Assessment of Acoustic Coherent Doppler and Cross-Correlation Techniques for Measuring Near-Bed Velocity and Suspended Sediment Profiles in the Marine Environment

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ABSTRACT

The simultaneous measurement of current flow and suspended sediment concentration in the marine environment is central to the study of sediment transport processes. In view of this, two acoustic approaches for measuring flow were tested in a tidal estuary to assess their capabilities in this environment. A coherent Doppler velocity profiler and a cross-correlation velocity profiler were assessed using conventional current meters and a commercially available acoustic Doppler velocimeter. Mean velocity profiles were obtained up to a range of 1.47 m in 0.046-m range bins over a number of flood tides. The measurements compared well with the reference instruments and regression analysis produced gradients close to unity. Turbulent velocities measured with the coherent Doppler profiler were comparable with turbulent fluctuations measured with the acoustic Doppler velocimeter. The cross-correlation velocity profiler was shown to be unable to measure turbulent velocities. The backscattered signals received on the cross-correlation transducers were also used to compute the sediment concentration profiles using an explicit solution to the acoustic backscatter equation. Combining the concentration and flow measurements enabled sediment flux profiles to be obtained, the results of which compared favorably with flux measurements obtained from the conventional current meters and pumped sampling.

1. Introduction

Coastal engineers have been able to measure currents and oscillatory wave flow for many years using mechanical and electromagnetic current meters. However, sediment transport is more difficult to measure, and the application of acoustics to observe near-bed sediment processes (e.g., Lee and Hanes 1996; Williams et al. 1999) is beginning to provide a useful tool in the field of sedimentology. In addition to obtaining sediment suspension parameters (Sheng and Hay 1988; Thorne et al. 1993; Crawford and Hay 1993; Lynch et al. 1994; Thorne and Hardcastle 1997), high-resolution acoustic instruments also offer the potential to simultaneously measure flow profiles (Zedel et al. 1996; Adams et al. 1998; Lu and Lueck 1999). The main advantages of these backscatter systems for both hydrodynamic and sediment measurements are that they are nonintrusive, the subsecond temporal resolution provides measurements of turbulent and intrawave processes, and the bed can be located and its morphology measured over time.

Conventional acoustic pulse-to-pulse incoherent Doppler current profilers (ADCPs) have been in use for more than 20 years. These instruments measure flow velocity directly from the Doppler frequency shift (Wilson et al. 1997). Incoherent Doppler systems are generally applied over long ranges of 10–100 m, for mean velocity measurements where large bin widths are used. The resulting trade-off between resolution and velocity accuracy statistically requires velocity measurements to be averaged over several minutes (Brumley et al. 1991), $\sigma_T \approx \lambda$, where $\sigma$ is the velocity error per pulse, $T$ the pulse length, and $\lambda$ the wavelength of the system. This system is therefore inappropriate for the fine spatial (centimetric) and temporal (subsecond) resolution that is required for turbulent and near-bed flow measurements. Coherent Doppler velocity profilers (CDVPs) which use coherence between pulses, are being developed for such measurements (Lhermitte and Serafin 1984; Rowe et al. 1986). In this case the velocity estimate is made as a “snapshot” in time and the variance is measured over the short pulse-to-pulse time. CDVPs also require a trade-off between range and velocity because of the Nyquist sampling frequency limit. The CDVP measures the radial component of the velocity profile along the transducer beam axis using the measured rate of change of phase between consecutive backscattered signals. It is assumed that there is continuity in the particle locations within the insonified volume and that the phase change is associated with the group
motion of the particles. The range resolution of CDVPs is typically of the order of centimeters.

Another approach to using coherent Doppler to measure hydrodynamics is the application of a cross-correlation technique. Cross-correlation velocity profilers (CCVPs) have been used to measure mean velocities in an estuarine environment and also in a flume facility (Thorne et al. 1998; Thorne and Taylor 2000). The CCVP consists of two adjacent transducers, directed vertically downward, which measure the sediment in suspension as it advects beneath them. The amplitudes of the backscattered signals are cross-correlated to determine the sediment advection time lag, and thus the flow velocity is obtained.

The two developing acoustic techniques have principally been assessed under laboratory conditions (Zedel et al. 1996; Lemmin and Rolland 1997; Adams et al. 1998; van Unen et al. 1998; Zedel and Hay 1999; Thorne and Taylor 2000). In the present study the CDVP and the CCVP have been assessed in the marine environment, in an estuary subject to strong turbulent tidal flow. In this deployment, the CDVP and CCVP obtained velocity profiles up to a range of 1.47 m in 0.046-m range bins. The acoustic backscatter (ABS) signal recorded by the cross-correlation transducers was also used to obtain the sediment concentration in the water column (Crawford and Hay 1993; Thorne and Hardcastle 1997). Pumped sample measurements were collected at four heights above the bed and provided reference concentrations. The acoustic backscatter equation was solved, via an explicit solution, from a knowledge of the concentration at one height above the bed (Lee and Hanes 1995; Thorne and Taylor 2000). Sediment flux profiles were then computed from combined concentration and velocity profiles.

The capability of the acoustic instrumentation to measure current profiles was assessed by reference to conventional current meters and a commercially available acoustic Doppler velocimeter (ADV). All instruments were mounted on a frame such that the current meters and ADV recorded flow at specific heights above the bed. Data collected over a number of flood tide cycles from each of the instruments have been analyzed. Mean velocities were obtained from the conventional current meters, the ADV, CDVP, and CCVP, and these measurements were compared using regression analysis. The capability of the instruments to measure turbulent velocities was also considered. Analysis of the collected data showed that the CCVP was not capable of resolving turbulent velocity flow; however, the CDVP gave turbulent velocities that were consistent between adjacent range bins and comparable with the ADV velocities.

2. Methodology

The methodologies used to obtain high-resolution near-bed current and suspended sediment concentration profiles from the backscattered signal are described below.

a. The cross-correlation approach

The backscattered signal may be used to measure the flow of sediments using the cross-correlation function of the amplitude of the backscattered signal from two adjacent transducers (Thorne et al. 1998; van Unen et al. 1998). The approach assumes that the sediment structures in the suspension field retain significant temporal and spatial coherence as the structures advect between the transducers. In this method the two transducers, separated by a distance \( d_{12} \), are directed vertically downward and in line with the flow direction. The velocity \( \bar{v} \) may be determined from the separation of the transducers and the cross-correlation function time lag \( \tau \). The lag is the time taken for the suspended sediment structures to advect the distance between the two transducers. The velocity is then calculated from

\[
\bar{v} = \frac{d_{12}}{\tau^*}
\]

The time lag \( \tau^* \) is the location of the peak of the normalized cross-correlation function, \( \rho_{12} \),

\[
\rho_{12}(\tau^*) = \max[\rho_{12}(\tau)]
\]

where \( \tau \) is the cross-correlation lag. The normalized cross-correlation function is given by

\[
\rho_{12}(\tau) = \frac{R_{12}(\tau)}{[R_{11}(0)R_{22}(0)]^{1/2}}
\]

and is the cross-correlation function \( R_{12}(\tau) \) divided by the square root of the product of the autocorrelation functions \( R_{11}(0) \) and \( R_{22}(0) \) at zero lag. The cross-correlation function \( R_{12}(\tau) \) of the backscattered signals from the transducer pair at a range \( r \) is expressed as

\[
R_{12}(\tau) = \int_{-\infty}^{\infty} p_i^2(t, r)p_j^2(t + \tau, r) \, dt
\]

where \( p_i \) and \( p_j \) are the zero mean backscattered square pressures from the two transducers, averaged to reduce configurational noise (Libicki et al. 1989), and \( \rho_{ij} = \langle P_i^2 \rangle - \langle P_i \rangle, i = 1 \) or 2, where \( \langle P_i^2 \rangle \) is the time average over the record length of the square backscattered pressure for the \( i^{th} \) transceiver.

The error in the cross-correlation time lag measurements can be obtained by calculating the standard deviation of \( \tau^* \) as described by Beck and Plaskowski (1987):

\[
\sigma(\tau^*) = \left[ \frac{0.038(2\gamma)^{1/2}}{L} \frac{1}{\rho_{ij}^2(\tau^*) - 1} \right]^{1/2}
\]

where \( L \) is the record length and \( \gamma \) is the width of the cross-correlation function \( \rho(\tau) \) defined at 2/\( \pi \) of the maximum value \( \rho(\tau^*) \).
The standard deviation of the velocity $\sigma(v)$ can be estimated by differentiating Eq. (1) to give

$$\sigma(v) = \frac{\sigma(d_{12}) - d_{12}\sigma(\tau^2)}{\tau^2}. \quad (6)$$

Therefore, $\sigma(v)$ varies with transducer spacing, cross-correlation peak and width, cross-correlation lag, and record length. In the present work, $\sigma(d_{12})/d_{12}$ was estimated to be $\pm 0.01$.

b. The coherent Doppler approach

Another approach to measuring velocity profiles is the use of coherent Doppler. The pulse-to-pulse technique determines the rate of change of phase from consecutive backscattered signals. The radial velocity $v_r$ is given by

$$v_r = \frac{c f_d}{2 \tau_0} \quad (7)$$

for $v_r \ll c$, where $c$ is the velocity of sound in water $f_d$ is the Doppler frequency, and $\tau_0$ is the transmit frequency. The Doppler shift frequency $f_d$ is obtained from the in-phase $I$ and the quadrature $Q$ components of the mixed transmitted and received signals. The Doppler shift frequency and its sign can be obtained, hence the magnitude and direction of the velocity can be determined. Zedel et al. (1996) and Lemmin and Rolland, (1997) describe how the mean Doppler frequency can be obtained using

$$f_d = \frac{1}{2 \pi T} \tan^{-1} \left( \frac{\langle (t)Q(t + T) - I(t + T)Q(t) \rangle}{\langle (t)Q(t + T) + I(t)I(t + T) \rangle} \right) \quad (8)$$

where $T$ is the time between transmissions and $\langle \rangle$ indicates an average over a number of pulse pairs. To avoid ambiguous range information, the return from the maximum range must be received before the following pulse is transmitted, and therefore $T \leq 2 r_m/c$, where $r_m$ is the maximum range. The pulse repetition frequency determines the maximum unaliased value of $f_d$, $f_d \leq 1/2 T$. This leads to the maximum range–velocity relationship

$$r_m v_m \leq \frac{c^2}{8 f_0}. \quad (9)$$

For the present work, which used a system with a maximum range of 1.47 m and operated at 524 kHz, the maximum unambiguous velocity that could be measured was 0.41 m s$^{-1}$. However, by tracking the velocities vertically upward from the bed and accounting for discontinuities in the signal, it was possible to obtain greater velocity measurements. Therefore, in the present work velocity measurements up to 1.2 m s$^{-1}$ were made.

c. Concentration profiles

The correlation transducers recorded the backscattered acoustic signal from the suspended sediment, and this information was used to obtain the sediment concentration. The mean-square backscattered pressure $P^2$ from suspended sediments can be shown to be (Hay and Sheng 1992; Crawford and Hay 1993; Thorne et al. 1991; 1993)

$$P^2 = \left( \frac{K_s K_e}{r \psi} \right)^2 M \exp \left[ -4 \alpha_w + \int_0^r \zeta M dr \right]. \quad (10)$$

where $K_s$ is a function of the scattering properties of the sediment, $K_e$ is a constant of the system, $M$ is the suspended sediment concentration, $r$ is the range from the transducer, $\alpha_w$ is the water attenuation, $\zeta$ is the sediment attenuation constant, and $\psi$ accounts for the nonspherical spreading in the transducer near-field region (Downing et al. 1995). If the concentration is known at one location, then an explicit solution for $M$ can be obtained as described by Lee and Hanes (1995) and Thorne and Taylor (2000). If the natural logarithm of Eq. (10) is taken, and this equation is differentiated, the resulting nonlinear differential Bernoulli-type equation may be solved to give

$$M = \frac{\chi^2}{\frac{\chi^2}{M_0} - \int_{r_0}^r 4 \zeta \chi^2 dr}, \quad (11)$$

with $\chi = (Pr \psi/K_e)e^{2\alpha_w}$ such that at range $r_0$, $M_0 = M(r_0)$ and $\chi_0 = \chi(r_0)$. Note that $K_e$ and $\zeta$ depend on the particle size $a_s$, and evaluation of these parameters requires knowledge of the variation of the particle size with height above the bed. Previous studies at the site used in the present work provided acoustic particle size profiles with a mean radius $\langle a_s \rangle = 65 \mu$m, which typically increased to 75 $\mu$m close to the bed (Thorne and Hardcastle 1997; Thorne et al. 1998). During most of the flood cycle the particle size was approximately constant above about 0.1 m above the bed. The previous particle size profiles were used in the Bernoulli solution, given in Eq. (11), to obtain the concentration profiles. The concentration $M_0$ at range $r_0$ was obtained from the pumped sample measurements.

3. Experimental site and instrumentation

The experimental work to assess the CDVP and CCVP measurements of the mean and turbulent velocities was carried out in the River Taw estuary in Devon, United Kingdom, in August 1996. The site was accessible at low tide and had a tidal range of approximately 6 m. The location of the site is shown in Fig. 1. Data were collected over flood cycles on days 241–244 (28–31 August), when the spring tides were among the highest of the year. Strong turbulent tidal currents occurred in the estuary, resulting in high concentrations of suspended sediments. No surface waves were present. The bed consisted of fine sand, with the particle size being normally distributed with a mean radius of about 75 $\mu$m and standard deviation of 20 $\mu$m. During the
first two days, 241 and 242, the rig was placed on a nominally flat bed region where no significant sand waves were present up to 20 m from the rig. The position was changed on days 243 and 244, and the rig was positioned among sand waves typically with a wavelength range of 10–20 m and amplitude of 0.5–1 m. The local topography was obtained from surveys that were carried out every other tide at low slack water. These measured the upstream and cross-stream height variations of the site. The bed profiles on day 242 and that following on day 243 are shown in Fig. 2a, and the profiles at the new location on day 243 and day 244 are shown in Fig. 2b. A 2-MHz sand ripple profiler (SRP) provided local profiles of the bed every 2 min (Bell and Thorne 1997), and this is shown in Fig. 2c. The bed profiles over the flood tide show that there was significant bed erosion over a short period of time, and this information is referred to later when assessing the velocity profiles.

The sandwave field is shown in the picture in Fig. 3a. The instruments that were deployed for the study are shown and labeled in Fig. 3b. The instrumentation rig was constructed at low water when the site was dry and the data were transferred by cable to an anchored barge. Data collection began when the rig was fully submerged. The correlation transducers were positioned on the rig pointing vertically downward so that they were aligned with the expected current flow direction. A spacing of 0.159 m for days 241 and 242 and 0.19 m on days 243 and 244 separated the transducers. The horizontal coherent Doppler transducer was positioned pointing in the direction of expected flow for days 241 and 242, parallel to the bed, and at an angle of about 34° to the vertical for days 243 and 244. The coherent Doppler transducer operated at 524 kHz and the correlation transducers operated at 2 MHz. Each transducer had a diameter of 25 mm, and the calculated −3-dB half-angle beamwidths for the correlation and Doppler transducers were 2.0° and 6.8°, respectively. The pulse repetition frequency was 512 Hz and the pulse length was 61 μs. The backscattered signal envelope for the CCVP and the quadrature components of the CDVP were sampled at 16 kHz, providing 0.046-m spatial resolution. The maximum range was 1.47 m. The coherent Doppler system measures returns from particles moving as a volume; however, the particles move relative to one another. Lemmin and Rolland (1997) suggested that an optimum velocity variance and temporal resolution were obtained if the Doppler system averages over 32 returns for one velocity estimate. The Doppler and correlation data was collected on the same computer, with the da-
taset interleaved. Each was collected over 100 s every 12 min. The data from the triple-frequency acoustic backscatter (ABS) shown in the figure is not discussed in this paper.

To assess the CDVP and CCVP measurements, a 5-MHz SonTek ADV measured the three orthogonal components of velocity $v_a$ at a sampling rate of 25.75 Hz. The volume measured was 18 cm below the transmitter and of the order of 3 cm$^3$ (SonTek 1995). Data were logged continuously on a separate portable computer with time synchronization with the CCVP/CDVP computer.

In addition to the acoustic instruments, electromagnetic current meters (ECMs) and impeller current meters were attached to the vertical bar, as seen in Fig. 3b. These reference measurements were made at 0.1, 0.2, 0.4, and 0.8 m above the bed. The ECMs were positioned with their heads aligned parallel with the flow direction, and measurements of horizontal and vertical flow were recorded at 4 Hz. The impeller current meters
were placed pointing into the flow direction and their rotation rate recorded. Problems arose with some of the ECM measurements as a result of drift in the signals and noise, particularly for those located at 0.4 and 0.8 m above the bed. The impeller current meters also produced some unreliable results. As a result of these problems, the CDVP and CCVP data could only be compared with some of the data obtained from the conventional flow meters, and the ADV proved the most reliable reference instrument.

Pumped sample measurements were collected at approximately 10-min intervals, at 0.1, 0.2, 0.4, and 0.8 m above the bed. These provided both an in situ calibration for and an assessment of the concentrations measured by the acoustic backscatter from the correlation transducers. The samples obtained at 0.4 m above the bed were used for the calculation of the Bernoulli concentration explicit inversion.

4. Results and analysis

Measurements were recorded during a flood cycle on four consecutive days. All instruments were recording on days 242 and 243; therefore, these results have been used to assess the capability of the CDVP and CCVP for measuring current profiles in the marine environment. The CCVP and CDVP velocities were obtained from Eqs. (1) to (4) and Eqs. (7) and (8), respectively. The conventional current meters and the ADV probe were used as reference instruments. Mean velocities were obtained from each of the instruments and turbulent velocities were measured with the CDVP and ADV. As shown later, the CCVP was unable to extract the turbulent velocities; however, the effective velocity-sampling rate of 16 Hz in the CDVP enabled turbulence to be measured. The turbulent velocity \( v' \) is given by \( v' = v - \langle v \rangle \), where \( \langle v \rangle \) is the mean velocity over the 100-s run.

The cross-correlation transducers enabled concentration profiles to be computed using the explicit inversion algorithm, with reference to the pumped sample concentration at 0.4 m above the bed. Consequently, the sediment flux, \( \Phi = vM \), could be computed from the mean velocity and concentration profiles. The flux measurements were assessed using measurements obtained from the pumped sample data and the ECM velocities.

a. Mean velocities

The CDVP and CCVP data were collected over 100 s every 12 min, while the ADV ran continuously. The mean velocities for the two profilors were calculated over this 100-s period, while the ADV data was averaged over 2 min. The error bars on the CDVP data points were calculated from two adjacent 50-s records by computing the standard deviation on the mean. The error bars on the CCVP measurements were obtained from Eq. (6), and these were consistent with error bars obtained from the standard deviation on the mean computed over two halves of the record.

One set of mean velocity results obtained for day 242, at a height of 0.2 m above the bed, is plotted in Fig. 4. The ADV data are indicated by the continuous line that shows a similar variation over the flood tide to the impeller current meter measurements (●) and the ECM measurements (○). On this day the coherent Doppler transducer was positioned horizontally into the flow. It was located slightly above the ADV measuring volume, and velocity profiles from subsequent days were used to adjust the CDVP measurements to the height of the ADV. This height-adjusted coherent Doppler velocity is plotted (●) in Fig. 4. The velocity obtained from the cross-correlation measurement (○) corresponds to the result from the range bin that was located in the same vertical position as that of the ADV measurement. The instruments needed to be submerged under water before the data could begin to be collected; therefore, the curve in Fig. 4 shows the velocity measurements beginning about 1 h into the flood period, before the maximum flow was reached. The flow is seen to increase for the first 30 min to peak flow at around 1630 UTC and then steadily reduce over a 2-h period, reaching slack high water at 1830 UTC. At the start of the data collection period the ADV was still being interfaced to the computer and, as can be seen in Fig. 4, no ADV data were collected for this period. For the decelerating phase of the tide, all five current measuring instruments were operational. It can be seen that from peak flow at about 1.2 m s\(^{-1}\) down to approximately 0.4 m s\(^{-1}\) the magnitude and form of the mean velocity time series are consistent for all instruments. However, below 0.4 m s\(^{-1}\) the impeller current meter, for reasons that are not clear, was not functioning correctly. It can be seen from these plots that in the range 0.2–1.2 m s\(^{-1}\) the CCVP, CDVP, and ADV gave the most consistent results, with the data from the ECM and impeller current meters showing greater variability. Toward the end of the flood...
cycle when the currents were less than 0.2 m s\(^{-1}\) there was a degree of divergence between the ADV and the CCVP and CDVP. This is ascribed to the very low concentration levels present at the end of the flood tide, which affected the performance of the instruments. However, the salient feature from Fig. 4 is the consistency of the flow measurements over most of the flood tide, when the suspended sediment concentration was above 0.05 kg m\(^{-3}\). To quantify the relationship between the measurements of the ADV, CCVP, and CDVP, regression analysis has been carried out and the results are presented below.

In Fig. 5 a number of comparisons of the CDVP, CCVP, and the ADV are made. Regression analysis on
Table 1. Regression analysis of mean velocities.

<table>
<thead>
<tr>
<th>Instrumentation</th>
<th>Day/range</th>
<th>Regression gradient</th>
<th>Regression coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDVP and ADV</td>
<td>242 and 243</td>
<td>1.008 ± 0.1</td>
<td>0.997</td>
</tr>
<tr>
<td>CCVP and ADV</td>
<td>242 and 243</td>
<td>1.012 ± 0.1</td>
<td>0.989</td>
</tr>
<tr>
<td>CCVP and CDVP</td>
<td>243, all ranges</td>
<td>1.021 ± 0.03</td>
<td>0.989</td>
</tr>
<tr>
<td>CCVP and CDVP</td>
<td>0.276 m</td>
<td>0.910 ± 0.10</td>
<td>0.995</td>
</tr>
<tr>
<td>CCVP and CDVP</td>
<td>0.598 m</td>
<td>1.016 ± 0.06</td>
<td>0.995</td>
</tr>
<tr>
<td>CCVP and CDVP</td>
<td>0.986 m</td>
<td>1.051 ± 0.08</td>
<td>0.992</td>
</tr>
<tr>
<td>CCVP and CDVP</td>
<td>1.15 m</td>
<td>1.036 ± 0.06</td>
<td>0.993</td>
</tr>
<tr>
<td>CCVP and CDVP</td>
<td>242</td>
<td>1.030 ± 0.08</td>
<td>0.997</td>
</tr>
</tbody>
</table>

The CDVP and ADV results for days 242 and 243 is plotted in Fig. 5a, with the data from day 242 indicated (●) and 243 as (○). The regression results are shown in Table 1 and, within the error analysis limits, the gradient is unity. The regression coefficient was 0.997. Most of the measurements lie close to the regression line, and show that the CDVP and the ADV velocities were very comparable. There is an anomalous measurement at the lowest velocity; the ADV measured 0.2 m s⁻¹, but the CDVP recorded a velocity of less than 0.05 m s⁻¹. This occurs when there was little suspended sediment in the water column, typically less than 0.05 kg m⁻³. At these lower concentrations of smaller particles it became difficult to extract the velocities. This is suspected to be associated with a poorer signal-to-noise ratio for the CDVP, as it operated at a significantly lower frequency (524 kHz) than the ADV (5 MHz).

The regression plot for the CCVP versus the ADV is shown in Fig. 5b. The regression coefficient is high, 0.989; however, it can be seen that there is a greater degree of scatter in the data about the regression line. Again the greatest discrepancy occurs at the lowest velocities, and below 0.3 m s⁻¹, as measured by the ADV, the CCVP is measuring smaller velocities. The CCVP requires the backscattered signals to be cross-correlated, which necessitates sufficient sediment in suspension for structures to be formed that advect beneath the transducers, and such structures may not be present in low-flow conditions.

Results obtained from all the equivalent range bin locations for the CDVP and CCVP were used in the regression analysis of Fig. 5c; the complete data gave a regression coefficient of 0.990. In this figure the error bars have been omitted for clarity; however, there was greater error in the CCVP measurements than the CDVP. The data from day 243 are shown (○) and the data from day 242 are indicated differently (●); on this day the CDVP was pointing horizontally so there was only one CCVP coincident range bin. Analysis showed that the mean error in the CCVP measurements was ±0.066 m s⁻¹, compared to ±0.014 m s⁻¹ for the CDVP, showing that the majority of the scatter in Fig. 5c arose from the CCVP measurements. The variation in the regression coefficient for the CDVP and CCVP over the flood cycle was computed and some of these coefficients are given in the table for four range bins to show that there was consistency between the regression analysis over the whole range of the water column.

Figure 5d shows an example of the velocity profiles obtained with the CDVP and the CCVP. These results were obtained on day 243 when the coherent Doppler transducer was pointing at an angle of 33.7° to the vertical, providing a vertical profile of horizontal velocities. The two instruments gave comparable velocity profiles. The root-mean-square difference in the velocity profiles was measured to be 0.043 m s⁻¹.

b. Turbulent velocities

In addition to the mean flow measurements, an assessment of the turbulence measuring capabilities of the instruments has been made. To compare the capabilities of the instruments, the effect of reducing the record length was examined. An analysis was carried out as the record length reduced from 100 s to about 0.1 s to assess the impact on the velocity measurements. The results are shown in Fig. 6, where the normalized standard error \( \sigma(v)/\nu \) is plotted against the record length used, for the ADV (●), CDVP (○), and CCVP (●). The ADV and CDVP measurements of \( \sigma(v)/\nu \) remained nominally constant, at about 0.02. However, for the CCVP data as the record length decreased, \( \sigma(v)/\nu \) was found to increase significantly. This is plotted in Fig. 6 for the theoretical value of \( \sigma(v)/\nu \) (●), where \( \sigma(v) \) was computed from Eq. (6) and also from the variability in the measured velocity, (+). These analyses of the CCVP error are very similar, and show a significant increase in the normalized standard error as the record length reduced. This increase was not due to turbulence being resolved, as the values of \( \sigma(v)/\nu \) are greater than an order of magnitude above the turbulence. The results
Table 2. Regression analysis of turbulent velocities; internal consistency of the CDVP.

<table>
<thead>
<tr>
<th>Range from transducer</th>
<th>Regression gradient</th>
<th>Regression coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.460–0.506 m</td>
<td>1.008 ± 0.02</td>
<td>0.857</td>
</tr>
<tr>
<td>0.506–0.552 m</td>
<td>0.969 ± 0.02</td>
<td>0.871</td>
</tr>
<tr>
<td>0.782–0.828 m</td>
<td>1.033 ± 0.04</td>
<td>0.764</td>
</tr>
<tr>
<td>0.828–0.874 m</td>
<td>0.991 ± 0.02</td>
<td>0.863</td>
</tr>
<tr>
<td>0.874–0.920 m</td>
<td>1.010 ± 0.02</td>
<td>0.882</td>
</tr>
<tr>
<td>0.920–0.966 m</td>
<td>1.016 ± 0.02</td>
<td>0.872</td>
</tr>
<tr>
<td>0.966–1.012 m</td>
<td>0.972 ± 0.02</td>
<td>0.873</td>
</tr>
<tr>
<td>1.012–1.058 m</td>
<td>1.035 ± 0.02</td>
<td>0.853</td>
</tr>
</tbody>
</table>

show that it was not possible to measure turbulence with the present incoherent cross-correlation system. Similar results were obtained under laboratory conditions by Thorne and Taylor (2000). Consequently, only the CDVP data has been analyzed to assess its capability to measure turbulent flow in the marine environment.

1) Internal Consistency

On day 242 the CDVP was aligned into the water flow and to assess the internal consistency of the turbulent CDVP measurements, regression analyses were performed on data from adjacent range bins. An example of this intercomparison is shown in Fig. 7. Figure 7a compares two independent range bin velocity time series at 16 Hz, at a range of 0.97 and 1.01 m, illustrated by the black and gray lines, respectively. For illustration the velocity time series from a range of 0.97 m is displaced by 0.3 m s\(^{-1}\) from the zero-mean position. The broad fluctuations of the two time series compare well, and many of the higher-frequency fluctuations are also very comparable, as seen in Fig. 7b, where a section of the time series is expanded between 25 and 35 s into the record. The comparability is quantitatively assessed in the regression plot of these velocity measurements as shown in Fig. 7c. The regression gradient was 0.972 ± 0.020 and the regression coefficient was 0.873. Regression gradients and coefficients for several range bin comparisons are shown in Table 2, and these indicate the consistency of the CDVP measurements. Figure 7d shows the probability density functions (PDFs) of velocity measurements from adjacent range bins, and the results demonstrate the similarity of the distributions of velocities. There is an overlap in the PDFs of the results from adjacent range bins. The root-mean-square velocities were also computed for range bins at 0.83 and 0.87 m. Figure 7e shows the regression plot of the root-mean-square velocity measurements; the regression gradient was 0.955 ± 0.090 and the regression coefficient was 0.998.

2) Comparison with ADV

In the marine environment a sampling frequency of 5 Hz is typically used to measure turbulence. Because the ADV and CDVP were spatially separated, the measured higher-frequency turbulent fluctuations were not expected to be identical, and therefore the ADV and CDVP velocity time series were decimated and resampled on a 5-Hz time base for intercomparison of the turbulent velocities.

The horizontal turbulent velocities measured with the ADV and CDVP were compared on day 242. Although the instruments were not measuring precisely the same region, it was interesting to attempt a comparison. Time series of the velocities for the CDVP range bin closest to the ADV measurement region were compared, and the results are shown in Fig. 8a. The ADV turbulent velocity time series is shown in black, and displaced by 0.3 m s\(^{-1}\), and the CDVP turbulent velocity time series is shown in gray. The instruments were not precisely collocated so, consequently, it was not expected that the measurements of the higher-frequency turbulent components would be comparable in detail. However, the time series do show the lower-frequency fluctuations to be comparable. As a result of this separation between the instruments, the CDVP measurements were assessed by comparing the spectra of frequencies, and an example of the results is shown in Fig. 8b. The spectra are plotted for a 1-Hz band of frequencies, where the mean over 10 frequencies (0.1 Hz) was computed, and the standard deviation of the mean is indicated as the error bars. The spectrum of the ADV frequencies (×) is comparable with that of the CDVP frequency spectrum (○). The probability density functions of the velocities for both instruments are plotted in Fig. 8c. The form and amplitude of the probability density functions are very comparable. The rms velocities were also calculated, and Fig. 8d shows the regression plot for the root-mean-square velocities \(v_{\text{rms}}\) and \(v_{\text{rms}}\). The regression gradient was 0.922 ± 0.151 and the regression coefficient was 0.994.

c) Concentration and sediment flux profiles

Although the main emphasis of the present study was to assess the capability of the CDVP and CCVP to measure currents, advantage was taken of the CCVP backscatter data to obtain suspended sediment concentration profiles and combine them with the flow profile to measure near-bed sediment flux.

The concentration profiles computed from the explicit solution of the ABS equation and the pumped sample data gave two sets of results corresponding to the two correlation transducer measurements for each data collection period. Examples of three concentration profiles obtained on day 243 from the backscattered signal (○) are shown in Fig. 9a, along with the results obtained from the pumped samples (●). The results are shown up to 0.9 m above the bed. The concentration profiles decrease with increasing height above the bed, as expected, and the pumped sample measurements are located within the concentration profile obtained by the acoustic backscatter measurements. Regression analysis was per-
formed to compare the acoustic and pumped sample concentration measurements, and the result is shown in Fig. 9b (dashed line). In this figure the one-to-one relationship, $M_{abs} = M_{ps}$, is also plotted (solid line), and data from day 242 (●) and from day 243 (○) are distinguished. The error bars were computed from the standard deviation of the mean of the two correlation transducer datasets. The regression results for days 242 and 243 are shown in Table 3 and show that the acoustic and pumped sample concentration measurements were comparable.

Examples of acoustically measured near-bed concentration (●), velocity (○), and flux profiles (+) are shown in Fig. 10. The data were collected on day 243, when the instrumentation was located among the sandwave field, and hence the results are not classic flat-bed profiles. The measurements show a steady increase in con-
centration and a reduction in flow as the height above the bed reduced. The acoustically measured sediment flux shows a marginal increase with reduced height above the bed, and with values that are comparable with fluxes (☐) obtained by combining the ECM (×) and pumped sample data (●). The present data shows that the flux continues to increase farthest away from the transducer faces, toward the bed. The location of the bed was monitored in the direction of the flow by the SRP, and as seen in Fig. 2c the bed dropped by approximately 0.5 m over the flood tide. By 1710 UTC the bed had fallen below the maximum range of the transducers and therefore the measured flux profiles were well above the bed after the first few records. Therefore, in this experiment it was not possible to extract the details of the flux profile very close to the bed, apart from a single result at the start of the flood cycle (Betteridge et al. 2001).
5. Discussion and conclusions

The primary aim of the present work has been to assess the capability of using the backscattered signal from sediments in suspension to measure velocity profiles in the marine environment. Two developing acoustic approaches were tested in a tidal estuary subject to strong turbulent tidal currents. In addition to the velocity measurements it was also possible to obtain sediment concentration profiles from the backscattered signal, and therefore sediment flux profiles from the combined velocity and concentration were presented.

The CCVP provided a technique for obtaining flow velocities using two transducers aligned with the water flow. It has been shown that mean velocity measurements agreed reasonably well with those of the reference instruments; however, the regression plots showed a notable degree of scatter. This suggests that the transducer’s separation may have been too large, and there was a loss of coherence in the sediment structures as they advected between the transducers. Previous measurements under laboratory conditions, by Thorne and Taylor (2000), provided excellent results with the separations used in this experiment. It is therefore possible that an imperfect alignment with the flow in the estuary or the greater turbulence present in the estuary may have disrupted the spatial coherence of the sediment struc-

![Fig. 9. (a) Suspended sediment concentration profiles computed from the ABS signal (○) and reference measurements obtained by pumped sampling (●). (b) Regression plot of the suspended sediment concentration comparing the concentration computed from the ABS signal and from pumped sampling; results from days 242 and 243 are indicated as (●) and (○), respectively. Also shown are the regression line for day 242 (---), the regression line for day 243 (--), and the line for $M_{ABS} = M_{ABS} (---)$.]

![Table 3. Regression analysis of ABS and pumped sampled concentration measurements.]

<table>
<thead>
<tr>
<th>Day</th>
<th>Regression gradient</th>
<th>Regression coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>242</td>
<td>0.975 ± 0.03</td>
<td>0.990</td>
</tr>
<tr>
<td>243</td>
<td>0.838 ± 0.05</td>
<td>0.980</td>
</tr>
</tbody>
</table>

![Fig. 10. Acoustic measurements of the concentration (○), velocity (●), and flux profile (++) on day 243. Also shown are concentration (●), velocity (×), and flux (○) measurements from the pumped sample and ECM data.]

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portions. Therefore, in order to retain coherence the transducer separation would probably need to be less than the smallest separation, 0.15 m, used in the present study. An analysis of the CCVP turbulent measuring capability was carried out by reducing the record length of the data used to compute the velocity. The standard error on the CCVP velocity was found to significantly increase as the record length reduced to turbulent velocity timescales. This did not occur with reducing the record length for the ADV and CDVP, which remained nominally constant. The CCVP system was therefore unable to measure turbulence. The current system used a pulse repetition frequency of 512 Hz and a spatial separation of 0.15 m, and measured the mean flow in one horizontal direction. A pulse repetition frequency of 512 Hz was the optimum value for obtaining a range resolution of centimeters over a total range of 1.3 m. If a smaller range was required then the pulse repetition frequency could be increased, enabling a greater sampling rate. Improvement of the velocity resolution would require small-scale structures to be present that could be detected by closely spaced transducers operating at significantly higher pulse repetition frequencies. Therefore, the ability to observe 1D turbulence with a CCVP may depend on the location, sediment type, and local conditions giving rise to the small-scale structure.

The CDVP yielded accurate measurements of mean velocity profiles as shown by comparison with the reference instruments. There was significantly less scatter of the data about the regression line than that noted with the CCVP. It was also possible to measure the turbulent velocities. Analysis of independent turbulent velocity measurements between adjacent range bins showed good agreement. Comparison of the CDVP turbulent velocities with those measured with the ADV showed comparable time series, with spectra, velocity probability distribution and root-mean-square velocities showing good agreement. The CCVP transducers were also used to obtain the concentration profiles using the pumped sampled measurements. The explicit solution of the ABS equation provided an accurate method for obtaining concentration profiles. In conjunction with the velocity measurements, the concentration profiles enabled sediment flux profiles to be computed from the product of the velocity with the concentration. These results were consistent with the flux obtained using the reference measurements, showing that acoustics could be used directly to successfully obtain the sediment flux.

Finally, the results from this field deployment of the CDVP and CCVP have shown the limitations and capabilities of the two acoustic techniques for measuring profiles of flow in the marine environment. The results have also illustrated that the flow data can be coupled with a standard ABS treatment of the backscattered signal to obtain concentration profiles and hence direct sediment flux measurements.

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