Measurements of the scattering properties of suspensions of marine sand

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Abstract

The scattering properties of canonically shaped bodies are reasonably well understood for a number of profiles. However, as the scatterers become less regular in form, predictions are more problematic. Nevertheless many natural scatterers are irregular in shape and a description of such bodies is required. Therefore as part of an ongoing study into the application of acoustics to sediment entrainment processes, the backscattering properties of suspensions of irregularly shaped marine sands have been measured and the results are reported here.

1. Introduction

The application of acoustics to the measurement triad of bedform morphology [1], suspended sediments [2], and the hydrodynamics [3], is significantly advancing our capability to probe the fundamentals of boundary layer sediment transport processes. The basis of the acoustic approach is the propagation of a narrow beam, typically a few degrees beamwidth, high frequency, 0.5-5 MHz, short pulse, ~0.01 m from a vertically downward looking monostatic transducer. As the pulse propagates down to the bed, sediment in suspension backscatter a proportion of the sound which is used to extract information on the suspension and hydrodynamic fields, and the bed echo is used to measure the time history of the bedform morphology. In the present study the focus is on the measurement and description of the backscattering characteristics of the sediment particles in suspensions. This description is at the kernel of the inversion to extract the suspended sediment component of the triad.

To date the data published on the backscattering characteristics of suspensions of irregularly shaped sand particles have been limited to the works of Hay [4, 5]. This fundamental work forms the basis of our current description of the backscattering properties of suspensions of marine sands. A further work has supported the present description [6]. However, a comprehensive study of the attenuation characteristics of sand suspensions showed significantly higher attenuation values than predicted by the commonly employed sphere based scattering models [7]. This result led the present authors to revisit the backscattering characteristics of suspensions of sand, and a series of measurements were collected on different sand samples to examine their backscattering properties.

2. Suspension backscattering

The backscattered root-mean-square voltage, V, from a suspension of sediments insonified with a piston source transducer can be expressed as [8-11]

$$V = \frac{K_s K_t M^{1/2}}{r\psi} e^{-2r\alpha} \tag{1}$$

where

$$K_s = \frac{f}{(\rho a_s)^{1/2}}, \quad K_t = RT_V P_o r_o \left\{\frac{3\tau c}{16}\right\}^{1/2} \frac{0.96}{k a_t} \quad \alpha = \alpha_\omega + \frac{1}{r}\int_o^r \zeta M dr \tag{2}$$

The term K_s represent the sediment backscattering properties, ρ is the sand grain density, a_s is the particle radius, and f is known as the form function and describes the backscattering characteristics of the scatterer. For fixed settings K_t is a system constant comprising of: R the transducer receiver sensitivity, T_V the voltage transfer function, P_o is the reference pressure normally defined at r_o=1 m, τc is the pulse length, where τ is the pulse duration and c is the velocity of sound in water, k is the wavenumber of the sound in water and a_t is the radius of the transducer. The term α_ω is the sound attenuation due to water absorption, ζ is the sediment attenuation constant, M is the concentration of sediment in suspension, r is the range from the transducer, and ψ accounts for the departure from spherical spreading within the transducer nearfield.

In the present study the backscatter form function was required and therefore this can be expressed as

$$f = \frac{Vr\psi}{K_t}\left\{\frac{\rho a_s}{M}\right\}^{1/2} e^{2r\alpha} \qquad (3)$$

All the parameters on the RHS of equation (3) were measured or could be calculated and the form function obtained. To evaluate equation (3) the commonly employed high pass sphere model [8] was used to calculate the sediment attenuation. However, Ref 7 shows that this description may underestimate the attenuation. Therefore in the present study concentrations were kept reasonably low (0.3-0.6 kgm^{-3}) to reduce the impact any error in ζ may have had on the form function measurements.

3. Experimental arrangement, calibration, and sediments

3.1 Description of the sediment tower

The experimental set-up is shown in Figure 1. The sediment tower consisted of a re-circulating water flow with extraction at the bottom of the tower, and re-injection at the top through a mixing chamber designed to homogenise the suspended sediments in the tower. To further assist suspension homogeneity a triple unit near the base of the tower consisting of a turbulence grid, impeller and a propeller were rotated to generate a turbulent flow directed upwards. This combination generated a homogeneous suspension over the central section of the tower as indicated in the figure. To assess the homogeneity of the suspension in the tower a number of experiments were conducted using pumped sampling. Figure 2 shows samples of the suspension taken from the tower between 0.4-0.8 m below the transducers, and located on the central vertical axis of the tower (o), at 0.07 m from the axis (x), and at 0.14 m from the axis (+). The results for three different sediments are shown in figure 2. The data clearly show that suspensions could be generated within the tower which were uniform both vertically and horizontally.

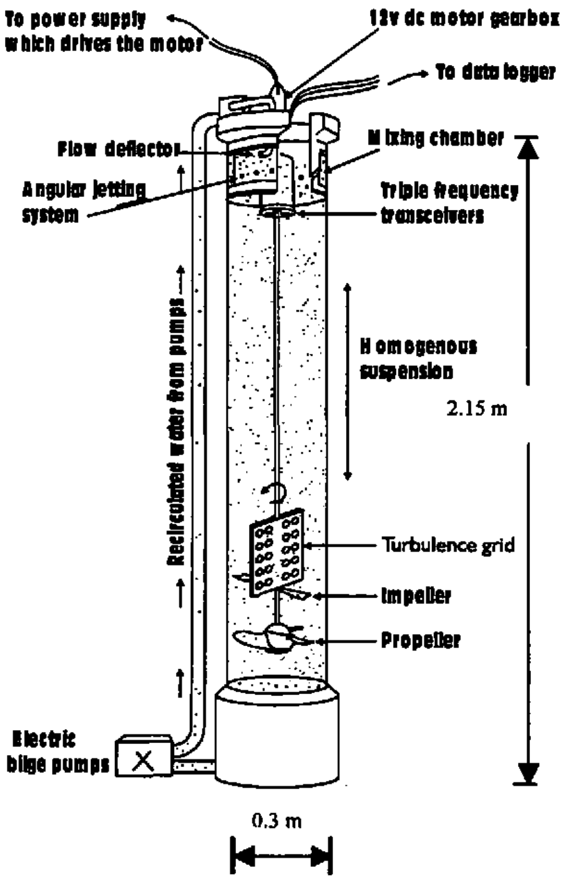

Figure 1. The sediment tower used for the measurements

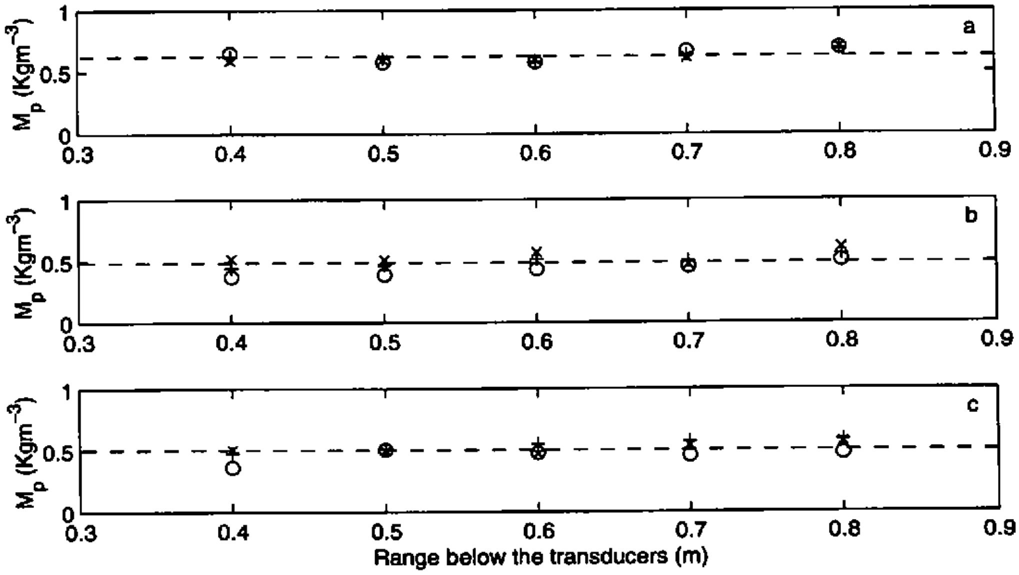

Figure 2. Pumped sample measurements of the suspended sediment concentration in the tower with range below the transducers. Data were collected on the central axis of the tower (o), at 0.07 m from the axis (x) and at 0.14 m from the axis (+). a), b), and c) are three sediment types.

To obtain the form function measurements a triple frequency acoustic backscatter system operating at 1.0 MHz, 2.0 MHz and 4 MHz was mounted in the upper section of the tower. The system measured the envelope of the backscattered signal at 0.01 m intervals over a range of 1.28 m. For data collection a low pulse repetition frequency of 4 Hz was used to allow the sound from one transmission to dissipate before the following transmission. For each experimental run 320 backscatter profiles were collected at each frequency. These profiles were averaged and the form function calculated. Four runs were conducted for each experiment to provide a mean form function with error bars. This averaging is required to offset the effects of configurational noise [12] and fluctuations in the homogeneity of the suspension.

When collecting the form function measurements a consistent experimental procedure was followed. After the tower had been filled with water, a period of several hours to days was allowed to elapse with the recirculating and mixing systems running to provide time for the micro-bubbles present in the water to dissipate. Acoustic backscatter data were collected over this period, and when the background signal became insignificant in comparison with the levels recorded when sediment was in suspension, water saturated degassed sediments were added to the tower. Typically a period of a few hours were allowed for the suspension to become homogeneous. The acoustic data were then recorded, followed by pumped sampling to establish the concentration and homogeneity of the suspension. At the end of the experiment the sediments were extracted from the tower by placing a fine gauss net within the body of the tower. This extraction continued until acoustic background measurements showed there was no significant residue of sediment in the tower. A different sediment sample was then introduced into the tower and new acoustic and pumped sample data collected.

3.2 Calibration of the backscatter system

To evaluate equation (3) requires the system constant K_t to be known. This can be obtained by evaluating the terms in equation (2) or by rearranging equation (1) and taking measurements on a suspension of known scatterers. In the present work the latter is done. Therefore rearranging equation (1) gives

$$K_t = \frac{Vr\psi}{K_s M^{1/2}} e^{2r\alpha} \tag{4}$$

To obtain K_t measurements were taken in the sediment tower on suspensions with known scattering characteristics. The suspensions used were composed of glass spheres. These can readily be obtained in the required size range, and the scattering from such spheres is well documented [12]. Therefore using suspensions of glass spheres, measurements were collected on samples having a mean radius of 98 μm, 115 μm, 137 μm and 195 μm. Figure 3 shows profiles of K_t for the three different frequencies averaged over the four particle size measurements with error bars. It can be seen that K_t was constant with range, and the small error bars show that for the different suspensions measured, consistent values of K_t were obtained.

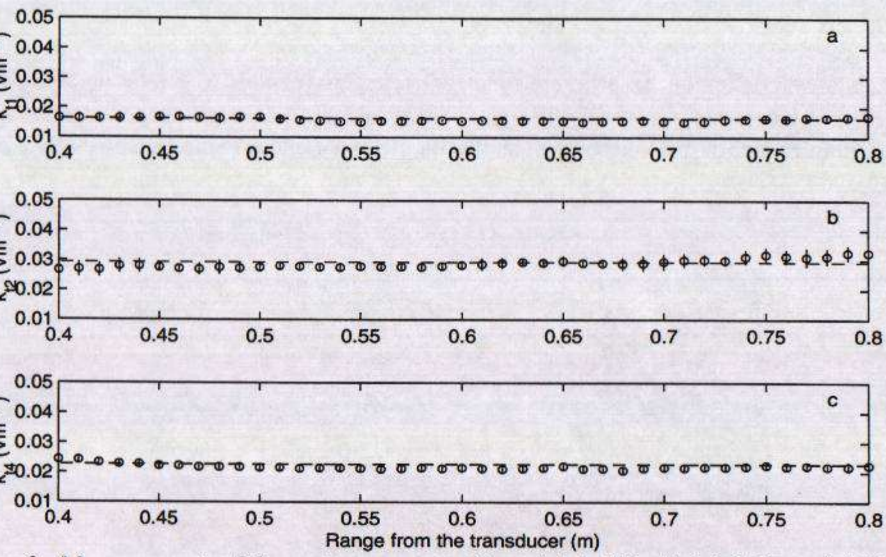

Figure 3. Measurements of the system constant, K_t at a) 1.0 MHz, b) 2.0 MHz and 4.0 MHz

Using the values of K_t shown in Figure 3 a series of measurements were taken on suspensions of glass spheres interleaved with the measurements on suspensions of sand sediments. These glass sphere measurements were used to assess the stability of the acoustic backscatter system over the programme of measurements. The results are shown in Figure 4 and are presented in terms of the backscatter form function. The dashed line represents the form function for a suspension having a single particle size, the solid line was calculated on the basis of a size distribution in suspension arising from the ¼ ϕ sieves used (ϕ=-$\log_2 d$ were d is the particle diameter in millimetres) to sieve the sediments. Figure 4 shows excellent agreement between the predicted form function and the measured values, and illustrates the accuracy of the form function measurements collected in the sediment tower.

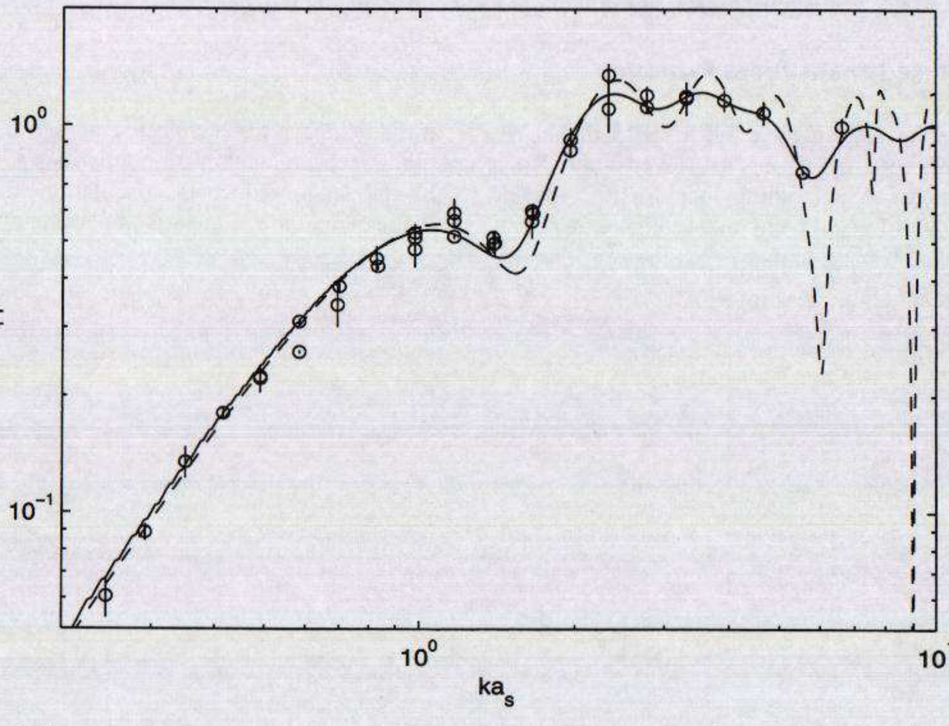

Figure 4. Predicted and measured (o) form function for a suspension of glass spheres. The dashed line represent the case of a single particle size in suspension and the solid line accounts for the size distribution due to the ¼ϕ sieves used.

3.3 Suspended sediments

A series of measurements were taken on six different sands collected from an estuary, a beach and different quarries. The sediments were sieved into ¼ϕ samples covering the range a_s=58 – 390 μm. An example of the form of the particles is shown in the micrograph in Figure 5. The micrograph shows the irregular and complex shape of sand grains extracted from a marine site.

Figure 5. Micrograph of the sand collected from an estuarine site

4. Suspended sediment form function

As mentioned in the previous section a series of backscatter measurements were collected at 1.0, 2.0, and 4 MHz on different sediments covering a range of sieved sizes. To compare the measurements with predictions a mobile rigid sphere model was adopted. A smoothing function was applied to this model to reduce the oscillation in the form function associated with the diffracted component. Figure 6a shows a typical example of a comparison between the predicted form

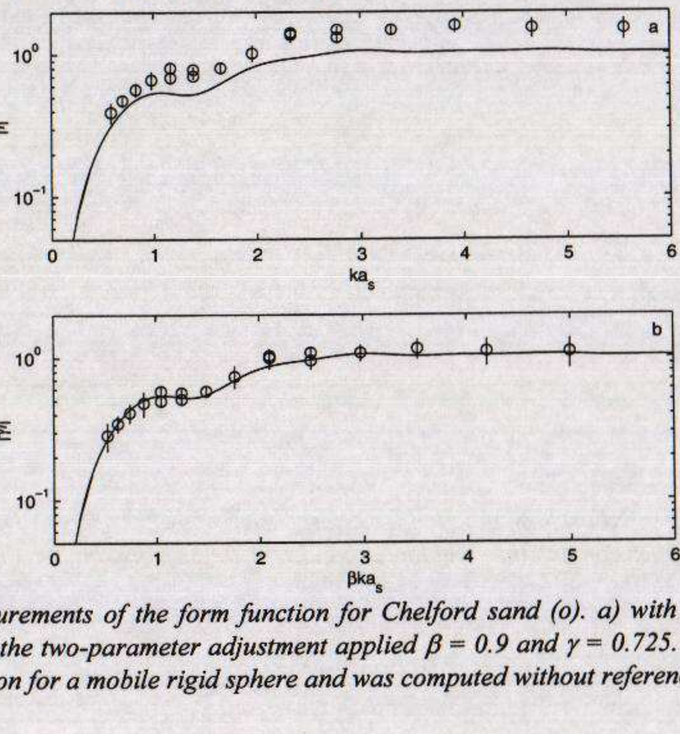

Figure 6. Measurements of the form function for Chelford sand (o). a) with no adjustment applied, b) with the two-parameter adjustment applied β = 0.9 and γ = 0.725. The solid line is the form function for a mobile rigid sphere and was computed without reference to β and γ.

function with the measured data. Essentially it can be seen that the measured values are greater than the smoothed rigid mobile sphere predictions. This is consistent with observations from previous form function [4-6] and sediment attenuation [7] measurements. To address this difference the concept of an effective particle radius, as described in references [6, 7], is utilised. This is based on the effective sphere equivalent radius for the volume and surface area of irregularly shaped sand grains not necessarily being the same, and not identical to that measured using a sieve. Two scaling parameters are therefore introduced to account for the departure from sphericity of the sand grains. The first, β scales ka_s and is associated with the volume of the particles. The second γ, scales the form function and is associated with the backscattering cross-section. The theoretical curve remains unchanged, since particle size is not explicitly used in the form function calculation. The result of using the two-parameter approach is shown in Figure 6b, where $\beta = 0.9$ and $\gamma = 0.73$. These results clearly show the rescaling of the effective sphere equivalent radii yields consistent results with the predicted form function.

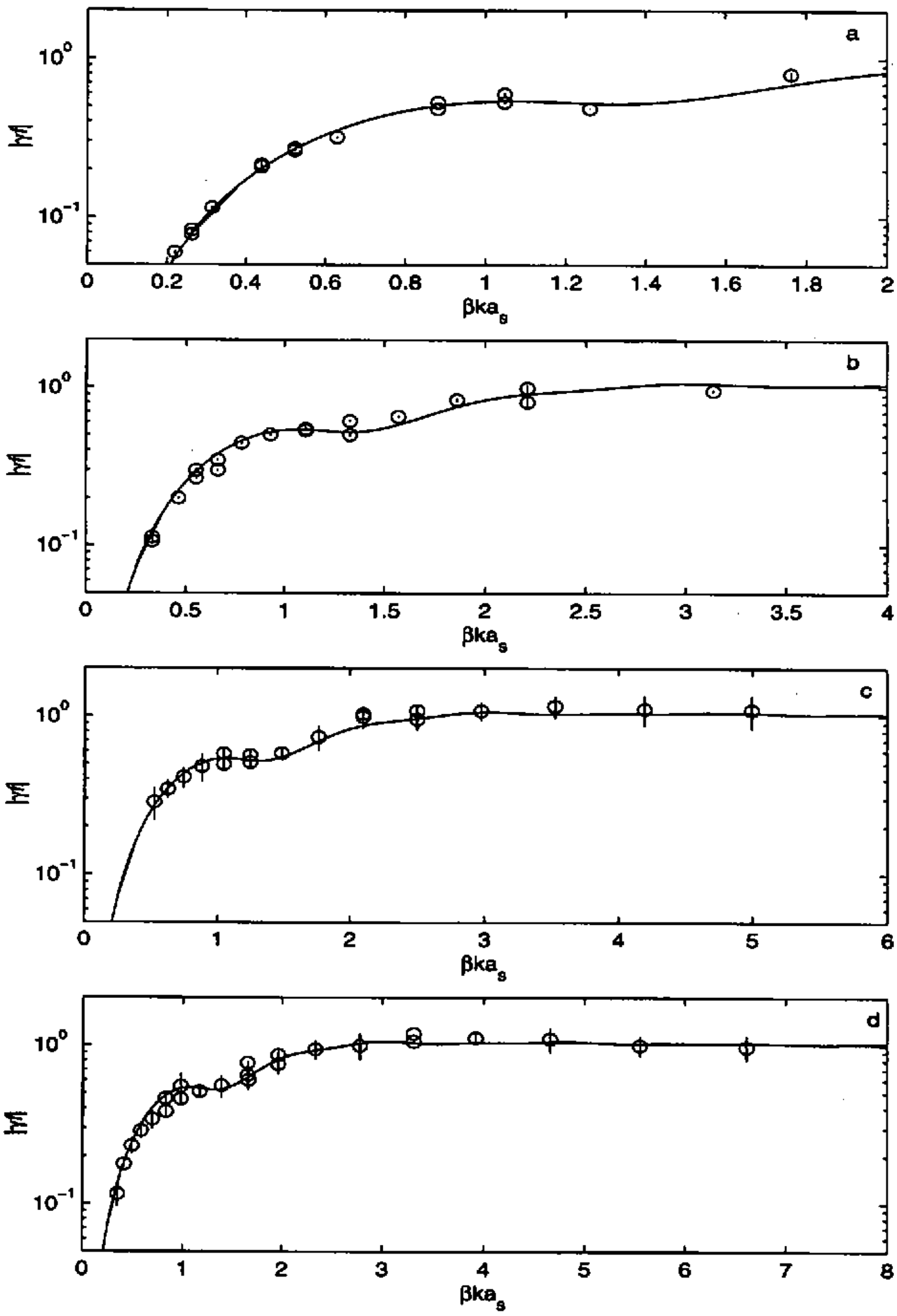

Figure 7. Measurements of the form function of sand from four different sources. a) Redhillt sand $\beta = 0.9$, $\gamma = 0.8$; b) Oakmoore sand $\beta = 0.9$, $\gamma = 0.75$; c) Chelford sand $\beta = 0.9$, $\gamma = 0.725$, and d) Redhill30 sand $\beta = 1$ and $\gamma = 0.7$. The solid line is the form function for a mobile rigid sphere and was computed without reference to β and γ.

To show that the results in Figure 6b are generic, measurements are presented for four different sediments in Figure 7. For each case the measured form functions have been scaled using the two parameter approach of selecting β and γ for optimum agreement between the observations and the mobile rigid sphere model. For the results shown in Figure 7, β varied between 0.9 – 0.95 and γ between 0.7 - 0.8. Mean values were $\overline{\beta} = 0.91 \pm 0.03$ and $\overline{\gamma} = 0.74 \pm 0.04$. Essentially the results show that the relatively simple smoothed mobile rigid sphere model provides an accurate description of the backscattering characteristics of irregularly shaped sediment particles when the appropriate two parameter adjustment is made to the measured form functions.

5. Discussion and Conclusion

Measurements of the backscatter form function have been made on homogeneous suspensions of marine sands. To describe the observations, a model using a mobile rigid sphere with the diffraction oscillations damped was used. Comparison of the data with this model showed the measured form functions to be greater than the observations. This essentially arises because of difficulty in establishing the equivalent sphere radius for the surface area and volume of the irregularly shaped sand grains. The physical measurement obtained is a particle size derived from sieving the sediment samples. However, it is not clear how this measurement relates to the equivalent sphere size or an appropriate acoustic dimension. Therefore in the present work a two-parameter approach was adopted which re-scales the effective particle radius relative to the sieve measurements to allow a direct comparison with the mobile rigid sphere model. Using this approach showed that consistent agreement could be obtained between the observation and the mobile rigid sphere model. The implication of these observations for the application of acoustics to the measurement of near bed sediment processes, is that particle shape does affect the backscattered signal level. However, the limited variability of β and γ observed in this study suggests that mean values of $\beta \approx 0.9$ and $\gamma \approx 0.74$ should be reasonable estimates for these parameters when dealing with unknown suspensions of marine sands.

Acknowledgements

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