Limnol. Oceanogr., 44(7), 1999, 1793–1801

Evaluating the spatial resolution of an acoustic Doppler velocimeter and the consequences for measuring near-bed flows

Abstract—The acoustic Doppler velocimeter (ADV) has recently been suggested as a promising instrument for characterizing near-bed flows, particularly in the first 10 mm above the bed where many benthic organisms live. Flow characteristics in such settings often exhibit steep vertical gradients, however, so the reliable use of the ADV requires knowledge of the size and location of the instrument's acoustic sampling volume. We describe simple procedures for quantifying the vertical size of the ADV's sampling volume and assessing its height above the bed. Our results indicate that the vertical size of the sample volume for the ADV we tested was much larger than expected based on the values predicted by software configuration. Moreover, this system incorrectly reported several distances needed to accurately position the sample volume near the bed (e.g., the transmitter-to-bed distance, the sample volume-to-bed distance, and the transmitter-to-sample volume distance). We also demonstrate that incorrect assumptions about the size and location of the sampling volume can lead to inaccurate near-bed flow measurements by comparing the time-averaged flow speed profiles generated by our ADV with those obtained using a hot-film velocimeter (HFV). At heights > 10 mm above the bed, both instruments yielded similar flow speed estimates. Closer to the bed, however, the flow speeds reported by ADV were as much as 60–80% less than those from HFV. These large errors in estimating near-bed flow speeds are a direct consequence of incorrect assumptions about the centerpoint and size of the ADV's sample volume. Specifically, when the vertical size of the sampling volume is larger than its nominal size, users may mistakenly position the ADV so that the bed is included within the sampling volume, which in turn results in the underestimation of flow speeds. By validating the size and location of the sampling volume, as well as carefully monitoring signal quality parameters, users can ensure proper placement of the ADV relative to the bed and avoid erroneous measurements.

Aquatic scientists working in both marine and freshwater environments often need to measure the near-bed flow conditions that affect benthic organisms and processes (Nowell and Jumars 1984; Davis and Barmuta 1989; Eckman et al. 1990; Dodds et al. 1996). Investigators face several challenges in making accurate and informative measurements of near-bed flow characteristics, however. First, many benthic organisms are relatively small, projecting < 10 mm above the bed. Second, flow fields in this near-bed region are often strongly sheared and are usually three-dimensional among the roughness elements where benthic organisms often live (e.g., on rocky shores or streambeds) (Denny 1988; Carling 1992). Third, and following from the second, it is often difficult to predict near-bed flow characteristics at a specific locale from coarse-scale measurements made farther above the bed (e.g., Hart et al. 1996). Collectively, these factors place a premium on the use of flow instruments with sufficient spatial resolution to make measurements within the steep gradients associated with near-bed flows. Unfortunately, flow measurement devices with high temporal and spatial resolution, such as hot-film anemometry or laser Doppler velocimetry, are often costly or difficult to deploy in the field.

The ADV potentially offers solutions to many of the problems associated with near-bed flow measurement. The ADV operates by emitting a burst of sound energy of known duration and frequency that is subsequently reflected back to the probe by suspended particles moving with the water current. Because the suspended material in the water is moving, the backscattered sound energy is shifted in frequency (known as a Doppler shift), and the magnitude of this shift is proportional to flow speed (for more information, *see* Kraus et al. 1994; Lohrmann et al. 1994; Zedel et al. 1996). ADV systems are sufficiently robust to be field portable, offer moderate temporal and spatial resolution, and do not require routine calibration. Because the ADV measures velocities from a volume of water (or ''sample volume'') located some distance from the physical probe, ADV measurements are noninvasive, which provides a considerable advantage over hot-film, propeller, or electromagnetic flow sensors.

SonTek manufactures the ADV most commonly used in aquatic research. These probes consist of a central circular transmitter (6-mm diameter) surrounded by three equally spaced receivers (Fig. 1). Depending on configuration, the sample volume is located at the intersection of the transmit and receive ''beams,'' either 50 or 100 mm from the probe (Fig. 1). In addition, the manufacturer specifies that the sample volume for this probe be approximated by a cylinder with a diameter equal to the transmitter diameter (6 mm) and a software configurable height ranging from 1.2 to 9.0 mm (Lohrmann et al. 1994; SonTek 1997). Because the sample volume cannot be directly observed, however, its precise size and spatial position are difficult to define.

Accurate knowledge of the size and position of the ADV's sample volume is essential for near-bed flow measurements. These two parameters not only determine where flow characteristics are measured, but also how close to the bed the transmitter can be placed without the sample volume incorporating part of the bed. For example, the position of the sample volume, and thus the location at which velocities are measured, is referenced to the vertical center of the cylindrical sample volume. Therefore, a measurement made at a height of ''10 mm'' above the bed is actually a spatial average that is vertically centered at 10 mm. Theoretically, for use near solid surfaces, the ADV can be operated reliably even when the lower end (or ''bottom'') of the sample volume is placed 0.5 mm above the bed surface (Lohrmann et al. 1994; SonTek 1997). If these assumptions are correct, then the ADV can be safely deployed with the center of the

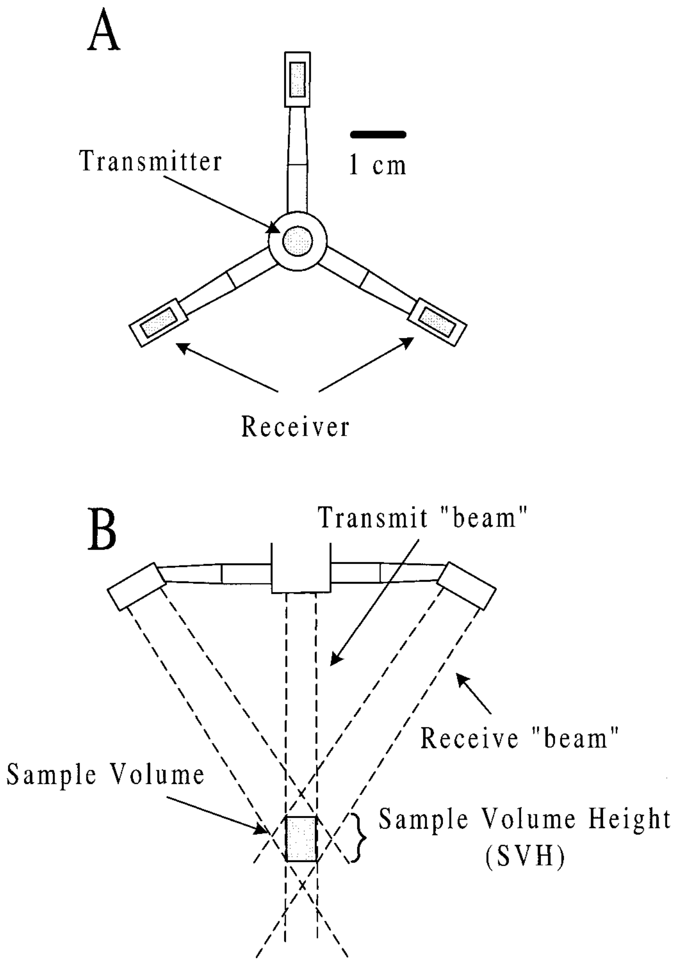

Fig. 1. (A) Bottom view of the ADV probe showing the locations of the central transmitter and three acoustic receivers. (B) Side view of the ADV probe showing acoustic transmit and receive "beams" and the approximate position and height of the sample volume.

sample volume located from 1.1 to 5 mm from the surface of the bed, depending on the height of the sample volume. For example, according to these specifications, the minimum measurement point when using the 9.0-mm sample volume height would equal 9 mm ÷ 2 + 0.5 mm, or 5 mm. The validity of this assertion is dependent, however, on the true spatial extent of the sample volume.

The purpose of our note is to present simple methods for determining the vertical size of the sample volume and its position relative to the probe transmitter. These methods allow ADV users to reduce the potential for inaccurate flow measurements stemming from incorrect assumptions about the location of the sampling volume. We also compare the results of flow speed measurements made with an ADV and an HFV within 25 mm of a flume bed. This comparison demonstrates that the ADV can significantly underestimate near-bed flow speeds if the assumptions about its position are incorrect. The results of our study highlight the need to test individual ADV systems and the consequences of uncritical use of the ADV in near-bed flows.

Mapping the vertical size of the sample volume—We tested a SonTek ADVfield (firmware vers. 2.0) equipped with a 10-MHz down-looking probe (SN 1218). The ADV's sample volume is the spatial region from which the backscattered acoustic signal is strong relative to background noise (i.e., elevated signal-to-noise ratio, SNR) (SonTek 1997). For our probe, the manufacturer specifies that the vertical center of the sample volume is located 50 mm from the central transmitter. We used software configurations that were predicted to produce sample volume heights (= nominal SVH) of 9.0, 4.8, and 1.2 mm.

When measuring flow velocities using an ADV, particles moving through the sample volume reflect sound back to the receivers. By design, particles in the center of the sample volume produce a stronger acoustic signal than particles located at the edges of the sample volume (SonTek 1997). Thus, in the absence of scattering particles, sound can be reflected from discreet locations within the sample volume using a stationary acoustic target (e.g., Sheng and Hay 1993), and the SNR will vary in proportion to the target's location in the sample volume. By systematically varying the distance from the transmitter to the acoustic target and measuring the SNR, the vertical size of the sample volume can be accurately defined. Ideally, the SNR would rise rapidly as the bottom of the sample volume encounters the target, reach a peak value at the vertical midpoint, and then drop off steeply.

We made a spatial map of the sample volume using the procedure described above. We created an acoustic target by stretching two lengths of monofilament fishing line (0.30-mm diameter, Eagle Claw 10-lb test) horizontally across a cylindrical tank filled with tap water (RubberMaid 24-gal trash can; 450-mm diameter × 555-mm height). The target was secured at the tank sides 345 mm from the bottom of the tank and 200 mm below the water surface such that the monofilament lines crossed at 90° at the tank's center. We allowed the water to de-gas and any particles to settle for at least 24 h so that the primary backscatter would be from the acoustic target. The ADV probe, which was mounted on a three-axis micromanipulator, was centered directly over the crossed monofilament lines. In addition, none of the three receivers was located directly over the monofilament, to avoid introducing interference from the lateral portions of the sample volume. We collected SNR estimates for 10 s at 10 Hz with the ADV transmitter positioned at a variety of heights above the acoustic target using the SonTek supplied ADF.EXE (vers. 2.5) program. The distance from the transmitter to the acoustic target ranged from 70.0 to 35.0 mm. We moved the probe in either 5.0- or 1.0-mm increments until the SNR began to rise, after which the increments were 0.2 mm until the SNR values returned to their background values. This protocol was repeated for SVH = 1.2, 4.8, and 9.0 mm.

The ADV provides separate SNR data for the three receivers to ensure that each is functioning properly. We computed a mean SNR value for each receiver and distance from the acoustic target from the 10-s time series. We then calculated a grand mean SNR value for each height above the acoustic target from the means of each receiver. This method is warranted because the three receivers were closely aligned over the acoustic target, which resulted in considerable spatial overlap in the SNR values from each receiver.

Identification of "elevated" SNR values from which the actual SVH can be determined requires an objective estimation of the background SNR levels. Inspection of pilot data showed that the center of the ADV sample volume was located approximately 50 mm from the transmitter. In addition, SNR measurements made $\geq$ 10 mm above or below this centerpoint (i.e., measurements from $\leq$40 mm and $\geq$60 mm above the target) were very low (i.e., typically 5, 10, and 20% of the observed maximum SNR values for the 1.2-, 4.8-, and 9-mm SVH, respectively). Therefore, we estimated background SNR values using the average of measurements made with the transmitter 35, 40, 60, 65, and 70 mm above the acoustic target. The background SNR levels were 3.34, 8.04, and 12.80 dB for the 1.2-, 4.8-, and 9.0-mm SVH, respectively (e.g., solid vertical lines in Fig. 2). The increase in background noise at progressively larger SVH is a function of the amount of time during which reflected sound is "listened" for by the ADV (SonTek 1995). The point at which the SNR exceeds these background levels represents the edge of the sample volume (Fig. 2).

The size of the sample volume was much larger than expected (Fig. 2). For example, with a nominal SVH = 1.2 mm, SNR values were elevated relative to background levels over a 17.0-mm distance (i.e., when the transmitter was between 43 and 60.0 mm from the acoustic target). The sample volume extended 17.0 mm (between 41.5 and 58.5 mm) when the nominal SVH was 4.8 mm and extended 21.5 mm (between 41.0 and 62.5 mm) when the nominal SVH was 9.0 mm. In each case, a steep increase in SNR above background levels clearly demarcated the edges of the sample volume (Fig. 2).

A second estimate of SVH can be obtained by analyzing SNR on a linear rather than a logarithmic (i.e., dB) scale. We linearized the raw SNR data according to a formula supplied by SonTek:

$$\text{Relative SNR} = \text{RSNR} = \text{Maximum SNR} - \text{SNR}$$

$$\text{Linearized SNR} = 10^{(\text{RSNR}/10)}.$$

We calculated mean values of linearized SNR for each receiver and each height above the target. In addition, a grand mean was calculated for each height from the three receivers. The vertical size of the sample volume as defined by these linearized SNR values was more consistent with the nominal SVH, spanning approximately 3, 5, and 10 mm for the 1.2, 4.8, and 9.0 SVH, respectively. These results indicate that the vertical extent of the acoustic signal is smaller when expressed in linear rather than logarithmic units.

The discrepancy between these two estimates of SVH based on logarithmic and linearized SNR raises the question as to which should be used in positioning the sample volume with respect to a solid surface. As we show below, the height above the bed at which ADV-generated flow speed profiles begin to diverge from HFV profiles corresponds more closely to logarithmically based SVHs. In view of these results, we believe that ADV positioning using linearly based SVHs is much more likely to produce errors in measuring near-bed flows.

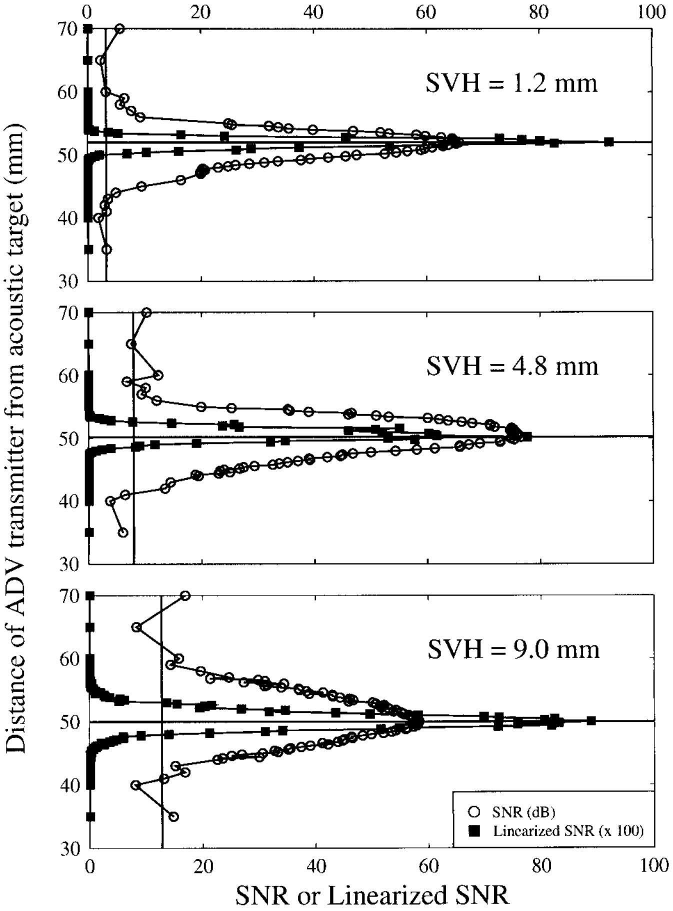

Fig. 2. Results of the sample volume mapping trial for the three nominal SVHs. Raw and linearized values of the SNR are shown as functions of distance from the ADV transmitter to the acoustic target. Vertical lines indicate an estimate of background noise, while horizontal lines indicate the center of the sample volume as measured by the location of highest intensity. Raw SNR values indicate that strong backscatter can be detected over a much larger area than expected, whereas linearized values are more consistent with nominal values of the SVH.

Because the size of the sample volume is larger than predicted by software configuration, there is the potential for users to mistakenly position the ADV such that the sampling volume incorporates a portion of the bed. This can lead to the collection of spurious data (SonTek 1997; this study). In such situations, the ADV will underestimate flow speed, as readings from the stationary bed are averaged with readings from the overlying water (SonTek 1997). Thus, if ADV users plan to make measurements close to the bed, they need to determine the size of the sampling volume for their particular instrument. Because the size of the sample volume also determines the scales of turbulence that can be resolved, accurate information about the ADV's spatial resolution will also lead to more robust inferences about the nature of turbulent flows (e.g., Nikora and Goring 1998; Voulgaris and Trowbridge 1998).

Location of sampling volume—Accurate placement of the sample volume within a velocity gradient requires knowledge of the spatial position of the sample volume, as well as its size. There are two putative methods for positioning the ADV relative to a solid bed. First, the ADV software reports the distance from the transmitter to the bed (i.e., the transmitter-to-bed distance) and the distance from the sample volume to the bed (i.e., the sample volume-to-bed distance). These values can be used directly to position the ADV. Second, given precise knowledge of the sample volume's position relative to the transmitter (i.e., the transmitter-to-sample volume distance), one can position the sample volume independently by measuring the transmitter-to-bed distance with a ruler. We estimated the transmitter-to-sample volume distance based on the mapping trial described above and evaluated the accuracy of three interrelated measurements of sample volume position based on output of the ADV (i.e., transmitter-to-sample volume distance, transmitter-to-bed distance, and sample volume-to-bed distance).

The position in space of the sample volume is referenced to its vertical center. The ADV determines this location based on the maximum signal strength of reflected sound energy or SNR (SonTek 1997). In our mapping trials, the vertical center of the sample volume (i.e., the location of maximum SNR) was 52.0, 50.2, and 50.0 mm from the transmitter when the ADV was configured for a 1.2-, 4.8-, and 9.0-mm nominal SVH, respectively. These lengths represent the ''transmitter-to-sample volume'' distance. Knowledge of this distance allows ADV users to position the sample volume without relying on the ADV software. For example, if the mapping study showed that the sample volume was centered 50 mm from the transmitter and the transmitter was located 90 mm from the bed, then (by difference) the center of the sample volume should be 40 mm from the bed.

We compared our independent estimates of sample volume-to-bed, transmitter-to-sample volume, and transmitter-to-bed distances to those provided by the ADV software in a small recirculating flume (Vogel and LaBarbera 1978). The flume channel (2,500-mm L × 260-mm W × 130-mm H) is constructed of clear acrylic, while the return pipes are made of polyvinyl chloride. These tests were performed in still water, although for tests in running water (*see below*), a propeller connected to a variable electric motor drove the current. Water depth was 120 mm. The ADV probe was mounted on a micromanipulator located 1,250 mm from the upstream end of the flume. For each measurement, we moved the probe into position and measured the transmitter-to-bed distance to the nearest 0.5 mm using a ruler. From this measurement and our estimate of the transmitter-to-sample volume distance, we calculated the sample volume-to-bed distance. The ADV system was then allowed to stabilize for 10–20 s before transmitter-to-bed and sample volume-to-bed distance measurements were read directly from the computer screen (SonTek ADF.EXE vers. 2.5). We repeated this protocol at a series of heights for nominal SVH = 1.2, 4.8, and 9.0 mm.

When the transmitter-to-bed distance was $\geq$ 80 mm (and the sample volume-to-bed distance was $\geq$30 mm), the ADV's distance-measuring function estimated the transmitter-to-bed distance to within the 1-mm tolerance specified by SonTek (1997) (Fig. 3). As the transmitter was moved closer to the bed, however, this estimate became increasingly unreliable (Fig. 3). There was also a conspicuous 4-mm offset between the ADV's estimation of the sample volume-to-bed distance and our estimate. This discrepancy arose because the ADV calculated a transmitter-to-sample volume distance of 54 or 56 mm (depending on the nominal SVH), which was 4 mm greater than in our mapping trials.

The manufacturer's documentation acknowledges that the ADV's distance-measuring capabilities are faulty when the sample volume-to-bed distance is $<$20 mm (SonTek 1997). Our results show that such errors may appear when the sample volume-to-bed distance is as much as 30 mm (Fig. 3). Therefore, in close proximity to a solid bed (i.e., within 30 mm), ADV users should use the ADV's distance-measuring capability with caution. To position the ADV in the near-bed region, the manufacturer suggests that distance measurements be taken from higher in the water column, after which the ADV transmitter can be lowered toward the bed a known distance, thereby avoiding this problem (SonTek 1997). Unfortunately, in many stream and flume applications, readings from higher in the water column cannot be made because of shallow water. In addition, this procedure cannot compensate for errors in the transmitter-to-sample volume distance produced by the ADV (i.e., the 4-mm offset shown here). Thus, researchers are encouraged to use a mapping technique such as we describe to determine the actual transmitter-to-sample volume distance and then manually position the ADV for all near-bed deployments.

Evaluating the accuracy of near-bed flow speed profiles generated by ADV—Invalid assumptions about the size and position of the sampling volume, such as those documented previously, can lead to inaccurate estimates of near-bed flow characteristics. For example, the manufacturer cautions that improper placement of the sample volume too close to the bed will lead to the underestimation of velocity (SonTek 1997). Whether this problem is severe enough to warrant an independent assessment of the size and position of the sampling volume for a particular ADV, however, depends in part on the magnitude of error that could arise when making near-bed flow measurements.

One way to validate the ADV is to compare its performance with conventional technology for flow measurement. Although the ADV's performance in open-water deployments compared favorably to laser Doppler systems (Lohrmann et al. 1995) and vector-averaging current meters (Anderson and Lohrmann 1995), much less is known about its performance in near-bed flows. Voulgaris and Trowbridge (1998) conducted the most comprehensive test of the ADV for mean velocity and turbulence measurements in a benthic boundary layer. In a flume designed to produce one-dimensional flow (i.e., gradients in flow only in the vertical direction), they compared the ADV to a laser Doppler ve-

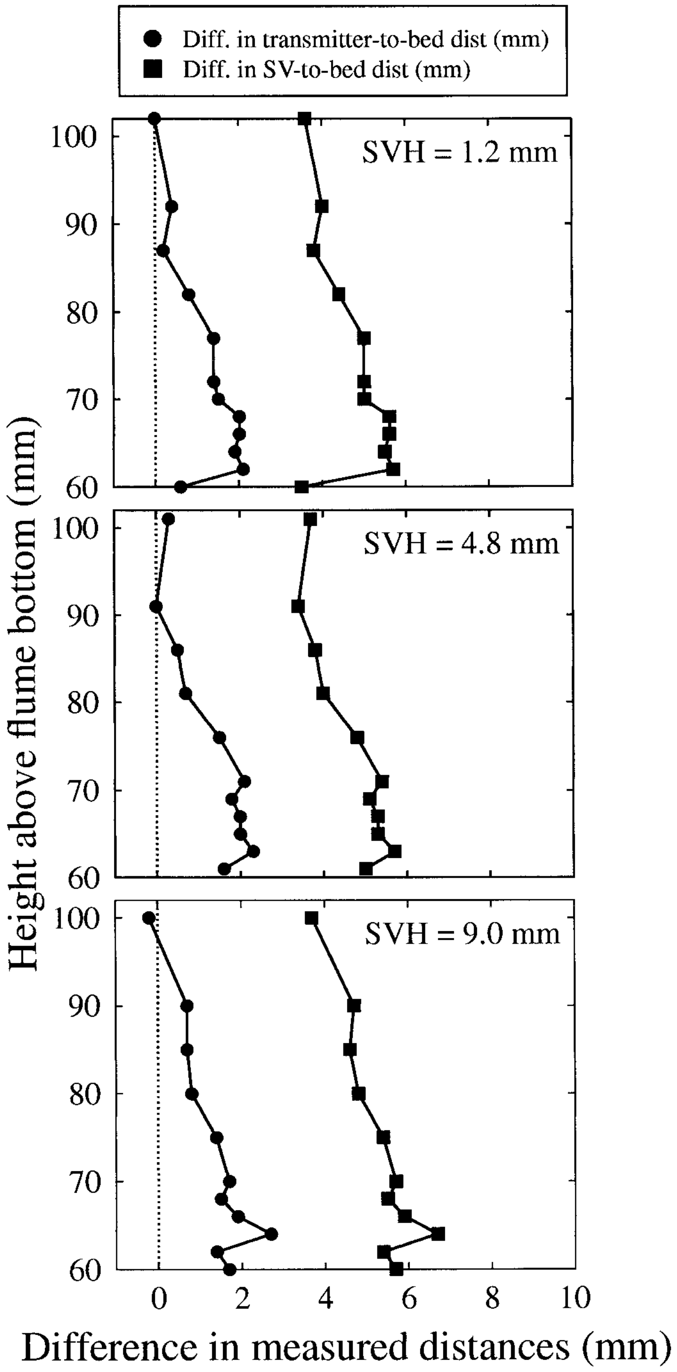

Fig. 3. Results of the test of the ADV distance-measuring capability. Data are plotted as absolute difference between the ADV reported value and either the value measured with a ruler or predicted by our mapping trial. Vertical axis is the distance from the ADV transmitter to the flume bed. The conspicuous 4-mm offset in the sample volume-to-bed distance arises because the transmitter-to-sample volume distance estimated by the ADV is 54–56 mm, whereas our tests indicate that this distance is 50–52 mm from the transmitter (depending on nominal SVH).

locimeter (LDV). They also computed a "ground truth" for flow measurements that was based on the idealized hydrodynamic conditions of their flume and the predicted measurement error associated with each of the flowmeters. At heights $\geq$ 7.5 mm above the flume bottom, the ADV compared favorably to the LDV and the ground truth for mean velocity measurements and some turbulence measurements. Unfortunately, the conclusions of Voulgaris and Trowbridge (1998) may be less useful for assessing performance closer to the bed. They do not present data testing whether the actual height of the sampling volume was the same as its nominal size (i.e., 9 mm), and their analysis includes relatively few data points collected within 10 mm of the bed. Furthermore, most of the data points collected within 10 mm of the bed are not compared to the LDV or ground truth because of failure of the LDV (i.e., Voulgaris and Trowbridge 1998, experiment C). Thus, we believe that further tests are needed of the ADV's performance within 10 mm of the flume bed (i.e., a location of considerable interest to many benthic ecologists) and that these tests should include an independent assessment of the true size and position of the sample volume.

We measured vertical profiles of mean flow speed (i.e., magnitude of the velocity vector) using an HFV and ADV at 16 heights above a flume bed ranging from 1 to 25 mm. This study was performed in the flume described above at two flow speeds (measured 25 mm above the bed) for each nominal SVH: a slow flow speed $\approx$ 200 mm s^{-1} and a fast speed $\approx$ 400 mm s^{-1}. We added 10 ml of liquid seeding material supplied by SonTek to the flume to increase the acoustic backscatter in the water.

The HFV system consisted of a Dantec 55M control unit and an R14-type platinum film probe configured for a 6% overheat ratio. The R14 probe is "L" shaped, and the cylindrical element (0.070-mm diameter × 1-mm length) is held horizontally between two needles that comprise the bottom of the "L." We positioned the probe such that the bottom of the "L" faced into flow and was parallel with the flume bottom. In this configuration, the long axis of the cylindrical element is perpendicular to flow. We calibrated the probe before each run by moving it through a still water bath while the speed of the probe (measured by a linear velocity transducer) and the HFV bridge output were recorded simultaneously (*see* Hart et al. 1996). The bridge output was then regressed on probe speed using a modified version of King's Law, and the resulting calibration equations yielded $r^2 >$ 0.99. We cleaned the probe element periodically with a sable-hair brush to remove air bubbles or bits of debris and rinsed it with a 10% acetic acid solution at the end of each day.

The ADV and HFV quantify and report flow velocity differently. The HFV provides a single scalar estimate of flow speed (i.e., the magnitude of the velocity vector) that incorporates all three components of the velocity vector (*u*, *v*, and *w*). Further, the HFV probe is more sensitive to the downstream and vertical components of velocity (*u* and *w*, respectively), than it is to the cross-stream component, *v* (e.g., Lomas 1986). In contrast, the ADV provides separate estimates for each of the three spatial components of the velocity vector. Thus, to compare the two instruments directly, it is necessary to collapse the ADV velocity data into a scalar estimate of flow speed using the following relation: flow speed = $(u^2 + v^2 + w^2)^{0.5}$. Because the HFV is less sensitive to the v component of velocity, flow speeds from the ADV may be increased relative to the HFV. This bias should not change our results dramatically, however, because in this flume, the v and w components of flow velocity are $<10\%$ of the u component.

In the flume, the hot-film probe was located a short distance downstream from the ADV probe to avoid any interference with the acoustic beams. Specifically, we positioned the ADV in the center of the flume and manually adjusted its height above the bed using our mapped estimates of the size and location of the sample volume. Then, we positioned the HFV probe such that it was 60 mm downstream from the ADV probe and aligned with the vertical center of the ADV sampling volume. Once the probes were aligned, flow speeds were measured at 128 Hz for 10 s using the HFV and ADV simultaneously at each height above the flume bed. Data were collected using a National Instruments DAQCard 700 A/D board interfaced with a laptop computer. We used the ADV's auxiliary voltage output to record velocity data, and the ADV's velocity range parameter was set to 30 cm s^{-1} during the slow flow trial and 100 cm s^{-1} during the fast flow trial.

We collected a separate profile of ADV data quality parameters immediately following the collection of flow speed profiles. Using software supplied by the manufacturer, the ADV system provides SNR values and correlation coefficients between transmitted and received pulses to be used in assessing data reliability. These data quality parameters are not available, however, when using the auxiliary voltage output; only a composite "signal amplitude" could be measured for data quality assurance during these tests. Therefore, we also collected a separate profile of SNR and correlation coefficients (sampled at 25 Hz for 10 s) using the ADF.EXE (vers. 2.5).

We collected an additional flow speed profile using the HFV to assess whether the 60-mm streamwise distance that separated the ADV and HFV probes contributed to any difference in their respective boundary layer profiles. Therefore, we placed the HFV probe in the upstream position that had previously been occupied by the ADV and collected speed data using the A/D system described above at 128 Hz for 10 s. For this upstream HFV profile and the data quality profile described previously, data were collected from only a subset of heights above the bed.

For all four profiles (ADV and HFV collected simultaneously, ADV data quality, and HFV in the upstream position), four replicate 10-s data records were collected for each height above the bed. Mean flow speeds were calculated for each replicate time series. We then calculated a grand mean flow speed for each height from the four replicates.

Flow speed—In both the slow and fast flow trials, flow speed measured by ADV and HFV decreased as the probes were moved closer to the bed (Figs. 4, 5). There was considerable overlap between the upstream and downstream HFV profiles, indicating that streamwise flow gradients were small in this section of the flume (Figs. 4, 5). Profiles of mean flow speed measured simultaneously by the HFV and ADV were similar at heights > 10 mm above the bed (Figs. 4, 5). In this upper region of the profile, flow speeds measured with the ADV were within 5% of those measured by the hot film. In the lowermost portions of the flow speed profiles, however, the ADV underestimated flow speed relative to the HFV (Figs. 4, 5). The percent difference between the ADV and HFV profiles increased steadily as the probes were placed closer to the bed, reaching values of 60–80% at heights of 1–5 mm.

Some divergence between flow speed profiles measured by the HFV and ADV is expected due to differences in spatial resolution between the two instruments. However, the differences in flow speed profiles at heights < 10 mm above the bed are too high to be explained solely by differences in spatial resolution. For example, at 3 mm above the bed and with a nominal SVH of 1.2 mm, the ADV measures flow speeds of 58 and 43 mm s^{-1} for the slow and fast flow trials, respectively. If the actual SVH = nominal SVH (i.e., 1.2 mm), then these ADV measurements should correspond to the averages of HFV-measured flow speeds from 2 to 4 mm above the bed. However, the averages of HFV flow speeds over this range are 151 and 300 mm s^{-1} for the slow and fast flow trials, respectively. Similarly, if the actual SVH = SVH based on linearized SNR values (i.e., 3 mm), then the ADV flow speeds should correspond to the average of HFV flow speeds spanning 1–5 mm. In contrast, the averages of HFV flow speeds from this range are 147 and 296 mm s^{-1} for the slow and fast flow trials, respectively. Finally, if the actual SVH = SVH based on logarithmic SNR (i.e., 17 mm), then at 3 mm above the bed, the ADV averages over a range from -5.5 to 11.5 mm. Under these conditions, it is expected that the ADV will more severely underestimate flow speed (SonTek 1997).

The results of our comparison between the ADV and HFV are consistent with this final set of predictions based on an SVH of 17 mm. For example, the point where the ADV began to underestimate flow speed corresponds to the location at which sample volume heights based on logarithmic SNR (i.e., Fig. 2, measured in decibels) would first begin to intercept the bed (i.e., the dashed lines in Figs. 4, 5). For a flow speed measurement at 8.5 mm above the bed (i.e., the location of the dashed line in Figs. 4, 5) with a nominal SVH of 1.2 mm, the ADV would putatively average speeds from 0 to 17 mm. Consequently, the bed's speed (i.e., 0 mm s^{-1}) would be included in the average, causing an underestimation of the true flow speed. This underestimation should worsen as the probe is moved closer to the bed and a larger fraction of the sample volume is occupied by the bed, a phenomenon we observed (Figs. 4, 5; also SonTek 1997). In contrast, if the actual SVH were equal to the nominal SVH, the flow speed profiles measured by the HFV and ADV would diverge at heights much closer to the bed (i.e., the dotted lines in Figs. 4, 5). These results suggest that estimates of SVH based on the logarithmic SNR values (i.e., measured in decibels) are more valid than estimates based on software configuration (i.e., nominal values) or linearized SNR.

There was a conspicuous local increase in the flow

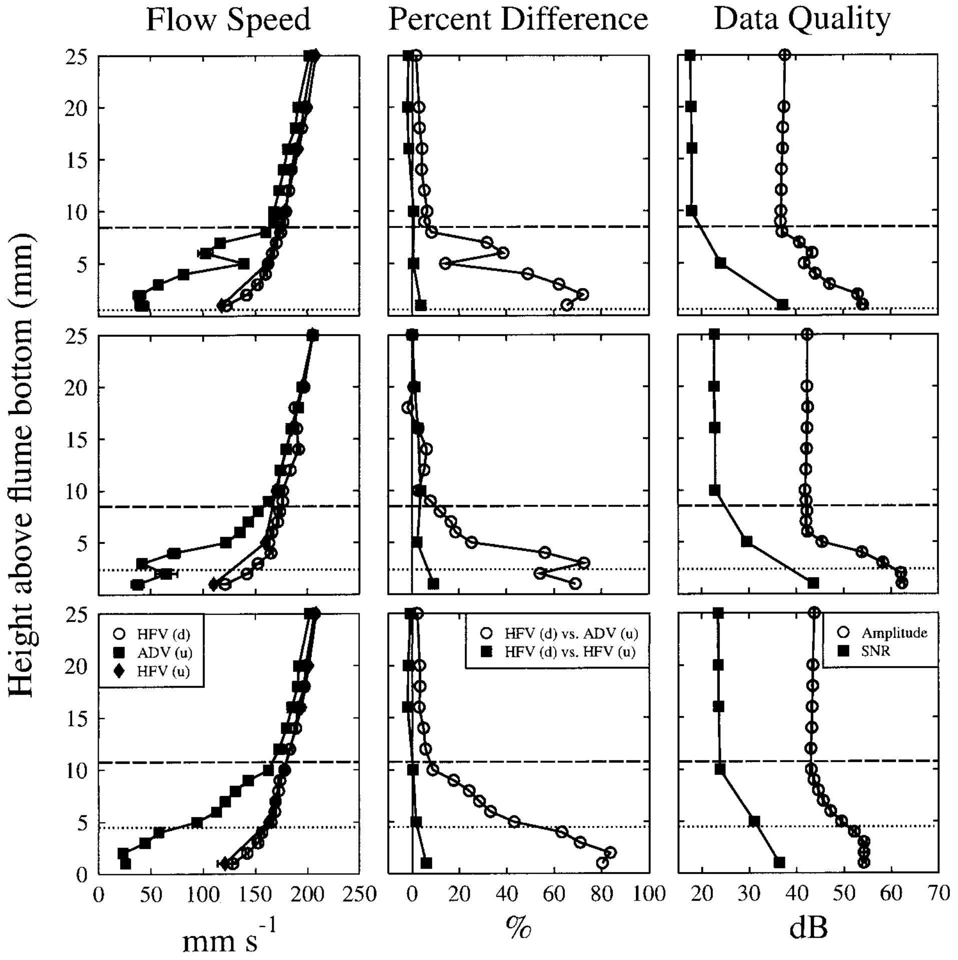

Fig. 4. Vertical profiles of mean flow speed, percent difference in mean flow speeds, and data quality parameters as measured by the ADV and HFV for our slow flow trial. The vertical axis is the height of the HFV probe above the bed or the estimated sample volume-to-bed distance. The upper dashed line shows the predicted minimum measurement point at which the "bottom" of the sample volume contacts the bed based on SVH measured from raw SNR during our mapping trial. The lower dotted line indicates the corresponding point estimated from predicted nominal SVH. In all profiles except "Percent Difference," the mean value of four replicates is plotted with error bars representing 1 SD. In many cases, the error bars are smaller than the plotted symbols. In the key to each graph, lowercase letters in ( ) indicate the relative position of the HFV probe in the flume as either (u)pstream or (d)ownstream.

speed and signal amplitude profiles collected using the ADV with a nominal SVH of 1.2 mm at heights between 5 and 8 mm above the flume bottom (Figs. 4, 5). We suspect that this is an artifact caused by interference between sound reflected from the solid bottom and sound reflected from the sample volume (SonTek 1997). This interference problem is described in the manufacturer's technical documentation in cases when echoes from the solid bed are returning to the receivers coincidentally with echoes from the sample volume (SonTek 1997). Thus, ADV users should interpret such anomalously high measurements with caution.

Data quality parameters—The ADV system provides three diagnostic measurements for monitoring data quality: SNR, correlation coefficient, and signal amplitude. We collected such data to ensure that the ADV was operating within the guidelines recommended by the manufacturer. Specifically, high-quality data should have correlation coefficients $> 70\%$ and SNR values > 15 dB (SonTek 1997). These levels were exceeded in all of our trials, even in those where the sample volume intersected the bed. For example, mean correlation coefficients for each combination of SVH and flow speed were $>90\%$, and SNR values were >18 dB (Figs. 4, 5).

Profiles of SNR and signal amplitude values can be used to detect when the sample volume begins to intercept the bed. For example, as the ADV probe moved closer to the bed, SNR and signal amplitude values began to rise, indicating that strong backscatter from the solid bed was being

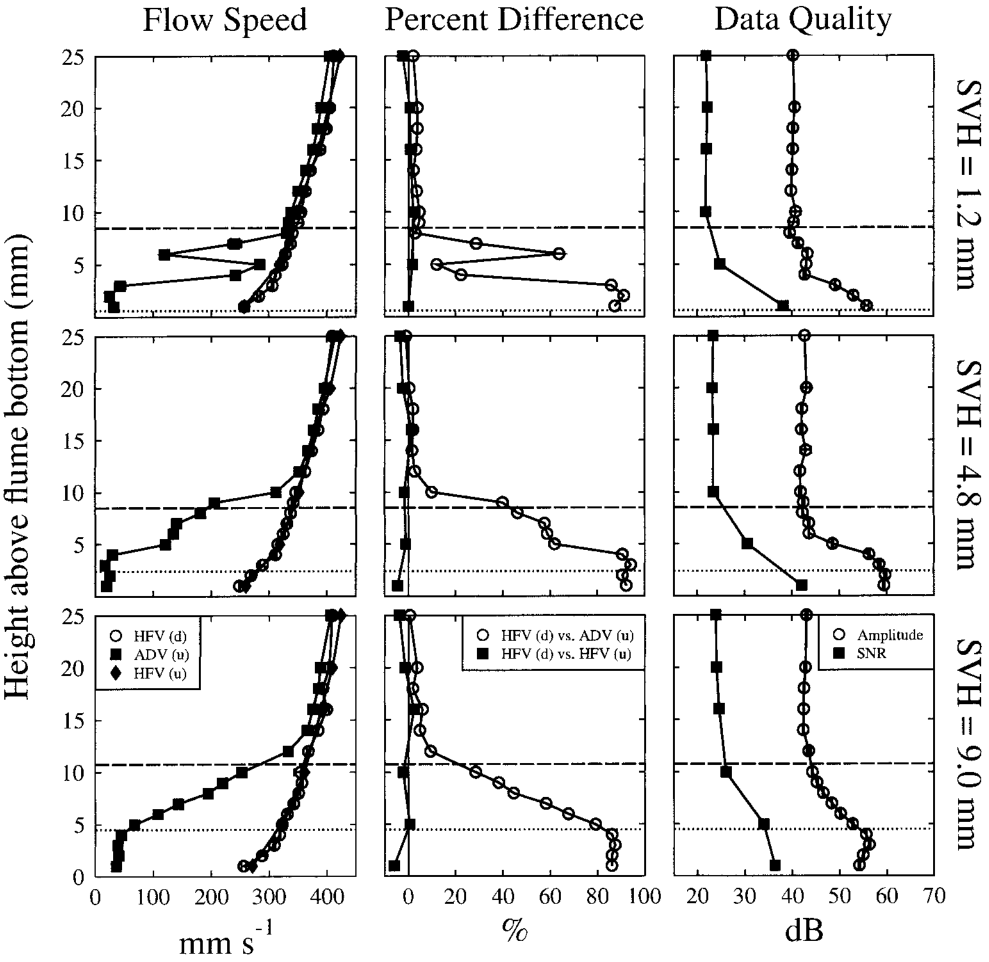

Fig. 5. Vertical profiles of mean flow speed, % difference in mean flow speeds, and data quality parameters as measured by the ADV and HDV for our fast flow trial. All graphic information as in Fig. 4.

detected by the ADV (Figs. 4, 5). The height at which SNR and signal amplitude began to rise corresponded to the height at which the ADV began to underestimate flow speed relative to the HFV; this is the same height at which the sample volume (measured in decibels) would start intercepting the bed (Figs. 4, 5). That this apparent height of initial bed interception agrees with our logarithmically based estimates of SVH, but not with the linearized estimates, strongly supports our view that the linearized SNR provides a less valid estimation of SVH. Thus, we recommend that SVH be measured using raw (i.e., decibel) SNR values in future tests of the ADV.

Unfortunately, from the above, it will be difficult for investigators to ascertain whether a high value of SNR should increase or decrease their confidence in the flow data they are gathering. For example, in some cases, high SNR values may indicate high data quality, whereas in other cases, it may indicate a probe that is positioned too close to a solid surface. In particular, when making flow measurements at only one height above the bed, there will be no way to determine whether these data quality parameters are continuing to rise with increasing proximity to the bed. For these reasons, it is preferable to determine beforehand the size and location of the ADV sample volume rather than use a particular data quality value to decide how close to the bed the ADV can be safely deployed.

Implications—The purpose of our note is to inform aquatic researchers of potential measurement errors when using the ADV in close proximity to solid surfaces ($<$10 mm) and to describe simple tests that allow users to define for their own instruments when errors may occur. The larger than expected size of the sample volume and inaccuracies in its positioning that we documented may create fewer problems when working farther from the bed. Indeed, the ADV compares favorably to other flowmeters when used at distances $>$ 10 mm from a smooth bed (Lohrmann et al. 1994; Anderson and Lohrmann 1995; Voulgaris and Trowbridge 1998; this study). In contrast, if our test results are indicative of other ADV systems, then data collected within 10 mm of the bed should be interpreted with caution. In addition, many streams, estuaries, and rocky shores have rough beds that may pose greater challenges for positioning the sample volume than the smooth bed of a flume. This point underscores the need to evaluate the sample volume of individual ADV systems and to test their performance in a broad array of environmental settings.

Christopher M. Finelli
David D. Hart
Dina M. Fonseca[1]

Patrick Center for Environmental Research
Academy of Natural Sciences
1900 Benjamin Franklin Parkway
Philadelphia, Pennsylvania 19103

References

Anderson, S., and A. Lohrmann. 1995. Open water test of the SonTek acoustic Doppler velocimeter, p. 188–192. *In* Proceedings of the IEEE 5th Working Conference on Current Measurements.

Carling, P. A. 1992. The nature of the fluid boundary layer and the selection of parameters for benthic ecology. Freshwater Biol. **28:** 273–284.

Davis, J. A., and L. A. Barmuta. 1989. An ecologically useful classification of mean and near-bed flows in streams and rivers. Freshwater Biol. **21:** 271–282.

Denny, M. W. 1988. Biology and the mechanics of the wave-swept environment, 1st ed. Princeton Univ. Press.

Dodds, W. K., R. E. Hutson, A. C. Eichem, M. A. Evans, D. A. Gudder, K. M. Fritz, and L. Gray. 1996. The relationship of floods, drying, flow and light to primary production and producer biomass in a prairie stream. Hydrobiologia **333:** 151–159.

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.

Hart, D. D., B. D. Clark, and A. Jasentuliyana. 1996. Fine-scale field measurement of benthic flow environments inhabited by stream invertebrates. Limnol. Oceanogr. **41:** 297–308.

Kraus, N. C., A. Lohrmann, and R. Cabrera. 1994. New acoustic meter for measuring 3D laboratory flows. J. Hydraul. Eng. **120:** 406–412.

Lohrmann, A., R. Cabrera, G. Gelfenbaum, and J. Haines. 1995. Direct measurements of Reynolds stress with an acoustic Doppler velocimeter, p. 205–210. *In* Proceedings of the IEEE 5th Working Conference on Current Measurements.

———, ———, and N. C. Kraus. 1994. Acoustic Doppler velocimeter (ADV) for laboratory use, p. 351–365. *In* Proceedings of the Conference on Fundamentals and Advancements in Hydraulic Measurements and Experimentation.

Lomas, C. G. 1986. Fundamentals of hot wire anemometry. Cambridge Univ. Press.

Nikora, V. I., and D. G. Goring. 1998. ADV measurements of turbulence: Can we improve their interpretation? J. Hydraul. Eng. ASCE **124:** 630–634.

Nowell, A. R. M., and P. A. Jumars. 1984. Flow environments of aquatic benthos. Annu. Rev. Ecol. Syst. **15:** 303–328.

Sheng, J., and A. E. Hay. 1993. Spherical wave backscatter from straight cylinders: Thin-wire standard targets. J. Acoust. Soc. Am. **94:** 2756–2765.

SonTek. 1995. ADV for high resolution applications. SonTek application notes. SonTek.

———. 1997. ADV technical documentation. SonTek.

Vogel, S., and M. LaBarbera. 1978. Simple flow tanks for research and teaching. Bioscience **28:** 638–643.

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

Zedel, L., A. Hay, R. Cabrera, and A. Lohrmann. 1996. Performance of a single-beam pulse-to-pulse coherent Doppler profiler. IEEE J. Oceanic Eng. **21:** 290–299.

Received: 16 September 1998
Accepted: 10 May 1999
Amended: 19 May 1999

---

[1] Present address: Department of Entomology, Walter Reed Army Institute of Research, Division of Communicable Diseases and Immunology, Washington, D.C. 20307.

Acknowledgments

Funding was provided by NSF grant DEB-9627463 to D.D.H. Len Zedel helped in devising the mapping technique and provided useful advice on data interpretation. Vladimir Nikora provided expert advice on the ADV and useful criticism of earlier drafts of this manuscript. We also thank Leon Barmuta, N. LeRoy Poff, and two anonymous reviewers for their constructive reviews of the manuscript. We are grateful to Ramon Cabrera and other SonTek staff for advice about the acquisition and interpretation of our data, although we alone are responsible for the data and conclusions presented in this manuscript.