ESTIMATION OF SUSPENDED SEDIMENT CONCENTRATION IN ESTUARINE ENVIRONMENTS USING ACOUSTIC BACKSCATTER FROM AN ADCP

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Abstract: Acoustic current profilers were originally designed to measure 3-D flow structure but they also record the intensity of the return echo. The latter is proportional to the number of backscatters present in the water column and can be used as a proxy for suspended sediment concentration. The potential for remote, rapid and simultaneous measurements of current and suspended sediment concentration (SSC) fields with increased vertical and horizontal spatial resolution drives the development of methods for converting acoustic intensity to SSC. In this study, we present simultaneously collected acoustic Doppler current profiler (ADCP, RDI Workhorse, 1200kHz) and suspended sediment concentration data, obtained with an optical backscatter sensor (OBS). These data are utilized to calibrate a simplified version of the sonar equation that converts the recorded by the ADCP echo intensity into SSC. This simplified sonar equation lumps a number of immeasurable quantities into two parameters K_c and C_k.. The calibration procedure produced K_c and C_k values of 0.43 and -104.65, respectively. The calibrated sonar equation was verified with an independent set of data and found to agree within 90%. Combining the OBS data with particle size information obtained using a Laser *In-Situ* Scattering Transmissometer (LISST) it was found that ADCP estimates of suspended sediment concentration are more accurate when the sediment in suspension is predominantly fine sand. When the sediment is silt of finer then there is a slight bias in the acoustic estimates of suspended sediment. Although our results are more applicable to our environmental setting the procedure presented here can be followed and applied in other areas.

INTRODUCTION

Studies of erosion, transport and deposition of suspended sediments are essential in environmental programs that deal with contaminant transport and the cycle and redistribution of toxic materials. Furthermore, geomorphologic studies concerned with the development and changes of shoals or the maintenance of navigation channels require detailed information on sediment dynamics and in particular its spatial and temporal distribution.

In estuarine environments, suspended sediment concentration (SSC) varies significantly both in time and in space in response to freshwater discharge, tidal variability, and channel geometry. Traditional point measurements of SSC include filtering of water samples, optical methods (i.e., transmissometry, nephelometry, backscatterance) and acoustical backscatterance sensors (ABS). Even though these sensors can be calibrated easily and are widely acceptable, their application is limited to experiments at a single location. Furthermore, if calculation of sediment flux is desired, then additional sensors are required to measure the water flow.

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Acoustic Doppler current profilers (ADCP) are becoming the standard for measuring current speed both at stationary locations and as ship-borne, moving sensors. Over the past decade there has been increased activity in developing methods to measure SSC using acoustic backscatter intensity from such acoustic current profiling systems (Thorne et al., 1991, 1993; Holdaway et al., 1999; Gartner and Cheng, 2001; Poerbandono and Mayerle, 2001; Gartner, 2002). All types of acoustic current profile record 3-D current data but also measure the intensity of the return echo, which is proportional to the amount of backscattering particles present in the water column. When the majority of backscattering particles are of sedimentary nature, the acoustic intensity can be used as a proxy for total SSC. The relationship between acoustic backscatterance level and SSC is based on the sonar equation (Deines, 1999; Gartner and Cheng, 2001). The intensity of the backscattered echo is a function of distance from the sensor, attenuation due to the water itself, and total concentration of suspended particles.

In this contribution we use experimental data to evaluate the use of a 1200 kHz ADCP for measuring SSC. The specific objectives of this paper are to: (1) calibrate a conventional simplified sonar equation for use with a 1200kHz RDI ADCP to be used for estimating SSC; (2) verify the validity of the calibrated sonar equation; and (3) use the data to study SSC distribution in an estuarine environment.

THEORETICAL BACKGROUND

According to basic underwater acoustics theory, the equality between received signal level and background masking level can be expressed by the active sonar equation (Urick, 1983):

$$DT + NL = SL + 2 \cdot TL + TS + DI \qquad (1)$$

where DT represents detection threshold, NL is noise level, SL is source level, TL is transmission loss, TS is target strength, and DI is receiving directivity index. The source level (SL) and the directivity index (DI) are usually determined by the manufacturer of the acoustic transducer and can be regarded as constants for a specific instrument. Therefore, the output of acoustic signal (DT + NL) is influenced by the 2-way transmission loss (2·TL) and the target strength (TS) parameters, both of which are influenced by the amount of backscatterance within the water column. The 2-way transmission losses include attenuation by seawater and spreading and attenuation by the sediment particles. The target strength (TS) of suspended sediment is also a function of particle shape, size, rigidity, and acoustic wavelength.

Based on the power (or energy) of acoustic intensity, Deines (1999) simplified the theoretical sonar equation for the broadband RDI ADCP:

$$S_v = C + 10 \cdot \log_{10}((T_x + 273.16) \cdot R^2) - L_{DBM} - P_{DBW} + 2 \cdot \alpha_w \cdot R + K_c \cdot (E - E_r) \qquad (2)$$

where S_v = the backscatter coefficient (in dB), T_x = temperature of the transducer (in °C), R = range along the beam to the scatter (in m), L_{DBM} = 10·log$_{10}$(transmit pulse length), P_{DBW} = 10·log$_{10}$(transmit power), α_w = absorption coefficient of water, K_c = received signal strength indicator scale factor, E = echo strength (in counts), and E_r = received noise (in counts). The first right hand term of the simplified sonar Eq. 2 is parameter C - a constant that incorporates many of the combined parameters (e.g., noise power, transducer efficiency), which are impossible to be measured independently. The parameters L_{DBM}, P_{DBW} and E_r can also be regarded as constants for specific ADCP instruments and constant power supply. Based on the above assumptions, Eq. 2 can be simplified further as follows:

$$10 \cdot \log_{10}(SSC) = C_k + 10 \cdot \log_{10}(R^2) + 2 \cdot \alpha_w \cdot R + K_c \cdot E \qquad (3)$$

where SSC is suspended sediment concentration (in kg·m^{-3}), and C_k is a combined constant. The attenuation coefficient due to water absorption (α_w) depends primarily on the frequency of the transmitted pulse and partially on the temperature, salinity, density and depth of the water column (Rehman 1990). For an acoustic frequency of 1200 kHz, similar to the ADCP we used, 0.48 dB·m^{-1} is a typical α_w value (Rehman 1990; Deines 1999). Although C_k and K_c cannot be measured directly, they can be estimated through calibration with acoustic data backscattered by sedimentary particles of known concentration. In the following, we present experimental data that were used to calibrate Eq. 3 and estimate the parameters C_k and K_c.

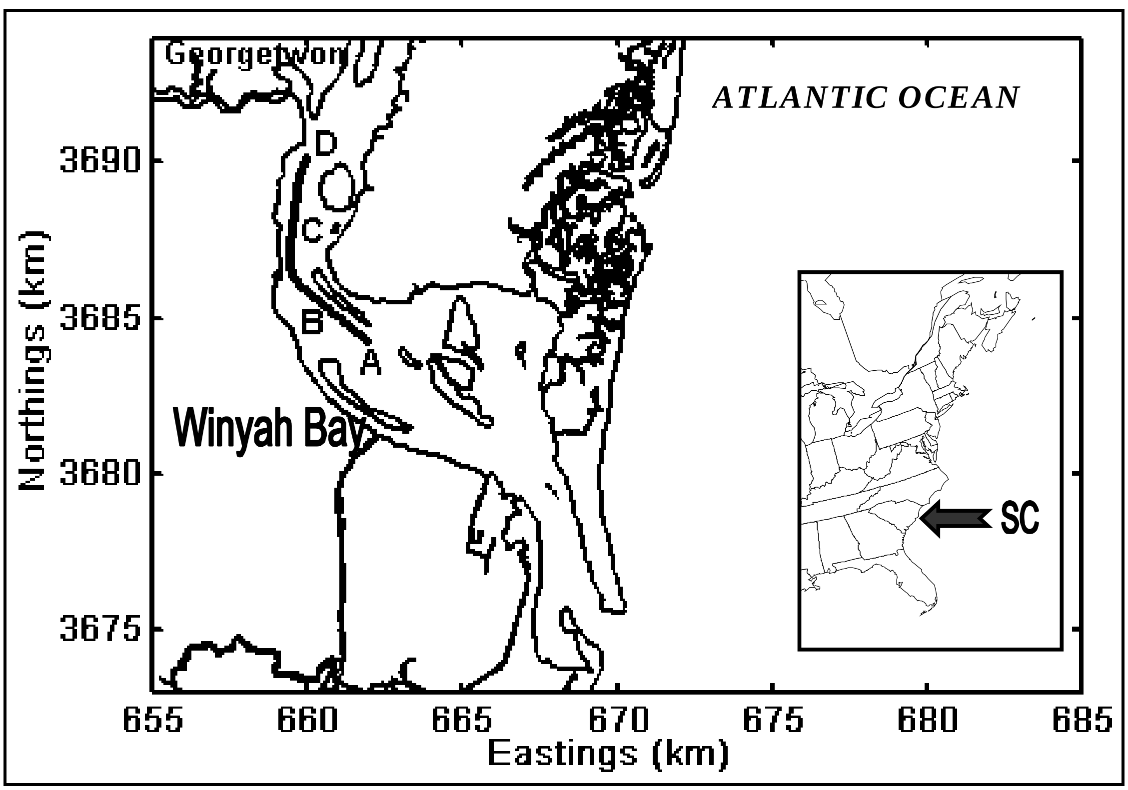

Figure 1. Map showing experimental site.

DATA COLLECTION

A field measurement program was conducted during the period October 3-6, 2001, in Winyah Bay, South Carolina, a partially-mixed estuary (Fig. 1) whereby a shipborne, 1200kHz RDI Workhorse ADCP was used to map the current structure along the main axes of the estuary.

Current and acoustic intensity data were recorded at a maximum of 42 elevations (bins). Although data logging occurred at 1s intervals, 1min time averaging took place during post-processing. The size of each bin size was 0.25m and the maximum total water depth never exceeded 12m.

In addition to the ADCP survey, hydrographic and sediment measurements were carried out at 4 stations (A to D, see Fig.1) along the survey line. An instrumented package consisting of a CTD (Ocean Sensors 200), an optical backscatterance sensor (OBS), and a Laser In-Situ Scattering Transmissometer (LISST) was slowly lowered through the water column at the station location and the data were transmitted and logged real time on board the ship. The sampling frequency of the instrumented package was approximately 1Hz, which resulted to a vertical resolution of approximately 2.3cm. The OBS data provided information that was later converted to total suspended sediment concentration. The LISST instrument uses a 670 nm Laser to measure *in-situ* grain size distribution without calibration. (Agrawal and Pottsmith 2001). Data from this device were used to obtain information on the dominant size of particles (i.e., scatterers) present in the water column. This dominant mode was expressed through the mean grain size of suspended sediments calculated from the LISST data using Folk's (1954) graphical method.

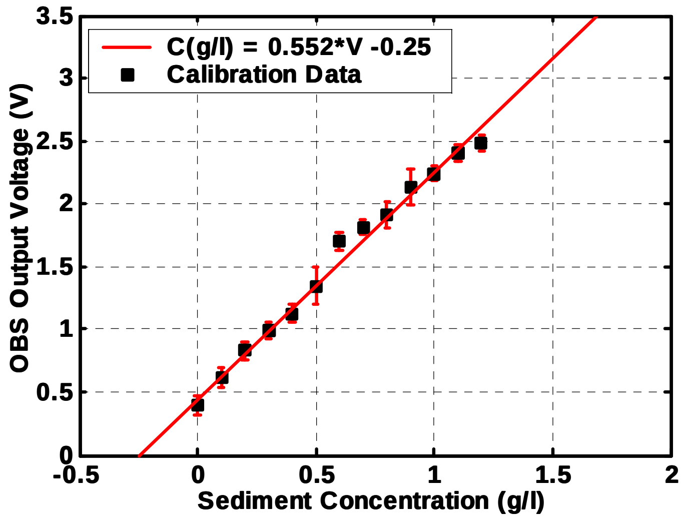

Figure 2. Laboratory OBS calibration curve with in-situ sediments.

In order to calibrate OBS in the laboratory immediately after the field experiment, pre-weighed 0.20g of dry sediment samples from the experimental site were added incrementally into 2.0l of mechanically stirred water. Figure 2 shows the calibration curve that was produced and subsequently used to convert the field-collected OBS data into SSC. The OBS-derived SSC data were used as standards for the analysis of the acoustic measurements.

Prior to analysis, the OBS-derived SSC data were spatially averaged in the vertical to match the size (0.25m) of the ADCP bins. Subsequently, the available cast data were equally divided into two groups of data. The one group was used to calibrate Eq. 3 and estimate the parameters K_c and C_k. The second group is used to verify the accuracy of the SSC estimates using the equation.

In order to avoid bias, the division into groups took place using a random number generator that generated 44 numbers from 1 to 88.

RESULTS

Calibration Procedure

During the calibration procedure, SSC and E values in Eq. 3 were substituted by the OBS-derived SSC from the first group of casts (calibration group) and concurrent acoustic intensity data collected when the ship was on station using the ADCP. Linear regression analysis was used to estimate the best values for the constants K_c and C_k (Fig. 3). It was found that the best–fit values for K_c and C_k were 0.43 and –104.65, respectively. The associated errors with 95% confidence interval are ± 0.0075 and ± 1.75, respectively.

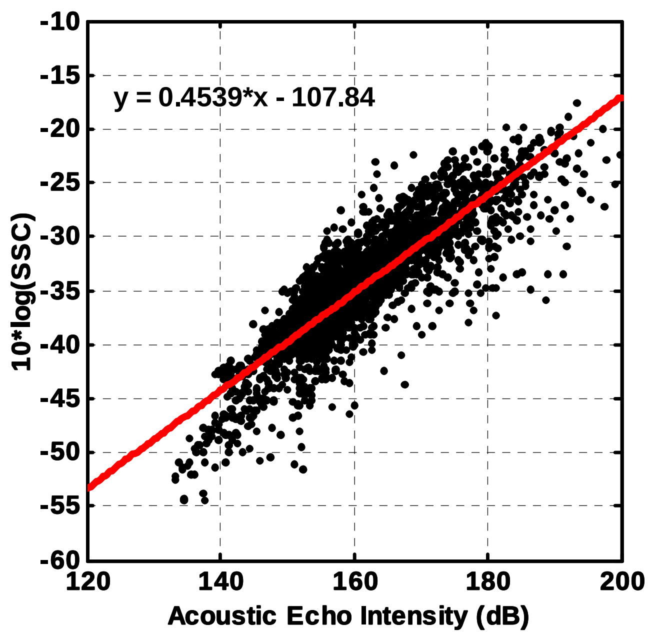

Figure 3. Linear Regression analysis of OBS-derived SSC and acoustic echo intensity from ADCP

The estimated value of RSSI scale factor (K_c) is within the range suggested by Deines (1999) for a similar instrument type. This agreement suggests that the value of K_c could be transferred to different instruments of the same manufacturer and same frequency. Substitution of the estimates of K_c and C_k into Eq. 3 leads to:

$$\log_{10}(SSC) = -10.465 + \log_{10}(R^2) + 2 \cdot 0.048 \cdot R + 0.043 \cdot E \qquad (4)$$

Verification Procedure

Using Eq. 4 and the remaining of the cast data (verification group) we estimated SSC using the ADCP recorded acoustic intensity. Figure 4 shows a comparison of vertical distributions of SSC derived using the OBS and the ADCP acoustic intensity data, respectively. Four typical examples are shown corresponding to a variety of ambient levels of suspended sediment concentration. In addition to the qualitative comparison shown in Figure 4, the OBS- and ADCP-derived SSC values are compared to each other in Figure 5 demonstrating a high correlation (R^2=0.90). However, comparing the 1:1 line with the best-fit linear regression line, the ADCP-based SSC estimates are 11% lower than the estimates based on the OBS measurements. This difference although not very high and certainly within the errors of a lot of experimental methods will be exploited further in the next section.

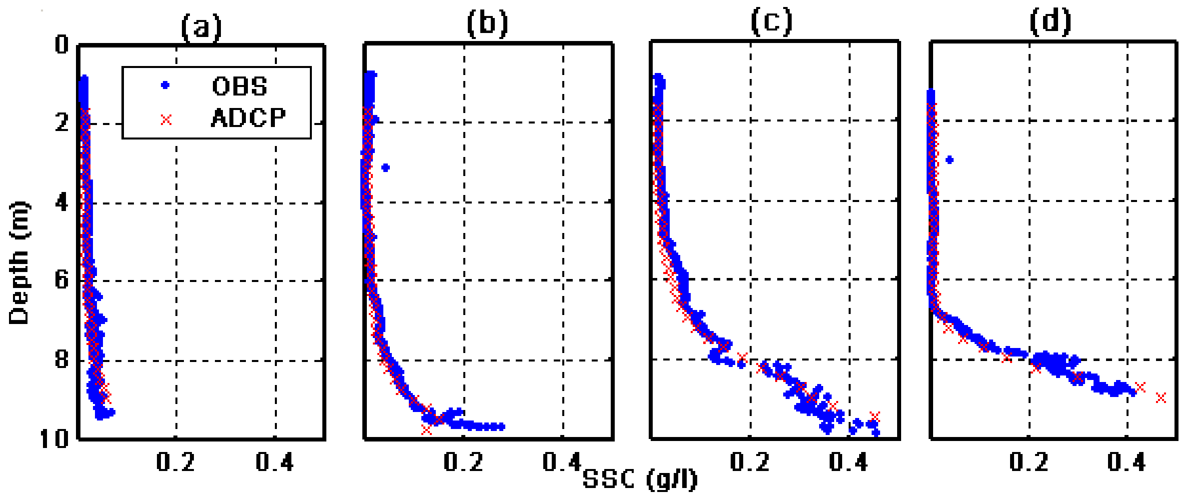

Figure 4. Examples of comparisons between SSC profiles measured by OBS (represented by blue dot) and ADCP (represented by red cross) from low (a) to high concentration (d)

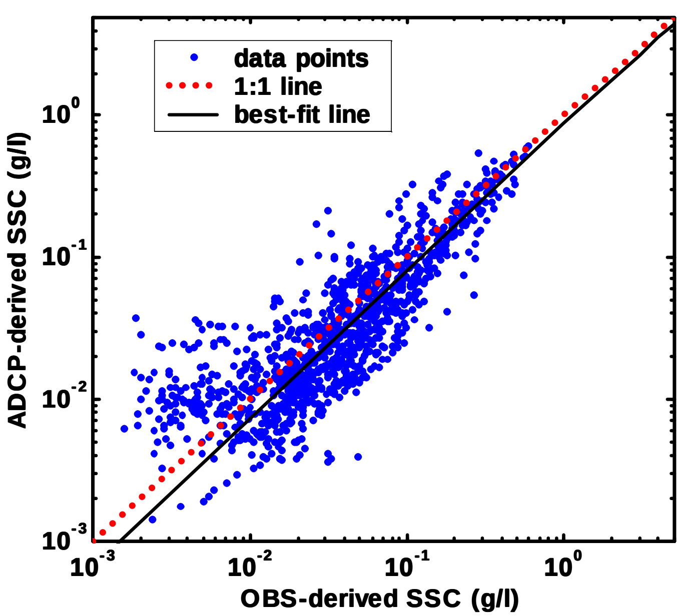

Figure 5. Correlation between OBS- and ADCP-derived SSC.

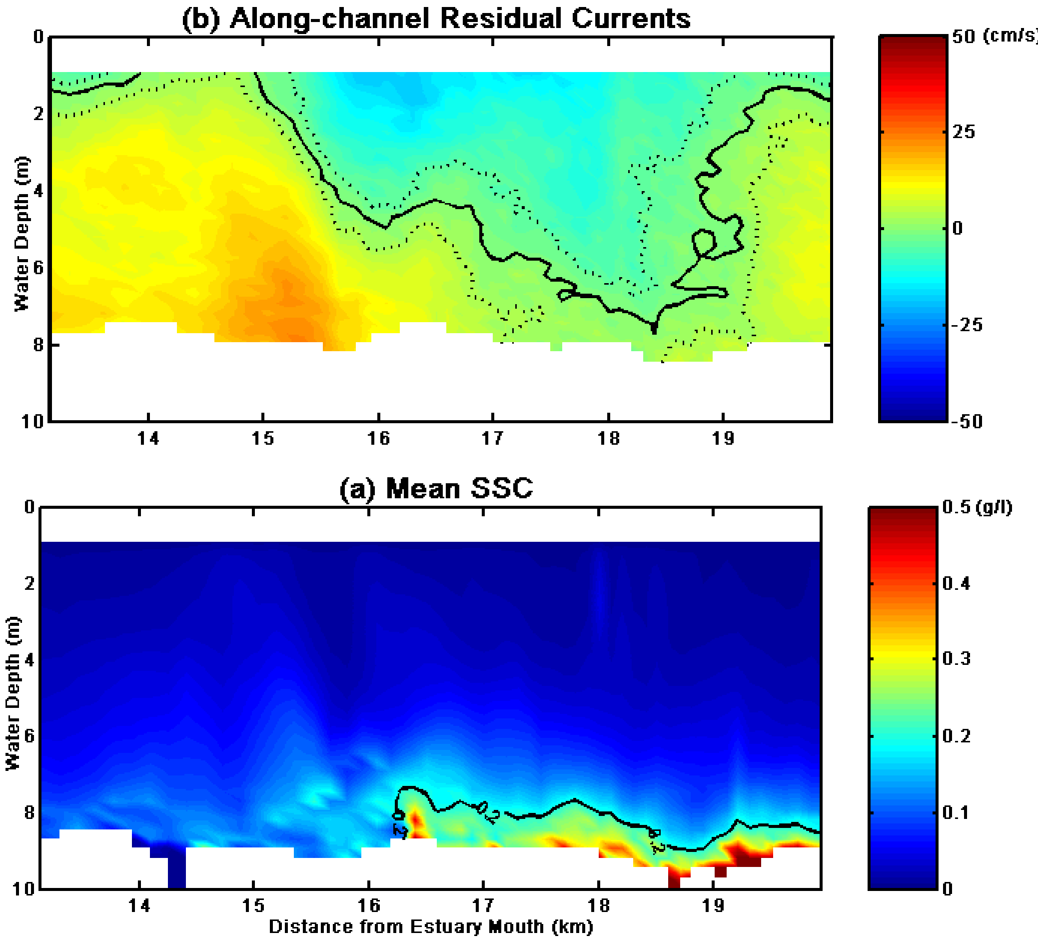

Figure 6. (a) Residual along-channel current in the main channel of the estuary. The solid and dotted contour lines represent 0 cm/s and 95% confidence interval, respectively. (b) Time-averaged SSC distribution of the longitudinal section of the Winyah Bay estuary estimated from ADCP return echo intensity using Eq. 4. The solid contour line represents 0.2 g/l.

Eq. 4 was applied to the ADCP records obtained during the whole cruise period and SSC values were calculated even for locations between cast stations where no OBS or LISST data were collected. This approach enabled us to map distribution patterns of SSC in the vertical and horizontal at very high resolution. The whole transect (A to D, see Fig. 1) was divided into 60 100m-long segments. The ADCP-derived SSC data collected within each segment were averaged horizontally and the distribution of sediment throughout the water column was revealed in a synoptic manner for various stages of the tide. Examination of the temporal variability of the SSC field in Winyah Bay is beyond the purpose of this paper. However, the time-averaged SSC for each segment was calculated for the whole survey line A-D and the results are shown in Figure 6. Elevated SSC values are found to persistently occur near the bed and in the area located 16-20km from the estuarine mouth (see Fig. 6b). Such analysis provides the means to accurately locate the area of the estuarine turbidity maximum for the tidal range and river discharge values of the period of the experiment.

The current data collected with the same ADCP instrument were used to calculate the residual circulation along the same part of the estuary. The residual currents were calculated from the same space-averaged data used to calculate the SSC after removing the tidal variation through a least square fitting of the semi-diurnal tidal constituent. The vertical structure of the along-channel residual flow is show in Figure 6a. Landward flow, represented by positive values, occurs near the bed of the outer half of the longitudinal section while seaward flow, represented by negative velocities, is developed in the surface layer of the inner estuary. This is the typical convergence of flow that results in the development of a frontal zone. This residual flow convergence area coincides with the area of elevated values of suspended sediment concentration. This corresponds to the expected location of the estuarine turbidity maximum for the Winyah Bay, which matches well with the zone of high SSC in Figure 6b.

DISCUSSION

The 2-way transmission loss parameter (2·TL) in Eq. 1 incorporates both the effects of attenuation by seawater and attenuation and spreading by sedimentary particles in suspension in the water column. Thorn et al. (1993) and Holdaway et al. (1999) attempted to calculate the amount of attenuation by suspended sediments, which is due to scattering and viscous absorption by the solids in suspension. Adopting their formulation and using our experimental data we found that the attenuation coefficient due to sediment (α_s) ranged from 10^{-3} to 10^{-4}. In our calculations, we assumed α_w =0.48 dB·m^{-1}. The α_s values are at least O(2) smaller than α_w, thus we can omit the effect of attenuation due to suspended solids. The same assumption was made in similar studies in San Francisco Bay (Gartner and Cheng, 2001).

Gartner and Cheng (2001) and Gartner (2002) mentioned the limitations of using ADCP echo data to estimate SSC. They compared the differences between acoustic and optical methods and concluded that acoustic sensors are more sensitive to large particles while optical sensors are more sensitive to small particles. In order to evaluate this, we divided the data from the casts on the basis of their mean grain size as it was estimated from the LISST data. Two groups of data were created: pairs of SSC-and ADCP-derived SSC data for periods where the mean grain size was greater than 62.5 μm and for periods when the size was finer than 62.5μm. This mean grain size was selected as the criterion for grouping the data because it defines the boundary between fine sand and silt.

A comparison between OBS- and ADCP-derived SSC for each group is shown in Figure 7. In the case of the fine sand samples the acoustic methods agree very well with the optical (OBS) method for estimating SSC (Fig. 7a). However, for the fine sediment (<62.5μm) the acoustic estimates are slightly lower than those from the optics. Based on Urick's work (1983) acoustic particle detection limit is determined by the ratio of the particle circumference (assuming a spherical shape) to acoustic pulse wavelength and is set to 0.1. This ratio value corresponds to a particle size of 40 μm for a 1200 kHz acoustic instruments (Gartner, 2002); therefore, sediments finer than 40 μm are underestimated during our experiment explaining the underestimation of SSC for fine sediments shown in Figure 7.

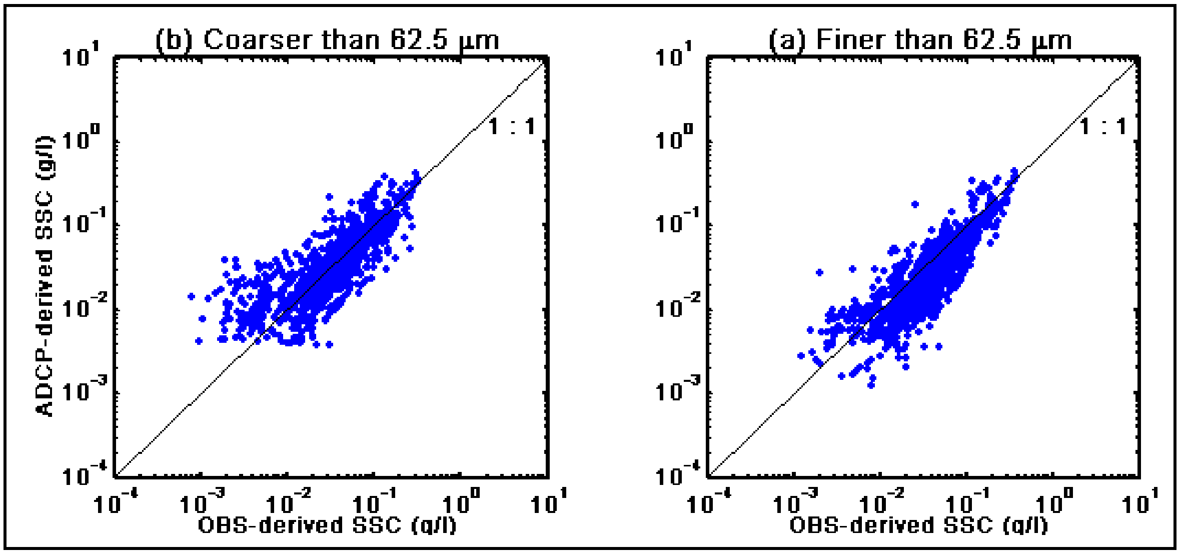

Figure 7. The different correlation pattern between OBS- and ADCP-derived SSC (a) for silt size sediments and (b) for fine sand size sediments. Black line represents the ratio of 1:1.

CONCLUSIONS

In the present work, suspended sediment concentration in an estuarine environment was estimated using acoustic backscatter from a 1200 kHz commercially available ADCP in an estuarine environment. The estimation methodology was based on the modified sonar equation. The two immeasurable constants in the Eq. 3 were calculated though a calibration process using optical measurements of SSC and a working sonar equation was developed for use in areas with no optical or direct measurements of SSC.

Verification of the working Eq. 4 took place by comparing ADCP-derived SSC with SSC values derived using OBS data that were excluded in the calibration process. The correlation coefficient was found to be 0.90.

The use of ADCPs in estimating SSC should be used with caution when the particle size of the sediment in suspension is below the detection limit as this is defined by the ratio of the particle circumference and the wavelength of the acoustic pulse.

We presented a methodology by which through calibration and verification processes a suitable equation can be developed for use with commercially available ADCP systems for continuous and simultaneous measurements of sediment in suspension and mean currents.

It should be noted that our data exhibited sediment concentrations that were monotonically increasing with depth, which is typical of estuarine environments. However, when higher concentrations of sediment are found near the surface then caution should be used.

ACKNOWLEDGEMENTS

This material is based on work supported by the Environmental Protection Agency/EPSCoR under grant No. R-82942401-O. Ship time was provided by NOAA on board the R/V Ferrel. The captain (Jim Meigs) and crew are thanked for their assistance. We appreciate Dr. M. Goni, Ms. M. Cathey, and the graduate and undergraduate students who helped with the data collection.

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