Experimental Study of the Multifrequency Acoustic Backscatter System using Field Sediment

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Abstract Measurements of suspended sediment concentration (SSC) and particle size (PS) are very significant in the study of sediment transport in estuarine and coastal areas. The multifrequency acoustic backscatter system (ABS) can be applied to measure the boundary layer SSC and PS profiles using backscatter strength data. The experiments in this study were conducted using an ABS equipped with sensors at multiple frequencies (0.5, 1, 2, and 4 MHz) in a test tank system in the laboratory. The fine sediment (average particle size $< 20 \mu\text{m}$) and coarse sediment (average particle size $> 100 \mu\text{m}$) used in the experiment were obtained from the Changjiang Estuary. The results were as follows: A linear relationship between the time-averaged strength of the backscatter measured by the ABS and the square root of SSC was detected; Different inverse models used to calculate SSC (IASC, IAMC, EASC) and PS (IAMP) from ABS data exhibited different patterns, and appropriate calibration or regression approaches should be used to obtain reliable results; The SSC and PS results for the field sediment indicate that the ABS is potentially applicable in coastal and estuarine areas, especially in the fine sediment environment. Further experiments are required to model sediment suspension in different environments, particularly with regard to the uncertainty of various PSs in the water column.

Keywords Acoustic Backscatter, ABS, Suspended Sediment Concentration, Particle Size, Field Sediment

1. Introduction

Boundary layer sediment transport is one of the most important processes in coastal and estuarine environments. It has received increasing attention in recent years, mainly due to the dynamic interactions between bed forms, hydrodynamics, and mobile sediments and their mutual feedback links. The movement of suspended sediment impacts water quality, biogeochemistry, and morphology [1-3], thus improving our ability to monitor and model the

suspended sediment profile near the sea bed is essential. Acoustic technologies, especially multifrequency acoustic techniques, have the potential to measure non-intrusively co-located profiles of suspended sediment concentration (SSC) and particle size (PS) with high temporal and spatial resolution [1,4,5,6,7]. The theory that underlies the acoustic method is based on the properties of sediment suspended in the water column and the effects of those properties on backscatter strength of sound.

The multifrequency acoustic backscatter system (ABS) was constructed, tested in boundary layer environments, and used to measure profiles of SSC and PS [2, 8]. Thorne and Hanes (2002) [5] demonstrated the ability of the ABS to measure SSC and PS profiles near a boundary layer (typically 1 m above the sea bed). Nevertheless, translating backscatter strength data to provide information about SSC and PS is affected by the frequencies of the ABS, variable field environments, and properties of the suspended sediment itself. To address these issues, a series of laboratory and field measurements of acoustic backscatter from suspended sediment were conducted [3, 6, 9, 10, 11, 12, 13, 14]. The aim of this study was to assess the performance of the ABS in a tank using both coarse sediment (CS) (average particle size $> 100 \mu\text{m}$) and FS (average particle size $< 20 \mu\text{m}$) obtained from the field in the Changjiang Estuary. The inverse models used to translate ABS backscatter strength data into values of SSC and PS have already been established in the literatures (Appendix A). Section 2 provides an overview of the acoustic method used, and section 3 describes the experimental setup, including ABS calibration using field sediments collected in the field, as well as the data processing approach. Different inverse models were compared, and the results and discussion are presented in sections 4 and 5, respectively. Conclusions are provided in section 6.

2. Acoustic Method

Researchers have studied in detail the backscatter, attenuation by suspended sediment, and acoustic inversion

method to extract SSC and PS data from acoustic backscatter strength data. For a homogenous suspension of spheres in the water column, the root-mean-square (rms) backscattered voltage recorded from a piston transducer, V_{rms} , can be written as follows [1,4, 5,15,16]:

$$V_{rms} = \frac{k_s k_t}{\psi r} M^{1/2} e^{-2r\alpha} \quad (1)$$

where:

$$k_s = \frac{\langle f_m \rangle}{\sqrt{\langle a_s \rangle} \rho_s} \quad (1a)$$

$$\psi = \frac{1 + 1.35z + (2.5z)^{3.2}}{1.35z + (2.5z)^{3.2}} \quad (1b)$$

$$\alpha_s = \frac{1}{r} \int_0^r \xi(r) M(r) dr \quad (1c)$$

$$\alpha_w = [2.1 \times 10^{-10} (T - 38)^2 + 1.3 \times 10^{-7}] \times f^2 \quad (1d)$$

$$\alpha = \alpha_s + \alpha_w \quad (1e)$$

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

$$s = \frac{9}{4\beta \langle a_s \rangle} \left[1 + \frac{1}{\beta \langle a_s \rangle} \right], \quad \sigma = \frac{\rho_s}{\rho_0}$$

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

where V_{rms} is the recorded voltage (rms); k_t is the system calibration constant (for a fixed system setting, it will be constant, or it will be a function of range if time varied gain is applied); k_s is the scattering constant, which depends on particle size, shape, and density; f_m is the form function, which describes the scattering properties of the sediment; M is the sediment concentration (g l^{-1}); r is the range from the transducer (m); α_s is the attenuation of the ABS due to scattering of suspended sediment in the water column (dB); α_w is the attenuation of the ABS due to water (dB); ψ is the range modification factor (-); a_s is the mean particle radius (m) (or the mean equivalent sphere radius of the suspended particles; the mean particle radius was used in this experiment); ξ is the sediment attenuation constant with units of Nepers $\text{m}^{-1} \text{kg}^{-1}$; $z = r / r_n$, where r is the range, $r_n = \pi a_t^2 / \lambda$, a_t is the effective radiating radius of the transducer, λ is the wave length ($\lambda = c / f$), and c is the

acoustic wave speed in the water (1500 m s^{-1} herein); ρ_s is the density of the particles (2650 kg m^{-3}); ρ_0 is the density of water; ν is the kinematic viscosity of water (the value used herein was $1.3 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$); $\omega = 2\pi f$, where f is the operating frequency of the ABS sensors (kHz); T is the temperature of water ($^{\circ}\text{C}$); and k is the wave number of sound in water ($k = 2\pi / \lambda$).

3. Experiment and Data Processing

The ABS was tested using FS (average particle size $< 20 \mu\text{m}$) and CS (average particle size $> 100 \mu\text{m}$). The experiments were conducted using the test tank system in the laboratory (Fig. 1). The system includes the test tank (600 mm diameter, 1500 mm height), the propeller and a pump at the bottom of the tank that recirculate the water, and a rubber tube to collect the water samples. The ABS (Aquatec Group Ltd, Hampshire, UK) equipped with sensors at acoustic frequencies of 0.5, 1, 2, and 4 MHz was mounted at the top of the tank facing directly down to the bottom of the tank. The FS and CS were obtained from sites in the Changjiang Estuary. The SSC in the test tank was relatively constant during each phase of the sampling. As the ABS was taking measurements, water samples were collected and analyzed separately for SSC and PS so that the ABS results could be compared with those determined using the traditional method (TM) [17] and the laser method (LM; i.e., using a laser diffraction particle size analyzer (Beckman Coulter, Miami, USA)).

Figure 1. The test tank used for the experiments

The experimental procedure was as follows: (1) Obtain the background value of the ABS in clear water without sediment; (2) Add the field sediment to the tank while the propeller and pump are working in order to mix the water and sediment into a homogenous state; (3) Collect water samples from different depths in the tank; (4) Analyze the

water samples for SSC and PS. The SSC values of the water samples were obtained using the TM, and the PS values were determined using the LM. The measured results were then compared with the SSC and PS results from the ABS backscatter strength data calculated using explicit (EASC) and implicit (IAMC, IASC, and IAMP) models (Appendix A).

4. Results

Figure 2 shows the SSC results from the water samples determined using the TM. The SSC values of FS varied from 0.18 to 0.34 g l^{-1} (Fig. 2a), and the SSC values of CS varied from 0.18 to 0.68 g l^{-1} (Fig. 2b). Peak value of SSC was found in the FS samples (Fig. 2a). Figure 3 shows the mean PS values of FS and CS in the water samples determined using the LM. The PS of FS varied from 9.7 to 30.6 μm , and the average value was 14 μm (Fig. 3a). The value for CS varied from 99.4 to 131.9 μm , with an average value of 118 μm (Fig. 3b).

Figure 2. Suspended sediment concentration (SSC) of (a) fine and (b) coarse sediment in the water samples

Figure 3. Mean particles size (PS) of (a) fine and (b) coarse sediment in the water samples

Different inverse models (EASC, IAMC, and IASC for SSC, IAMP for PS; Appendix A) were used to estimate SSC and PS from the ABS backscatter strength data. Figure 4 shows the calculated values of SSC for FS and CS using the different models. Generally, the fluctuation of SSC for FS (Fig. 4a,b,c) was smaller than that for CS (Fig. 4d,e,f). For FS, model EASC (Fig. 4a) provided better results than models IASC and IAMC (Figure 4b,c). EASC was the better model for CS as well (Fig. 4 d,e,f). For the different frequency sensors (0.5, 1, 2, and 4 MHz) of the ABS, the EASC model generally yielded the best results for both FS and CS (Fig. 4a,d). Different patterns for the four frequencies appeared when the other models were used. For example, compared to CS, the results for FS were better at 1 and 2 MHz for the IAMC and at 2 MHz for the IASC. The values of SSC close to the ABS sensor and at the bottom of the tank fluctuated much more than those in the middle of the tank. The differences between mid tank and bottom were more significant for CS than for FS (Fig. 4d,e,f).

Figure 4. Suspended sediment concentration (SSC) of (a-c) fine sediment (FS) and (d-f) coarse sediment (CS) obtained by the ABS and Traditional Method(TM)

The ABS system has four acoustic sensors (0.5, 1, 2, 4 MHz), and the values of PS can be obtained using the ratio of one frequency's form function (f) to that of another (4/2, 4/1, 4/0.5, 2/1, 2/0.5, 1/0.5 MHz). Figure 5 shows the PS results from the ABS calculated using the IAMP model. For FS, the low frequency ratio (1/0.5 MHz) exhibited greater fluctuation of PS values than the ratios of higher frequencies (Fig. 5a). For CS, the IAMP model using ratios of 4/0.5 MHz, 2/1 MHz, and 2/0.5 MHz agreed well with the LM measurements (Fig. 5b). Overall, the PS results for FS were better than those for CS, possibly because the variation of PS was smaller for FS (20.9 μm) compared to CS (32.5 μm).

Figure 5. Particle size (PS) of (a) fine sediment (FS) and (b) coarse sediment (CS) measured by the ABS and the laser method (LM)

Tables 1 and 2 show the relationship (R^2) between SSC/PS obtained from the water sample measurements and the ABS results for FS and CS, respectively. The values of SSC calculated using the EASC, IASC, and IAMC models are from the 2 MHz sensor, and that of PS calculated using the IAMP model is from the ratio of the form functions of two frequencies (2/1 MHz). For SSC, the R^2 value for the EASC model (explicit approach) was usually lower than those of the IASC and IAMC models (implicit approaches), and the value for EASC for CS was higher than that for FS. For PS, the R^2 value for CS was higher than that for FS.

Table 1. The linear relative coefficient (R^2) between suspended sediment concentration/particle size (SSC/PS) obtained from the water sample measurements and ABS results for fine sediment (FS)

FS	Number of water samples					
	24	20	18	16	14	10
EASC	0.02	0.10	0.13	0.17	0.26	0.52
IASC	0.16	0.42	0.59	0.74	0.94	0.99
IAMC	0.04	0.22	0.48	0.62	0.86	0.92
IAMP	0.07	0.20	0.27	0.35	0.50	0.65

The values of SSC (EASC, IASC, IAMC) are from the sensor at 2 MHz, and the value of PS

(IAMP) is from the ratio of the form functions of two frequencies (2MHz/1MHz).

Table 2. The linear relative coefficient (R^2) between suspended sediment concentration/particle size (SSC/PS) obtained from the water sample measurements and ABS results for coarse sediment (CS)

CS	Number of water samples					
	14	13	12	11	10	9
EASC	0.39	0.49	0.57	0.64	0.71	0.75
IASC	0.06	0.47	0.83	0.84	0.88	0.90
IAMC	0.29	0.54	0.66	0.75	0.82	0.89
IAMP	0.36	0.46	0.52	0.58	0.69	0.79

The values of SSC (EASC, IASC, IAMC) are from the sensor at 2 MHz, and the value of PS

(IAMP) is from the ratio of the form functions of two frequencies (2MHz/1MHz).

5. Discussion

In this experiment, different models were used to calculate SSC and PS results from the ABS backscatter strength data. The explicit approach (EASC model) applied to both FS and CS (Fig. 4a,d) yielded better SSC results than those of implicit approach models IAMC and IASC (Fig. 4b,c,e,f). The advantage of the EASC method is that there is no need to know the system calibration parameter k_t . Once the value of M is obtained, k_t can be circumvented. If the PS in the water column varies, however, some a priori reference information is required, such as β_r , M_r , k_s , and ξ . The explicit approach is only applicable to a single frequency and it uses the assumption that a_s is constant in the water column above the seabed [5]. Actually, experiments in the lab and field have shown that a_s varies within a certain range.

The implicit IASC and IAMC models provided information about SSC and the IAMP model provided data for PS in the water column. The fluctuations of SSC were smaller for FS than for CS when the IAMC and IASC models were used. This means that when used in a fine sediment environment, the ABS yielded reasonable results (Fig. 4b,c,e,f). Nevertheless, Tables 1 and 2 show that careful choice of frequencies and data analysis and processing methods are crucial to obtaining the best results. Unlike the explicit approach, the implicit approaches require the system calibration parameter (k_t) and accurate a_s and M values, and a strict choice of frequencies and data analysis methods must be used [5].

The results presented in Tables 1 and 2 show a linear relationship between the time-averaged ABS backscatter strength and the square root of SSC. Similar results were reported by other researchers [11,18,19,20,21]. The implicit approaches yielded higher R^2 values (> 0.89 for 10 CS samples and > 0.92 for 10 FS samples) than the explicit approach (0.79 for 10 CS samples and 0.65 for 10 FS samples). Nevertheless, the fluctuation of SSC in the ABS results obtained using the explicit approach (Fig. 4a,d) was smaller than that of the implicit approaches (Fig. 4b,c,d,e) to This result means that the implicit approaches might be more sensitive to changes of SSC [2, 22] than the explicit approach, but this premise requires further research. A new statistical method [12] recently was introduced for converting ABS backscatter strength data to SSC and PS values, and it yielded better results for CS (255 - 400 μm). This data processing method was not used in the present study.

The peak values (0.34 g l^{-1} SSC, 30.6 μm PS) occurred for the FS in the water samples (Fig. 2a, 3a). Similar peak values of SSC and PS obtained from ABS data can be seen in Fig. 4 a, b, c and Fig. 5a. This shows that the variety of PSs in the water column may have significant effects on the SSC and PS results obtained by direct measurement using the ABS or other acoustic instruments. This fact must be considered when calibrating the system and processing the data. For PS, given that errors may arise when the higher frequencies are

used, the ratio of the form functions of 2/1 MHz yielded the best result in this experiment (Fig. 5a,b). Thus, the particle radii derived from the 1 to 2 MHz backscatter information profiles may be suitable for the Changjiang Estuary and other environments [19, 23]. However, the results should be further researched using different types of sediment in different environments.

6. Conclusions

The development of acoustic technology to non-intrusively measure SSC and PS in the boundary layer with both high temporal and spatial resolution is of interest to many researchers. In the present study, SSC and PS were measured using an ABS equipped with sensors at four frequencies (0.5, 1, 2, 4 MHz). The measurements were conducted in the test tank in the laboratory. A linear relationship between the time-averaged ABS backscatter strength data and the square root of SSC was detected. The values of SSC obtained using model EASC were better than those obtained using models IAMC and IASC. The implicit approaches were much more sensitive to changes of SSC, thus these models require a strict choice of frequencies and data analysis methods. The results of the present study show that acoustic systems (such as ABS) using 1 to 2 MHz backscatter information profiles should be obtain reasonable results in the Changjiang Estuary. Thus, acoustic technology potentially could be used to monitor the SSC and PS profiles in estuarine and coastal environments, including FS environments. Furthermore, use of parallel measurements from instruments such as Optical Backscatter Sensors and Laser In-Situ Scattering and Transmissometry devices, in the field would increase the accuracy and reliability of ABS calibration and subsequent SSC and PS results.

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Appendix

1. Explicit Approach

Explicit Approach Sediment Concentration (EASC): if M and k_s are known at the reference range r_r , the following expression can be deduced:

$$M = \frac{\beta^2}{\frac{\beta_r^2}{M_r} - 4 \int_{r_r}^r \beta^2 \xi dr} \quad (3)$$

where $\beta = V_{rms} r \psi k_s^{-1} e^{2\alpha r}$ and $\beta_r = \beta$ at $r = r_r$

2. Implicit Approach

(1) Implicit Approach Single Frequency Concentration (IASC)

Rearranging Eq. (1)

Assuming the system has been calibrated:

$$M = \left\{ \frac{V_{rms} \psi r}{K_s K_t} \right\}^2 e^{4r\alpha_w} \quad (4)$$

(2) Implicit Approach Multiple Frequency Concentration (IAMC)

If using multiple frequencies, M_i can be obtained from:

$$M_i = \left\{ \frac{V_{rmsi}}{K_{si} K_{ti}} \right\}^2 \psi_i^2 r^2 e^{4r\alpha_i} \quad (5)$$

where i refers to the different frequencies.

(3) Implicit Approach Multiple Frequency Particle Size (IAMP)

Particle size can be obtained using the ratio of one frequency's form function (f) to that of another frequency. If multiple frequencies are available, α_s need not be assumed and can be obtained.

$$\frac{f_i}{f_j} = \frac{\left(\frac{\psi_i V_{averagei}}{k_{ti}} \right)}{\left(\frac{\psi_j V_{averagej}}{k_{tj}} \right)} e^{2r(\alpha_i - \alpha_j)} \quad (6)$$

where $i \neq j$ and i and j refer to the different frequencies (0.5, 1, 2, and 4 MHz in this study) [5,24].

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