2005. Turbulent flow over a dune: Green River, Colorado. E. Surf. Proc. Land. 30(3): 289-304.

Voulgaris, G., and J. H. Trowbridge. 1998. Evaluation of the acoustic Doppler velocimeter (ADV) for turbulence measurements. J. Atmos. Ocean. Technol. 15:272-289.

Yahel, R., G. Yahel, and A. Genin. 2002. Daily cycles of suspended sand at coral reefs: a biological control. Limnol. Oceanogr. 47(4):1071-1083.

Submitted 16 March 2006
Revised 20 September 2006
Accepted 12 October 2006