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CONTINENTAL SHELF RESEARCH

Comparison between ADCP and transmissometer measurements of suspended sediment concentration

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Abstract

For more than a decade, acoustic Doppler current profilers, ADCPs, have been in common use measuring current profiles. It has been recognised over this period that the backscattered ADCP signal could be used to not only evaluate the Doppler shift, but also offered the possibility to extract information on the scatterers. The present work reports on an analysis of opportunistic backscatter measurements collected using a 1 MHz ADCP system, to assess the potential of ADCPs to measure suspended sediment concentration quantitatively. The data were gathered during a water monitoring campaign which deployed ADCPs, near-bed and profiling transmissometers, and in situ bottle samplers. Although the original study was not specifically designed to test the capability of ADCPs to evaluate suspended sediment concentration, sufficient data were collected to examine the use of ADCPs for such measurements. The backscattered amplitude from one ADCP beam was recorded for quality control to assess the accuracy of velocity measurements. However, in this study these data have also been used to examine the potential of ADCPs for suspended sediment measurements. To investigate ADCPs in this role, the backscattered signals from one range cell has been calibrated against in situ bottle samples of the suspended material. Using this calibration, the backscattered signals have been inverted to give time series profiles of suspended particulate matter. To assess these profiles, comparisons have been made with in-situ calibrated profiling and moored transmissometers. The outcome from the present study shows ADCP results which are comparable with the transmissometer observations, and clearly demonstrate the potential of ADCPs for directly measuring suspended sediment profiles. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The measurement of suspended sediments and their transport, is central to understanding many coastal and estuarine processes. Although measurement techniques are continually evolving, it is generally acknowledged that presently available instruments only partially fulfill requirements. Traditional instruments used to evaluate suspended sediment concentration have been limited to measurements at a single location, and therefore variations in the suspended sediment concentration through the water column have been obtained either by profiling, or by using a fixed vertical array of measuring devices. Both methods have disadvantages: mechanical profiling techniques are time consuming and the measurements have a poor temporal resolution, and a vertical array of fixed instruments can have logistical problems in deployment, and requires the calibration of multiple devices. Consequently, conventional techniques can be restrictive in their capability to provide detailed spatial and temporal profiles of suspended sediment concentration. This has led to an interest in alternative methods for evaluating concentration profiles, and in particular, the application of acoustic measuring systems.

One approach has been the use of multifrequency acoustic backscatter systems. These have shown that accurate in situ profile measurements of near-bed suspended sediment concentration and particle size can be obtained (Sheng and Hay, 1988; Crawford and Hay, 1993; Thorne et al., 1993; Thorne and Hardcastle, 1997). These high-resolution systems use acoustic transducers operating at megahertz frequencies, and transmit sound pulses of the order of microseconds. As the pulse propagates through the water column, sediments in suspension backscatter a proportion of the sound to the transducer. This returned echo is used to give a measure of the suspension concentration and particle size. These acoustic systems typically provide high-resolution profile measurements of particle size and concentration in the bottom 1–2 m above the bed.

The acoustic Doppler current profiler, ADCP, has conventionally been used to determine current velocities by using the Doppler shift of the backscattered acoustic signal (Griffiths et al., 1987; Wilson et al., 1997). Although ADCPs typically transmit an acoustic pulse of the order of milliseconds, and normally operate up to frequencies of around 1 MHz, the analysis applied to the high resolution near-bed acoustic backscatter systems is also applicable to the backscattered signal measured by ADCPs. Hence, it should be possible to determine the concentration of suspended sediments from the backscattered signal, as well as current velocity. Combining these two measurements, the ADCP could then be used to directly evaluate profiles of suspended sediment flux, and hence transport.

Ideally, for quantitative concentration measurements, parameters such as transmit and receive sensitivities, and the directivity of the transducers used by the ADCP are required. In principle it is possible, but experimentally difficult, to determine these parameters through laboratory calibration. Recent works by Griffiths and Roe (1993), Jones and Jago (1994), Heywood (1996), and Kostaschuk and Villard (1996) have shown that the ADCP can provide qualitative measurements on the scatterers in suspension. Later work by Holdaway et al. (1996) showed that transmissometer measurements of the suspended sediment concentration could be used to provide a first order calibration of the ADCP backscattered signal strength.

In a recent experiment in the Mersey estuary, UK, a series of measurements were taken as part of a water quality monitoring programme (National Rivers Authority, 1995; Holdaway et al., 1996). The experiment was conducted in July 1992, in the hope of fine weather, so that major non-tidal influences on the currents (and hence the sediments) were minimised. Upward-looking ADCPs were mounted on low profile frames across a narrow transect of the Mersey estuary. These were primarily intended to measure current velocity profiles over a spring-neap tidal cycle (Lane et al., 1997), with transmissometers deployed near each ADCP to provide observations of suspended sediment concentration. However, to provide quality control estimates for the measured velocities the amplitude of the backscattered signal from one of the ADCP beams was recorded. Although the experiment was not configured to assess the potential of ADCPs for measuring suspended sediment concentration, use has been made of the collected backscattered signals to obtain profiles of the suspended sediment concentration. Comparison of these profiles with moored and profiling transmissometer observations of the suspended load were then used to assess the accuracy of the ADCP concentration measurements. These results offer an insight into the potential of ADCPs for directly monitoring sediment transport.

2. Acoustic methodology

High-resolution underwater acoustics has been applied to the problem of suspended sediment measurements in various studies (Hay and Sheng, 1992; Lynch et al., 1994; Thorne et al., 1994; Thorne and Hogg, 1996; Schaafsma and Hay, 1997). In the present work, the expressions developed from the studies above have been applied to the backscattered acoustic signal from a single ADCP beam, and profiles of the suspended sediment concentration evaluated. The following provides a summary of the acoustic methodology, and the expressions used to calculate suspended sediment concentration from the ADCP signal.

The suspended sediment concentration can be written as (Crawford and Hay, 1993; Thorne and Hardcastle, 1997)

$$M_{\mathrm{A}}(r) = \left\{\frac{V_{\mathrm{rms}}}{K_{\mathrm{s}}K_{\mathrm{t}}}\right\}^2 r^2 \mathrm{e}^{4r(\alpha_{\mathrm{w}}+\alpha_{\mathrm{s}})}$$

$$K_{\mathrm{s}}(r) = \frac{\langle f_{\mathrm{m}}(r)\rangle}{\sqrt{\rho_{\mathrm{s}}\langle a_{\mathrm{s}}(r)\rangle}}$$

$$K_{\mathrm{t}} = gR_{\mathrm{s}}P_0 r_0 \left\{\frac{3\tau c}{16}\right\}^{1/2} \left[\frac{0.96}{ka_{\mathrm{t}}}\right] \quad (1)$$

$M_{\mathrm{A}}(r)$ is the suspended mass concentration, V_{rms} is the recorded voltage from the transducer, α_{w} is the attenuation coefficient due to water absorption, and α_{s} is the attenuation coefficient due to scatterers in suspension. K_s contains sediment information, $\langle f_m(r) \rangle$ describes the scattering properties of the sediment, ρ_s is the sediment density, and $\langle a_s(r) \rangle$ is the mean particle radius. The angular brackets represent an average over the particle size distribution. K_t represents the system parameters, where a_t is the transceiver radius of the normally used piston source, k is the wave number of the sound in water, R_s is the receive sensitivity of the transducer, g is the system gain, P_0 is the pressure at range r_0 (usually 1 m) when there are no scatterers in suspension, τ is the pulse duration, and c is the speed of sound in water. The root-mean-square voltage, V_{rms}, is required to reduce the effects of random fluctuations in the backscattered signal, due to configuration noise (Libicki et al., 1989).

The absorption due to water, α_w can be found using an empirical formula (Fisher et al., 1977), which at 1 MHz, and at 14°C provides $\alpha_w = 0.03$ Nepers m^{-1}. Attenuation due to the suspended load, α_s, is dependent on scattering and viscous absorption by the suspension material. α_s can be written

$$\alpha_s = \frac{1}{r}\int_0^r \zeta M_A \, dr \tag{2}$$

where ζ is the sediment attenuation constant, and has units of Nepers m^{-1} kg^{-1}.

At frequencies of about 1 MHz and below, and for particle radii less than 5 μm (as was the case in the present study), ζ is dominated by viscous absorption due to the sediments in suspension. The viscous absorption term due to the suspension is given by Urick (1948)

$$\zeta = \frac{k(\sigma - 1)^2}{2\rho_s}\left[\frac{s}{s^2 + (\sigma + \delta)^2}\right]$$

$$s = \frac{9}{4\beta\langle a_s \rangle}\left[1 + \frac{1}{\beta\langle a_s \rangle}\right]$$

$$\sigma = \frac{\rho_s}{\rho_0}, \quad \delta = \frac{1}{2}\left[1 + \frac{9}{2\beta\langle a_s \rangle}\right], \quad \beta = \left(\frac{\omega}{2v}\right)^{1/2} \tag{3}$$

ρ_0 is the density of water, v is the kinematic viscosity of water, $\omega = 2\pi f$, where f is the operating frequency of the ADCP. The value of v used in the present work was 1.3×10^{-6} m^2 s^{-1}.

Particle size measurements were unavailable during the experiment in July 1992. However, an estimate of the size profile was obtained using a series of measurements conducted in January 1994, close to the site of the original experiment. Bottle samples were collected, and analysed using a Coulter counter. The results are presented in Fig. 1; the data show the overall mean particle radius was 2.5 ± 0.2 mm, and indicate that particle size was approximately constant with water depth. These data are the only recently available measurements of the particle size profile in the Mersey estuary. Hence, as a first order estimate, the particle size profile from the July 1992 experiment was assumed to be nominally the same as in January 1994.

Assuming that in the present environment the particle size and density remained approximately invariant with depth, as shown in Fig. 1, then $\langle a_s(r) \rangle$ and $\langle f_m(r) \rangle$ can be considered constant, and hence $K_s(r)$ remains constant. The value of K_t remained constant for each ADCP, and hence Eq. (1) can be written as

$$M_A = K_* V_{rms}^2 r^2 e^{4r(\alpha_w + \alpha_s)} \tag{4}$$

where $K_* = (K_s K_t)^{-2}$ is a constant.

In the current work, the ADCP transducers were not fully calibrated under laboratory conditions, and hence K_t was unknown. However, the backscattered signal can be calibrated by comparing with an independent reference concentration at one range cell. In this study, in situ reference samples of the suspension concentration, M_S, were available at a single height, r_s. Substituting M_S for M_A, Eq. (4) can be rearranged as

$$K = \left\langle \frac{M_S}{V_{rms}^2(r_s) r_s^2 e^{4r_s\alpha_w}} \right\rangle$$

$$K = K_* e^{4r_s A_s}$$

$$A_s = \frac{\zeta}{r_s} \int_0^{r_s} \langle M_A \rangle \, dr \tag{5}$$

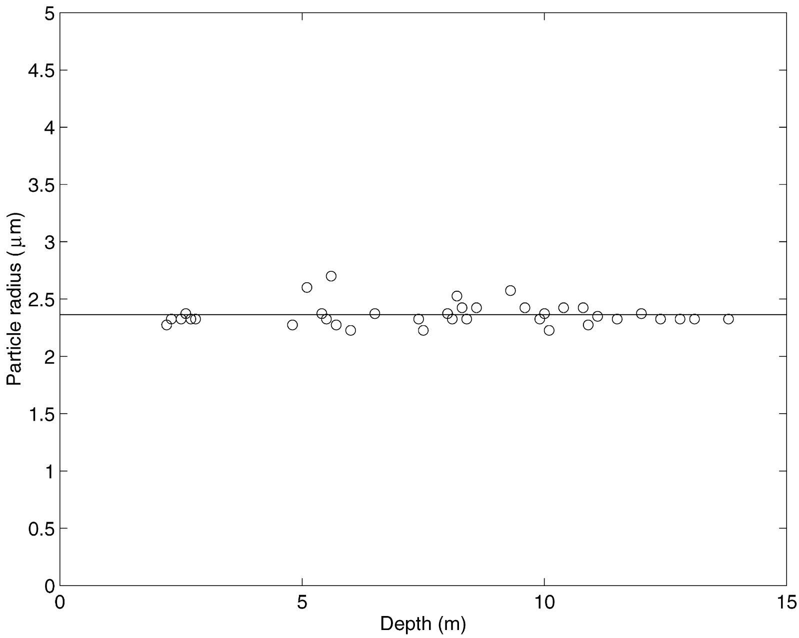

Fig. 1. Particle radius variation with depth in the Mersey estuary. (○) Measurements were taken at the site of MIDAS buoy as shown in Fig. 2; The mean particle radius, $\langle a_s \rangle$, is given by (—).

The angular brackets represent the average over all measurements corresponding to the times when bottle samples were collected. A_s represents the mean attenuation of the acoustic signal due to sediments up to r_s, and is absorbed into the constant K by the calibration procedure. A_s and K_* are never explicitly solved, but are implicit within the parameter K, which is obtained from the calibration using M_S at r_s.

With the same gain at each ADCP range cell, K can be used to estimate the absolute concentration of suspended material, M_A, through the water column beyond r_s. Combining Eq. (4) with Eq. (5) gives

$$M_A = K V_{rms}^2 r^2 e^{4(r\alpha_w + R\overline{\alpha_s})}$$

$$\overline{\alpha_s} = \frac{\zeta}{R} \int_{r_s}^{r} \overline{M_A(r)}\, dr$$

$$R = r - r_s \tag{6}$$

To accurately evaluate the mean concentration profile, $\overline{M_A}$, the mean attenuation path above r_s, $\overline{\alpha_s}$, is needed. However, Eq. (6) shows that $\overline{\alpha_s}$ requires a knowledge of the mean concentration profile, $\overline{M_A}$. This problem may be resolved by means of an iterative approach to the solution (Thorne et al., 1994). Temporal variations in the profile of suspended sediment concentration, M_A, can then be evaluated using this mean sediment attenuation profile.

Measurements of suspended load from optical beam transmissometers have been used in the present work to assess the accuracy of the acoustic inversion. Transmissometers have become established as a standard technique for determining sediment concentrations (Baker et al., 1984; Moody et al., 1987; Campbell et al., 1987; Jones and Jago 1994). The transmissometer light sensor records a voltage, V_T, proportional to the light intensity at a distance L from the light source, and is given by

$$M_T = \frac{1}{\Phi L} \log_e \left(\frac{V_0}{V_T} \right)$$

$$V_0 = V_{FSD} e^{(-L\mu_w)}, \qquad V_T = V_{FSD} e^{(-L\mu)}$$

$$\mu = \mu_s + \mu_w = \Phi M_T + \mu_w \tag{7}$$

where V_0 is the voltage measured with no suspended material, M_T is the suspended concentration, L is the optical path length of the transmissometer, and Φ is a constant optical sediment attenuation coefficient measured by calibration against bottle sample measurements (Moody et al., 1987). V_{FSD} is the voltage expected when the total attenuation is negligible, μ is the total attenuation, consisting of the attenuation of the light due to the water, μ_w, and the attenuation due to the suspended material, μ_s. In this paper, profiles of the suspended sediment concentration obtained using ADCPs are compared with moored and profiling transmissometer observations.

3. Site and instrumentation

Fig. 2 shows three sites across a transect of the river Mersey, UK (53° 25′N 3°1′W), where measurements were conducted between Egremont and Sandon Dock, from 8 to 28 July 1992 (Holdaway et al., 1996; Knight et al., 1993). Sites 2 and 4 were chosen as end-of-transect positions, both at an approximate depth of 8.5 m below chart datum (the level of lowest astronomical tide). Site 3 was chosen as a mid-channel position, and instruments were deployed 14.9 m below chart datum.

At each site ADCPs were deployed, mounted on low profile frames positioned on the river bed, as shown in Fig. 3a. At the end of the measurement period, the platforms were recovered. At site 3, an optical beam transmissometer was attached to the frame, as in Fig. 3a, allowing measurements of suspended sediment concentration to be obtained at 0.5 m above the river bed. At sites 2 and 4 a transmissometer was not attached to the frame, but to a tripod, as shown in Fig. 3b. Each tripod was deployed

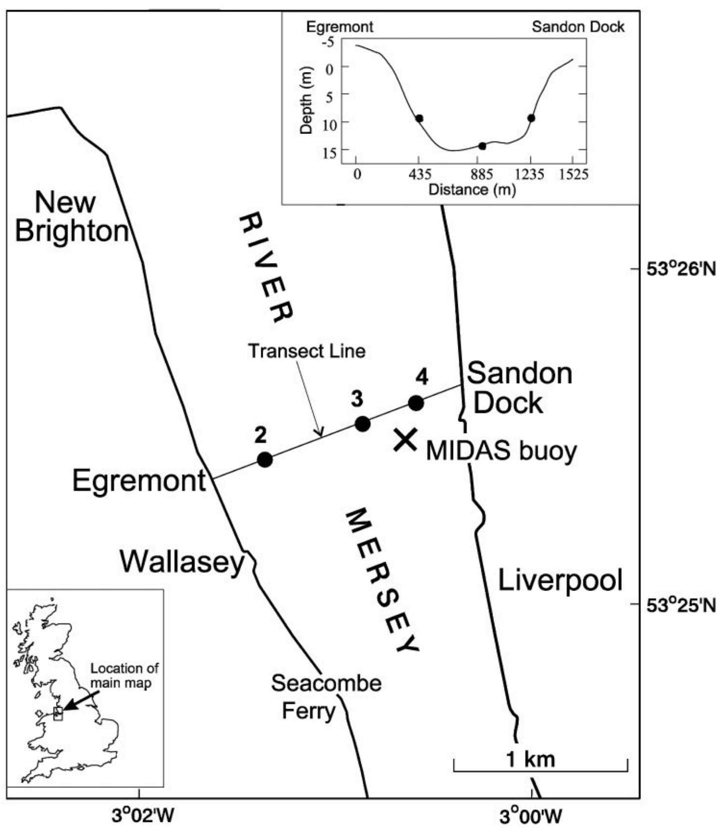

Fig. 2. Map showing the experimental site. (●) Positions of the instruments along the transect line across the Mersey estuary; (×) position of MIDAS buoy where particle size measurements were conducted.

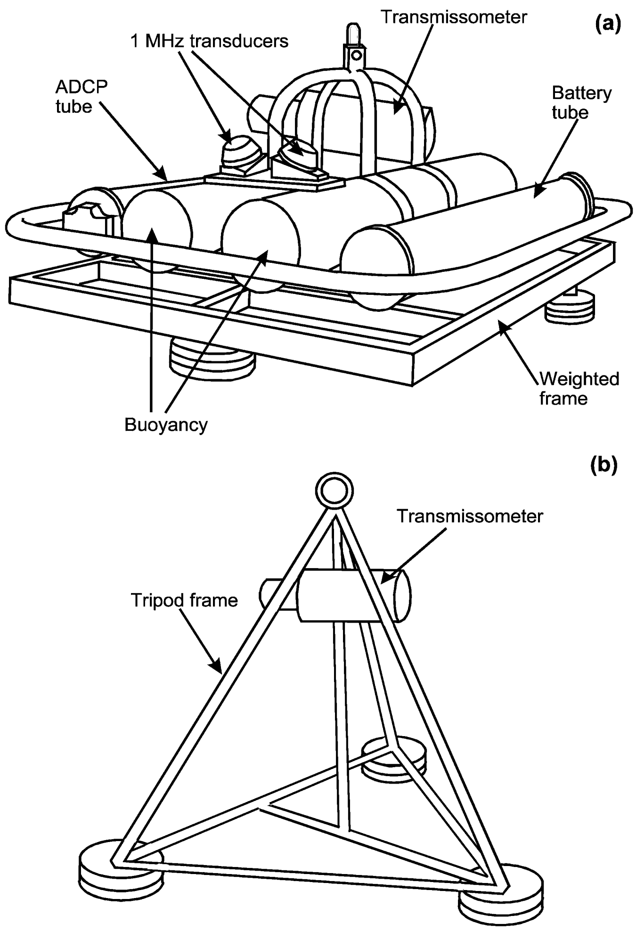

Fig. 3. Instrumentation deployed. (a) The low profile frame used at all sites with an ADCP attached, and in the case of site 3 a transmissometer attached. (b) Tripod used at sites 2 and 4 with a transmissometer attached.

within a few metres of the corresponding ADCP frame, and the transmissometers measured suspended sediment concentration at 1 m above the bed.

Each ADCP transmitted 1.5 ms acoustic pulses at 1 MHz, in two beams at an angle of 30° to the vertical. The distance between range cells was set at 1.4 m, and continuous profiles of current velocity and acoustic backscatter signal strength (for only one of the beams) were recorded on a system logging at 1 Hz. A total of 275 successive profiles were on-line averaged repeating every ten minutes. Each moored transmissometer operated using light of 665 nm wavelength, with a 4 cm path length, and was fitted with a solid state logger. This enabled instantaneous ambient-light-compensated transmittance to be measured at 1 min intervals, which were averaged over 10 min. At each site, a 5 cm path length transmissometer was profiled through the water column to the bed and back using a mechanical winch, allowing measurements of total beam attenuation, μ, to be made. Casts were taken sequentially at each site, with approximately 30 min between casts, for a duration of up to 12 h on 17, 21 and 24 July 1992. In-situ bottle sample measurements of the suspension concentration enabled absolute calibration of the profiling transmissometer data. This calibration also permitted the moored transmissometer measurements of total beam attenuation to be converted into concentrations.

As mentioned earlier, measurements of the suspended material were collected in January 1994 at the site of the MIDAS buoy, shown in Fig. 2. Fig. 1 showed that the mean particle radius, $\langle a_s \rangle$, was 2.5 μm, which places the sediment in the category of coarse clay. The particle radius was found to be constant with depth, and therefore absolute particle size was only required to obtain the second order effect of sediment attenuation, α_s, in the acoustic inversion procedure.

4. Calibrations

4.1. Transmissometer calibrations

Numerous profiles of the suspended sediment concentration at each site were evaluated using a profiling transmissometer. This measured the total beam attenuation, μ, at varying heights above the bed, and was calibrated against in situ bottle samples of the suspended sediment concentration, M_B, according to the calibration line in Fig. 4. The bottle sample concentrations were determined using gravimetric analysis. Comparisons between measurements of μ and M_B are represented in Fig. 4 by pluses, circles and crosses, at sites 2–4, respectively. The result of linear regression through the data is presented as a solid line. Relating this calibration line to Eq. (7), the value for Φ was determined as 147 $m^2\ kg^{-1}$. This value for Φ was then used on the moored transmissometer measurements of the total beam attenuation, μ, to obtain the suspended concentration at each site. This enabled detailed single height observations of the suspended sediment concentration to be evaluated. Both the profiling and moored transmissometer measurements of the suspended sediment concentration were then used to assess the accuracy of the ADCP concentration estimates.

4.2. Calibration of ADCP backscattered signal

To evaluate profiles of the suspended sediment concentration, the ADCP backscatter measurements needed to be calibrated. Hence, an absolute reference of the suspension concentration in at least one of the ADCP range cells was required. Such a reference was available from the bottle sampled concentrations, M_B, collected at a mean height of 1 m above the bed. However, the lowest usable range cell of each ADCP was at approximately 5.3 m above the bed, due to transducer ringing. Hence,

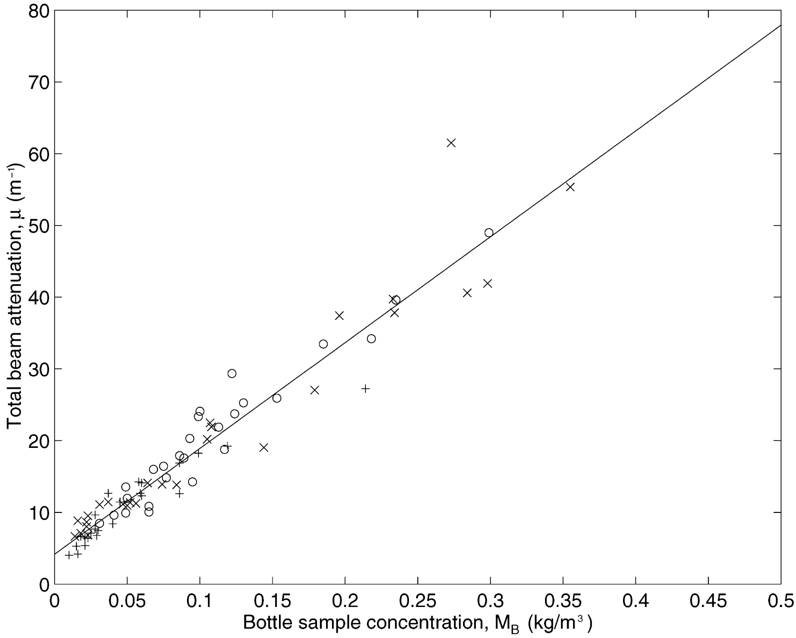

Fig. 4. Calibration of the profiling transmissometer. Measurements of total beam attenuation, μ, and corresponding bottle sample measurements of suspended sediment, M_B, at (+) site 2, (○) site 3, and (×) site 4; (—) least-squares fit, regressed through measured data.

because there was a concentration gradient, a direct comparison between M_B and the backscatter data from the lowest ADCP range cell would have yielded inaccurate profile estimates of the suspension concentration. This problem was resolved by using the profiling transmissometer data to obtain concentration gradients, and this information was used to translate the bottle samples collected at approximately 1 m above the bed to 5.3 m above the bed. This provided a direct comparison between the translated bottle sample measurements, $M_B(5.3)$, and the backscatter data from the lowest ADCP range cell, $V_A(5.3)$. Replacing M_S with $M_B(5.3)$ in Eq. (5), and using the values of $V_A(5.3)$ collected at the same time as M_B, it was possible to determine a value of K for each site. K was then substituted into Eq. (6), and using the complete time series record of $V_A(5.3)$, estimates of the absolute concentration time series at 5.3 m above the bed, $M_A(5.3)$, were evaluated.

Fig. 6 compares the values of $M_A(5.3)$ with the corresponding bottle sample measurements, $M_B(5.3)$, represented by pluses, circles and crosses at sites 2–4 respectively. Linear regression through these data showed that $M_A(5.3) = 0.008 + \{0.9 \pm 0.1\} M_B(5.3)$, with an associated correlation coefficient of 0.91. The probability that these two measurements were not linearly correlated was found to be less than 0.1% (Bendat and Piersol, 1971). Therefore, the calibration procedure provided values of K for each ADCP which could be used to invert the acoustic data.

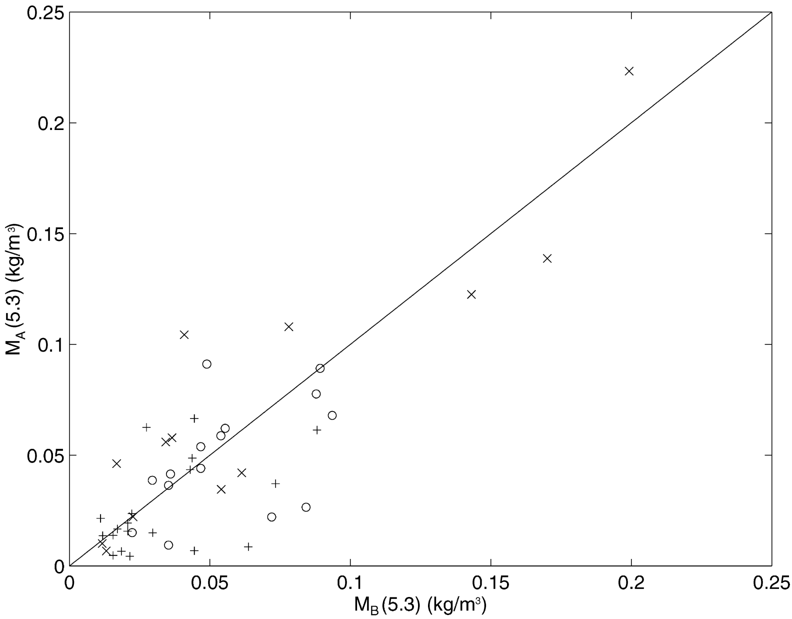

Fig. 5. Calibration of the ADCP backscattered signal amplitude. Comparison of calibrated ADCP concentration estimates, $M_A(5.3)$, with corresponding translated bottle sample measurements of suspended sediment, $M_B(5.3)$, at (+) site 2, (○): site 3, and (×) site 4; (—) unity gradient line through measured data.

Profiles of suspended sediment concentration were then obtained from the backscattered signal using an iterative inversion procedure originally developed for high-resolution ABS systems (Thorne et al., 1994). In the present work, this iterative approach was required in order to account for the attenuation of the acoustic signal caused by sediments in suspension above 5.3 m from the bed. For each iteration, the mean profile of the sediment attenuation above 5.3 m, $\overline{\alpha_s}$, was evaluated at each site using Eq. (6). From this new attenuation profile, Eq. (6) enabled updated values of the mean suspended sediment concentration, $\overline{M_A}$, to be obtained. In turn, these concentrations were used in the next iterative step to obtain improved estimates of the sediment attenuation. Typically, convergent solutions for $\overline{M_A}$ and $\overline{\alpha_s}$ were obtained after 10 iterations. In this study, accounting for the sediment attenuation led to increases in the suspension concentration of up to 26%.

5. Assessment of ADCP concentrations using transmissometer data

5.1. Time series comparison over the total record

Time-series profiles of M_A were evaluated using the values of K and $\overline{\alpha_s}$ determined by the ADCP calibration procedure. In order to examine the authenticity of the

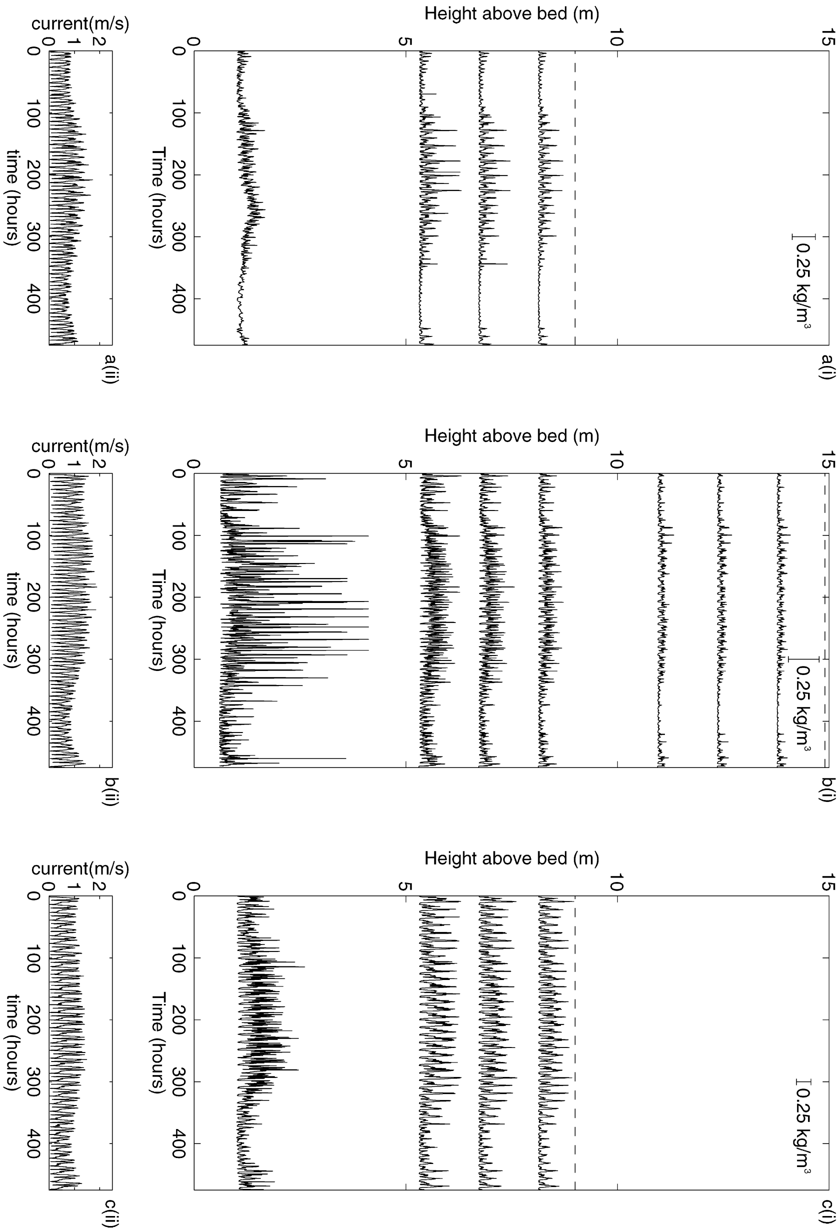

Fig. 6. Measurements of the suspended sediment concentration at (a) site 2; (b) site 3; (c) site 4. (i) Measurements of the suspended sediment concentration (—), the plot nearest to the bed is M_{MT}, from the moored transmissometer, and the plots above are M_A from the ADCP. (- -) is the level of lowest astronomical tide (chart datum); (ii) Current magnitude at 5.3 m above the bed measured using the ADCP (—).

variations in M_A, the ADCP concentration measurements were compared with the moored transmissometer measurements, M_{MT}. Fig. 6a(i)–c(i), show the profile measurements of M_A at sites 2–4, respectively, and the time series at the bottom of these plots are the corresponding near-bed measurements of M_{MT}. Additionally, in Fig. 6 a(ii), b(ii) and c(ii), the ADCP measurements of current magnitude at 5.3 m above the bed are presented for sites 2–4.

At sites 2 and 4, concentration estimates using the ADCP are presented up to 8.1 m above the bed. During times of low slack water, the tidal height was sometimes as low as 0.4 m above the chart datum level of 8.5 m. Hence, for all range cells above 8.1 m, reflections from the water surface by the side lobes of the main acoustic beam led to unreliable measurements of the suspension concentration. For site 3, the chart datum level was at 14.9 m. Even so, the profile of suspended sediment concentration measured by the ADCP at site 3 extended only to 13.7 m above the bed. This was due to a low signal-to-noise ratio of the acoustic backscattered signal beyond 13.7 m. Additional problems were experienced with ADCP measurements from 9.4 m above the bed, and these have been removed from the analysis.

The spring-neap and semi-diurnal variations observed in the current magnitude time series are clearly reflected in the concentration fluctuations of M_A and M_{MT}. It can be seen that the high concentrations of suspended material coincide with the higher current magnitudes of springs, which induce increased bed shear stresses and vertical mixing. Conversely, at neaps suspended sediment concentration levels are markedly reduced. Although there are generic similarities between the ADCP and transmissometer data sets, it is also clear that there are some differences in the structure of the concentrations observed with the ADCP and the moored transmissometers. For example, in Fig. 6a(i), the ADCP measured some high concentration events which the near-bed moored transmissometer did not appear to respond too, while in Fig. 6b(i) the opposite is the case. However, these discrepancies, although visually notable, account for less than 10% of the total observations, and the general trends and levels in the time series of the suspended sediment concentration were nominally consistent between instruments. Further attention is paid to these differences later when the detailed structure of the time series is considered.

5.2. Profile comparison

To assess the concentration profiles obtained at each site using the ADCPs, the profiling transmissometer measurements of the suspended load, M_{PT}, were compared with the profiles of M_A. Fig. 7 includes profile measurements of the suspended load at (a) site 2, (b) site 3, and (c) site 4. The dots represent the mean suspended sediment concentration observed using the profiling transmissometer, $\overline{M_{PT}}$, averaged over 15 profiles. Values of M_A and M_{MT} corresponding to the 15 individual profiles of M_{PT} were also averaged. These mean concentrations, $\overline{M_A}$ and $\overline{M_{MT}}$ are represented by the open circles and crosses, respectively. The mean profile measurements of $\overline{M_A}$ are consistent with $\overline{M_{PT}}$ to first order, and both exhibit the expected reduction in concentration with height above the bed. To quantify the degree of similarity, the profiling transmissometer concentrations were used as an absolute reference, and an

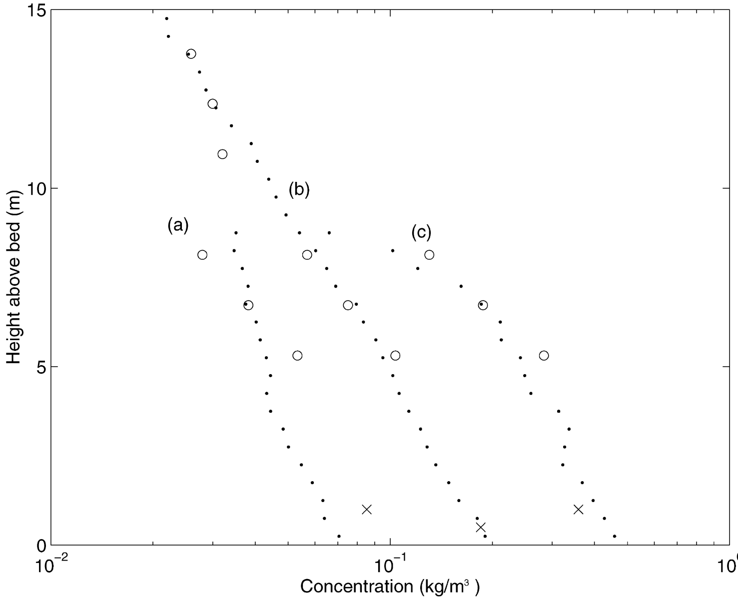

Fig. 7. Comparison of profile measurements of mean suspended sediment concentration with height above the bed at (a) site 2; (b) site 3; (c) site 4. (●) $\overline{M_{PT}}$; (○) $\overline{M_A}$; (×) $\overline{M_{MT}}$.

estimate of the error in $\overline{M_A}$ evaluated. The normalised standard error for each value of $\overline{M_A}$, calculated as $\sigma(\overline{M_A}, \overline{M_{PT}})/\overline{M_{PT}}$, were σ represents standard deviation, was determined, and this gave a mean value of 0.07. Similarly $\sigma(\overline{M_{MT}}, \overline{M_{PT}})/\overline{M_{PT}}$ was calculated, and this gave a value of 0.09. Hence, the differences between $\overline{M_A}$ and $\overline{M_{MT}}$; and $\overline{M_{PT}}$, were comparable. The agreement of the ADCP profiles with the profiling transmissometer was therefore of the same order as the internal consistency of the transmissometer measurements.

To provide a more detailed illustration of the profiling capability of the ADCP, Fig. 8 shows the variation with time and height above the bed of the suspended sediment concentration field at site 3 over an 8 h period. Fig. 8a shows the profiling transmissometer, M_{PT}, concentration observations, and Fig. 8b presents the corresponding ADCP, M_A, measurements. For comparison the profiling transmissometer measurements have been linearly interpolated to the same temporal resolution as the ADCP observations, and the ADCP concentrations were linearly interpolated to the same spatial resolution as the profiling transmissometer. It can readily be seen that the spatial and temporal features of the suspended field observed by the profiling transmissometer data are broadly reflected in the ADCP measurements. Periods of high and low concentration observed by both methods are ostensibly consistent, although the absolute level and concentration gradient with height above the bed tend to vary to some degree. These differences are not necessarily unexpected, given the actual

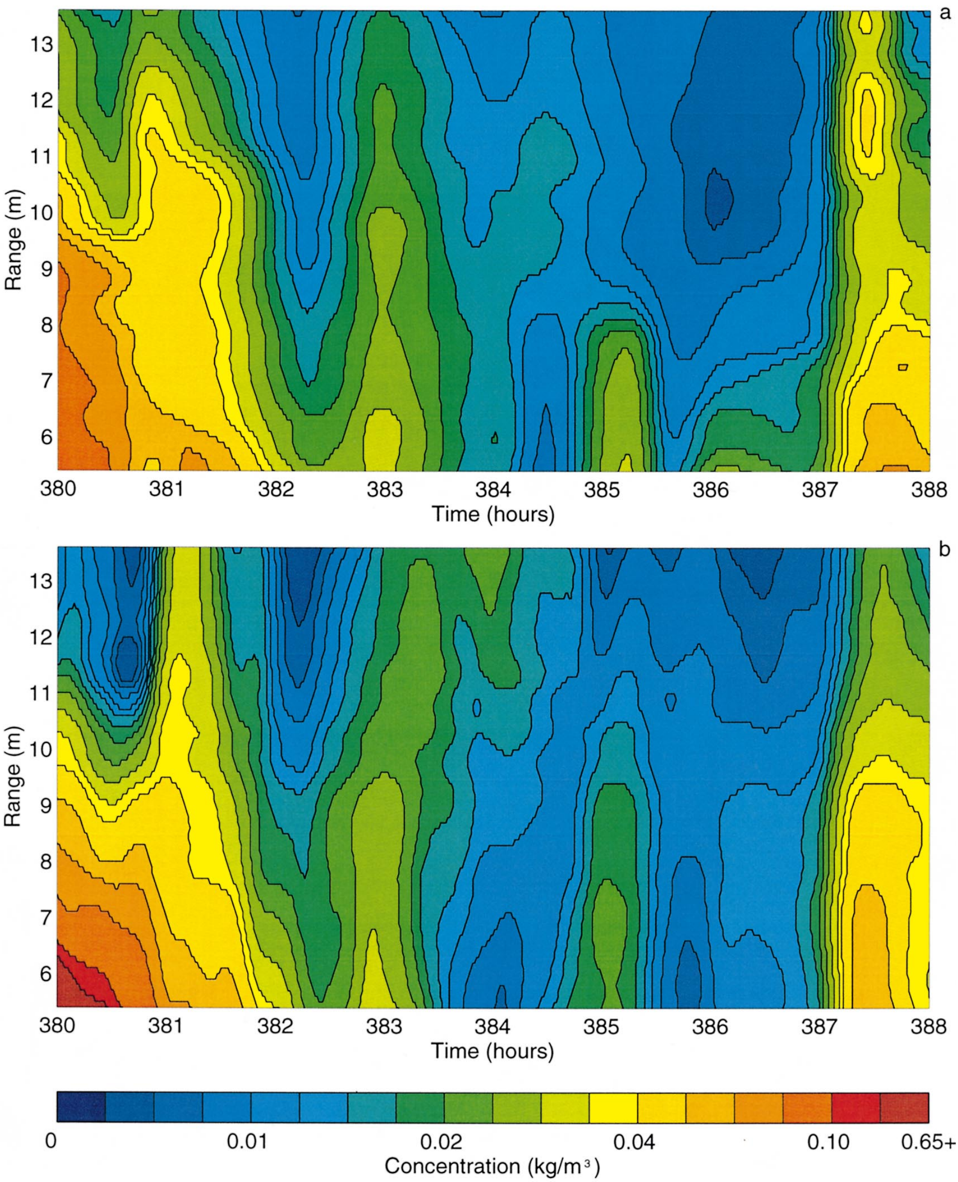

Fig. 8. Comparison of measurements of the suspended sediment concentration with time and height above bed at site 3. (a) M_{PT} and (b) M_A.

spatial resolution of the ADCP observations, and the temporal resolution of the transmissometer measurements. However, the comparison does demonstrate the capability of ADCPs for measuring the spatial and temporal form of the suspended sediment concentration.

5.3. Detailed comparison

The time series presented in Fig. 6 showed profile variations in the suspended sediment concentration for a period of approximately 20 days. Ideally, to quantify the accuracy of any fine-scale temporal variations in M_A, direct comparison with a detailed reference measurement from within at least one of the ADCP range cells would be needed. However, the only available measurements with the same temporal resolution as the ADCP were the data collected by the moored transmissometers. These instruments measured the suspended sediment concentration at 1 m above the bed at sites 2 and 4, and at 0.5 m at site 3, whereas the lowest usable range cell of each ADCP was at 5.3 m above the bed. To account for this difference in height, the mean concentration gradient between 5.3 m and the height of the moored transmissometers was evaluated at each site from the profiling transmissometer measurements. These gradients allowed the ADCP concentration time series from 5.3 m above the bed to be translated to 1 m above the bed at sites 2 and 4, and to 0.5 m at site 3. Consequently, direct intercomparison was possible between M_{MT} and the translated ADCP concentration time series, M_A.

Detailed comparisons of the height adjusted M_A values with corresponding measurements of M_{MT} from the beginning of the observational period at sites 2–4 are shown in Figs. 9a(i)–c(i). Synchronous current magnitude measurements from 5.3 m above the bed are also presented for each site, in Figs. 9a(ii)–c(ii). The flood and ebb periods are labelled 'F' and 'E', respectively. All ADCP time series are represented by a solid line, and the moored transmissometer measurements by a dotted line. The presented data starts at midday on 8 July 1992, and continues for 60 h (approximately five tidal cycles).

The measurements from all three sites presented in Fig. 9 show that the tidal variations in the current magnitude effect the concentration of sediments in suspension. Peaks in M_A and M_{MT} occurred during both the flood and the ebb of successive tides, and lowest concentrations were observed at times of slack water. The data presented show that there are similarities but also differences between M_A and M_{MT}. Using Fig. 9b(i) as an example, for approximately half of the presented time-series observations, during semi-diurnal flood periods, there was good agreement between M_A and M_{MT}. However, during semi-diurnal tidal ebb periods, comparisons between measurements were less consistent with M_A notably smaller than M_{MT}. Similar differences also exist in Figs. 9a(i) and c(i), but are less prominent than in Fig. 9b(i).

To quantify the degree of consistency between the concentration measurements at each site, the normalised standard deviation, $\sigma(M_A, M_{MT})/\bar{M}$, was calculated over the 60 h period indicated in Fig. 9, where $\bar{M} = (M_A + M_{MT})/2$. The mean normalised standard deviations for the data were calculated to be (a) 0.18, (b) 0.34, and (c) 0.30, for sites 2–4 respectively. Hence, ADCP and transmissometer measurements of the

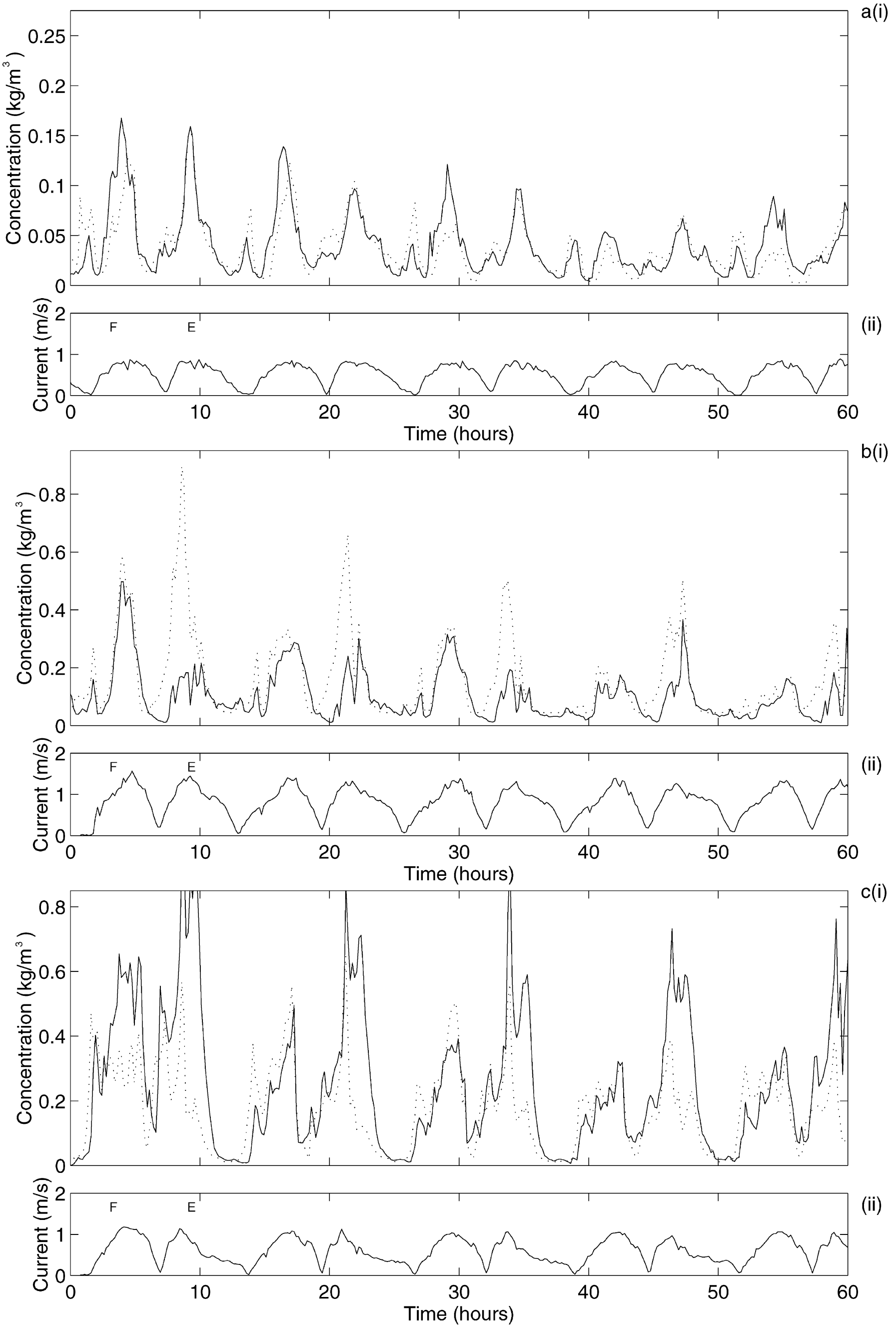

Fig. 9. Measurements over five tidal cycles at (a) site 2; (b) site 3; (c) site 4 of (i) detailed suspended sediment concentration; (—) measurements made by ADCP; (····) measurements made by moored transmissometer: (ii) current magnitude; (F) flood of semidiurnal tide; and (E) ebb of semidiurnal tide.

suspended sediment concentration were nominally consistent over this time period. An alternative approach used to assess the level of agreement between M_A and M_{MT} was to use linearly regression the data. Regression analyses gave linear correlation coefficients of 0.81, 0.69, and 0.64, for sites 2–4, respectively. This showed that there was a less than 0.1% probability that M_A and M_{MT} were not linearly correlated (Bendat and Piersol, 1971). According to the linear regression equation: $M_A = aM_{MT} + b$, values of a were calculated as 1.0, 0.5, and 1.0, for sites 2–4, and values of b were found to be 5×10^{-3}, 4×10^{-2}, and 6×10^{-2} kg m^{-3}. This analysis suggests that M_A and M_{MT} were generally consistent at sites 2 and 4. The value of a calculated for site 3 indicates that M_A was on average a factor of two smaller than M_{MT}.

As mentioned earlier, at site 3 the amount of agreement between M_A and M_{MT} varied significantly, depending on the tidal conditions. When only the concentrations associated with the tidal floods were considered, the mean normalised standard deviation was 0.22, the linear correlation coefficient increased to 0.94, and the value of a was equal to 0.9. However, when the same analysis was performed for ebb periods only, these values were calculated as 0.45, 0.67, and 0.3 respectively. Hence, at site 3, the correspondence between M_A and M_{MT} was improved only when successive floods of the tidal cycle were considered.

The observed differences between M_A and M_{MT} at the three sites, particularly those noted above for site 3, which were tidally dominated, are probably primarily associated with two factors. Firstly the moored transmissometer measured the suspension concentration at 1 and 0.5 m above the bed, whereas the lowest usable range cell of the ADCP was at 5.3 m. Therefore the two instruments were not sampling the suspended sediment concentration at the same height above the bed. Consequently, the height adjusted ADCP concentrations, derived from the average concentration gradients observed by the profiling transmissometer may have occasionally been problematic. Also in the ADCP calibration the particle size profile with height above the bed was assumed to be constant, this being based on earlier measurements. It is not unreasonable to expect some variation in particle size with the varying stages of the tide, and this would effect the measured concentration of both the ADCP and transmissometer. However, acknowledging these differences and their possible sources (and the restricted form of the data available), it is, nevertheless, clear from the detailed measurements that to first order the ADCP can be used to measure the temporal form of the suspended sediment concentration.

6. Conclusions

In the present work, an investigation has been conducted into the use of ADCPs for measuring suspended sediment concentration profiles. Originally, the collected backscatter data were intended to provide quality control of the Doppler shifts used by the ADCP to calculate current velocities. It is readily accepted by the authors that the configuration of the experiment was not ideal, however, it was still considered worthwhile to use this data, coupled with a description on the interaction of sound with marine sediments, to investigate the potential of ADCPs for measuring profiles of suspended sediment concentration. The backscatter data effectively comes at no extra cost, and therefore if it can be used to provide information on the scatterers, it contributes added value to the measurements.

Using theoretical descriptions of sediment scattering it has been possible to calibrate the backscattered ADCP signals against in-situ bottle samples of the suspended sediment. Using an iterative inversion procedure sediment attentuation was accounted for and time series profiles of the suspended sediment concentration obtained. These ADCP concentration data were compared with fixed height and profiling transmissometer measurements. Mean profiles of the suspended sediments, and 2-D plots of the variation in the suspension field with range and time (e.g. Fig. 8) showed comparable results. The detailed time series comparisons of the ADCP concentrations with the nearbed fixed height transmissometers measurements showed periods with a high degree of agreement and others where agreement was poorer. This was particularly noticeable for site 3 when the differences were clearly associated with the stage of the tide. Reasons for the differences were discussed, and a prime source was probably the lack of contemporaneous suspended sediment size measurements collected with ADCP and transmissometer data. This arose because of the use of an opportunistic data set for the present work, however, future studies should aim to measure particle size.

Finally, this investigation has provided a coupling of acoustic sediment scattering theory with an opportunistic data set to examine the potential of using the backscattered signals from ADCPs to measure suspended sediment concentration. It has shown that providing in-situ calibration data are available at one height, and an estimate can be made for the particle size profile, ADCPs can be used to measure suspended sediment concentration quantitatively through the water column. The ADCP concentration profiles and detailed time series observed in the present work have been shown to compare favourably, at least to first order, with independent transmissometer measurements of suspended sediment concentration. These developments show that ADCPs have the capability to directly measure suspended sediment transport, and given our present limited ability with conventional techniques to obtain high temporal and spatial resolution measurement of suspended matter throughout the water column, the acoustic approach offers an alternative with the potential for further developments.

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