VOLUME SCATTERING BY MARINE SUSPENSIONS

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1. INTRODUCTION

Increasing concern over the past decade regarding the possibility of mean sea level rising due to global climatic changes has heightened interest in the subject of sediment transport. Over a similar period acoustics has begun to play an important role[1-4] in the measurement of suspended sediment transport processes. The motivation for applying acoustics is that it provides the opportunity to obtain detailed observations of suspension profiles, and these can be employed to study the impact of the fluid dynamics associated with waves and turbulent flow upon sediment transport. The acoustic approach therefore provides the potential for advancing physical models of basic sediment transport mechanisms and furnishes the opportunity for improving coastal management.

The technique is based on propagating megahertz frequency sound through the water column, and if there are any scatterers in suspension some of the scattered signal will be backscattered. This backscattered signal is interpreted to provide information on the suspension. The technique is non-invasive, produces high resolution measurements, and uniquely to the acoustic method provides profile measurements, rather than single height observations available using other techniques. Support for using the acoustic approach has strengthened in recent years as a series of laboratory, marine, and theoretical studies [5-9] have shown that accurate measurements of suspended sediment concentration and particle size using acoustics can be achieved. The present article continues this development and illustrates the application of the acoustic technique in two marine experiments.

2. SCATTERING

To develop the backscattering from a suspension of sediments it is first necessary to describe the scattering properties of the individual grains. Conventionally in acoustics the scattering of a target is described by a term known as the form function. In the present work the sphere definition is adopted, and the magnitude is simply expressed experimentally as

$$f=\frac{2r}{a}\frac{P_s}{P_i} \qquad (1)$$

P_s is the scattered pressure, P_i is the insonifying pressure at the particle, a is the particle's equivalent sphere radius (a sphere of the same volume as the particle), and r is the range of the receiver from the particle. Measurements of the backscattered form function[6] have been conducted on a limited number of suspensions of sediments covering the range a=50-230 µm (fine to coarse sand), and using frequencies 1.0 2.5, and 5.0 MHz. Other observations[10] have been conducted on individual irregularly shaped particles with a=2-26 mm covering the frequency range 40-240KHz. The outcome of these studies are shown in figure 1a. The abssica is given by ka where k is the wave number of the insonifying radiation in the fluid. The figure therefore represents the scattering characteristics in a dimensionless form. The data show a steadily increasing form function for low values of ka, and a relatively uniform value for values of ka beyond ka≈4. Comparison of the two data sets shows moderate agreement in the overlapping region ka=1-5, although the single particle measurements are somewhat lower in value. However, both data sets show an inflection point near ka=1.5, a lack of the resonance structure which would be seen in the case of a sphere, and absolute levels being of the order of unity above ka=4. Therefore although the two data sets were collected under very different circumstances the non-dimensional formulation used to describe the response of spherical targets has applicability in describing the response of irregularly shaped particles. To characterise the data analytically semi-heuristic functions have been developed based on sphere scattering. These effectively have Rayleigh scattering for ka≤0.5, geometric scattering for ka≥5, and have an extra term in the intermediate sector to model this region. Two curves are compared with the observation, the dashed line[11] was fitted to the suspension data and the solid line[10] was matched to the suspension and single particle data. These are given respectively by

$$f_1 = \frac{0.6 + 1.33a}{1 + a} \times \frac{0.4x + b}{1 + b} \times \frac{1 + 0.91c}{1 + c} \tag{2a}$$

$$f_2 = \left(1 - v_1 e^{-[(x-x_1)/\eta_1]^2}\right)\left(1 + v_2 e^{-[(x-x_2)/\eta_2]^2}\right)\left\{\frac{K_f x^2}{1 + K_f x^2}\right\} \tag{2b}$$

The rational fraction used to describe the backscattered form function, f_1, has $a = (x/1.91)^{10}$, $b = (x/0.6)^3$, and $c = (x/3.7)^{16}$, x = ka, and the expression has been calibrated for $0.2<x<4$. For equation (2b) the values were $v_1=0.3$, $\eta_1=0.5$, $x_1=1.4$, $v_2=0.25$, $\eta_2=2.2$, $x_2=2.8$ and $K_f=1.1$. Both the curves compare reasonably well with the data. In similarity with the measurements there is a Rayleigh response at low ka, a change of gradient around ka=1.5, the form of the curve in the ka=2-5 range compare well with the results, and the uniform form function at the higher ka in the optical scattering region is of the order of unity (1.2 for equation (2a)).

The backscattered form function describes the level of the backscattered signal, however, it also is necessary to establish the total backscattering cross section which is related to the attenuation of the sound due to the scattering by the particle. There have been a number of attenuation measurements using suspension of sediments, and the results expressed as a normalised total scattering cross section are shown in figure (1b). Compared with the data is a semi-heuristic expression[5] based on sphere scattering which is given by

$$\chi = \frac{(4/3)K_\alpha x^4}{[1 + x^2 + (4/3)K_\alpha x^4]} \tag{3}$$

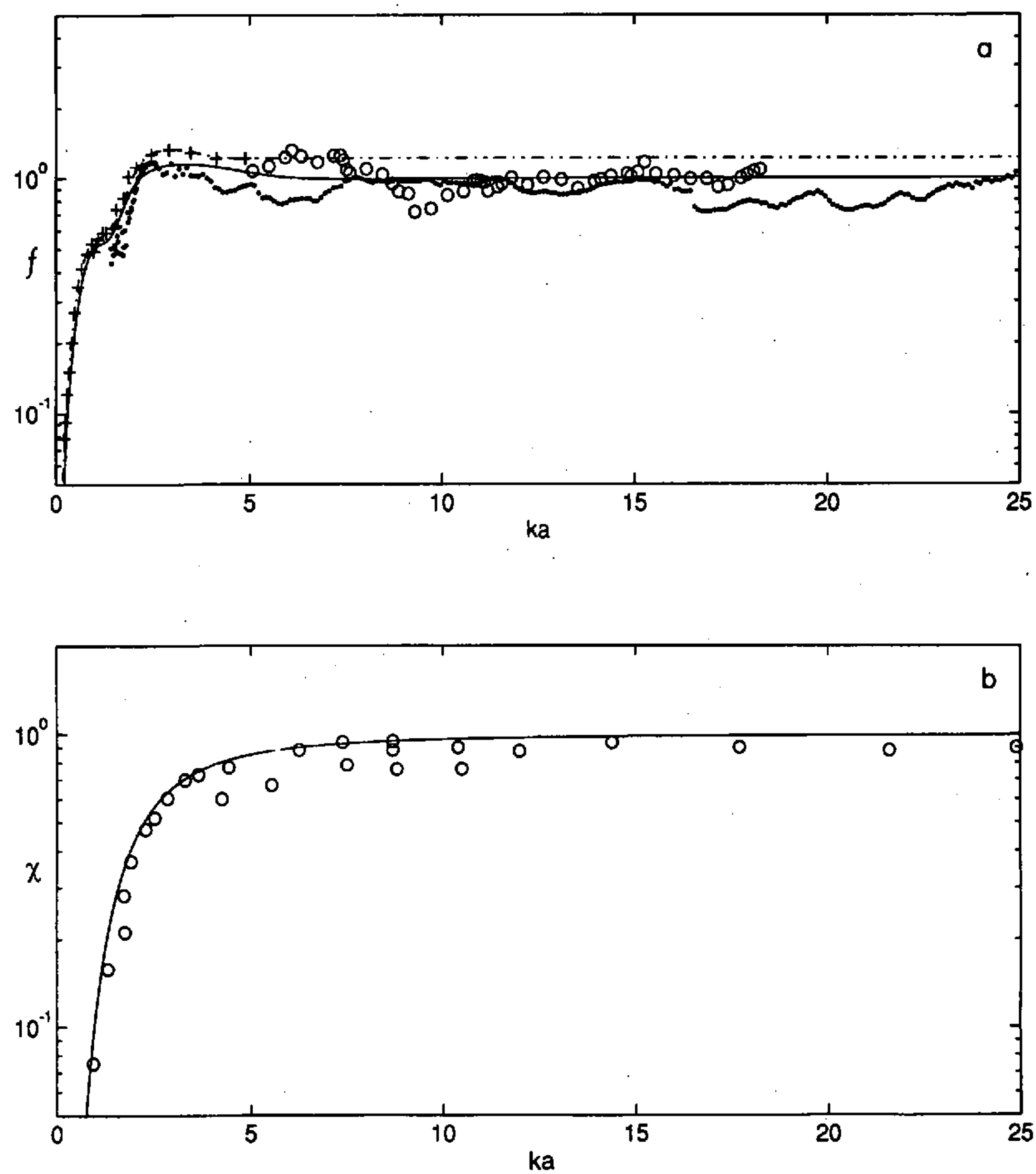


Fig. 1. a) Measurement of the form function, + Ref [6], o and · Ref [10]. ----- Equation (2a), and —— Equation (2b). b) Comparison of the total normalised scattering cross section data [5] with equation (3).

where K_α=0.18. As with the form function expressions it can be seen that the semi-heuristic description compares favourably with the observations.

Using the form function as the basic description for scattering and summing incoherently the backscattered signal from the particles in the volume insonified by a narrow band pulse the root-mean-square backscattered pressure at the transceiver can be expressed as[5-7]

$$P_{rms}=K_s K_t \frac{\sqrt{M}}{R(r)} e^{-2r\alpha} \tag{4}$$

where

$$K_s=\left\{\frac{f_a^2}{\rho_s\langle a_s\rangle}\right\}^{1/2}$$

$$K_t=P_o r_o \left\{\frac{3\tau c}{16}\right\}^{1/2}\left[\int_o^{\pi/2}\left\{\frac{2J_1(ka_t Sin\theta)}{ka_t Sin\theta}\right\}^4 Sin\ \theta\ d\theta\right]^{1/2}$$

$$\alpha=\alpha_w+\alpha_s\ , \qquad \alpha_s=\frac{1}{r}\int_0^r \zeta M dr$$

$$\zeta=\frac{3}{4\langle a_s\rangle\rho_s}\chi_a$$

$$\langle a_s\rangle=\int_0^\infty a_s\ p(a_s)\ da_s$$

$$f_a=\left[\frac{\int_0^\infty a_s p(a_s) da_s \int_0^\infty a_s^2 |f|^2\ p(a_s)\ da_s}{\int_0^\infty a_s^3 p(a_s) da_s}\right]^{1/2}$$

$$\chi_a = \frac{\int_0^\infty a_s p(a_s) da \int_0^\infty a_s^2 \chi p(a_s) da_s}{\int_0^\infty a_s^3 p(a) da}$$

$$R(r) = r \quad \text{for } r > ka_t^2 \quad \text{(farfield)}$$
$$R(r) \approx (2r + ka_t^2))/3 \quad \text{for } r < ka_t^2 \quad \text{(nearfield)}$$

P_{rms} is the root-mean-square pressure. The rms pressure needs to be formed because the magnitude of the backscattered signal from a suspension is Rayleigh distributed due to the varying random location of the particles in the insonified volume[7]. M is the suspended concentration. K_s contains the sediment information; ρ_s is the sediment density, $\langle a_s \rangle$ is the mean particle size, and f_a is the mean form function. K_t consists of the system parameters; P_o is the pressure at r_o, τ is the pulse duration, c is the sound velocity, k is the wave number, J_1 is the first order Bessel function which describes the directivity for the usual disc transceiver employed, a_t is the transceiver radius, and θ is the angle subtended to the acoustic axis. α_w is the attenuation due to water absorption, α_s is the sediment scattering attenuation, and ζ is known here as the sediment attenuation constant. R(r) approximately accounts for the departure of the backscattered signal from spherical spreading in the transceiver nearfield[12]. Only first order multiple scattering has been included, there is therefore an expected upper limit to the applicability of the expression of the order of a few 10's kgm^{-3}.

Equation (4) effectively deals with the acoustics problem, if the suspension parameters are known the backscattered pressure can be predicted. However, the requirement is to extract sediment parameters from the backscattered pressure using equation (4). This is an inverse problem and the inversion can often have uncertainties associated with it because of the large number of variables that can affect the measured quantity, the pressure, and all of the parameters may not be known. However, with this proviso equation (4) can readily be rearranged to make M the dependent variable which gives

$$M(r) = \left\{ \frac{P_{rms}}{K_s K_t} \right\}^2 R^2(r) e^{4r\alpha_s} \qquad (5)$$

If multiple frequencies are avaliable it is possible to use the different scattering response of the sediment at the frequencies to estimate particle size. From equation (4) it can be seen that this can be expressed as

$$\frac{f_{ai}}{f_{aj}} = \frac{(R_i(r) \langle P_i \rangle / K_{t_i}) e^{2r\alpha_s}}{(R_j(r) \langle P_j \rangle / K_{t_j}) e^{2r\alpha_s}} \qquad (6)$$

If it is then assumed that the scattering properties of the sediment are accurately known then the form function ratios can be used to obtain particle size.

3. MEASUREMENTS

3.1 Laboratory

In the laboratory work the forward problem of comparing predictions for the backscattered pressure with observations was examined. Measurements were conducted in a vertical perspex sediment tower with a hopper arrangement at the top. Sediment fell at a regulated rate into the water, and the suspension was stirred near the top of the water column to generate a uniform concentration over approximately 1.5m of the tower. Pumped samples could be obtained at any height in the tower and these samples were used as the absolute measure of the suspended concentration. Measurements were conducted to examine the vertical homogeneity of the suspension and variations over the height of the tower were typically within ±8% of the mean. A hydrophone was mounted near the top of the tower to measure directly the attenuation of the signal due to the propagation through the suspension. Acoustic transceivers were mounted near the base of the tower. The suspension was prevented from settling on the transceivers by passing a horizontal stream of water just above their surface. The systems operating in the tower consisted of a single frequency 3.0 MHz transceiver, with which most of the laboratory data has been collected to date, and a triple frequency transceiver arrangement operating at 1.0, 2.5, and 5MHz. The signal backscattered from the suspension was amplified, filtered, envelope detected, digitised on-line and recorded for analysis. All transceivers have been calibrated using a PVDF hydrophone and beam patterns measured. The transfer function of the electronics was measured, which coupled with the acoustic calibration allowed absolute comparisons of predictions with observations. Typically 100 backscattered pressure profiles were incoherently averaged to obtain P_{rms}, this gave a standard deviation in the mean of approximately 5%.

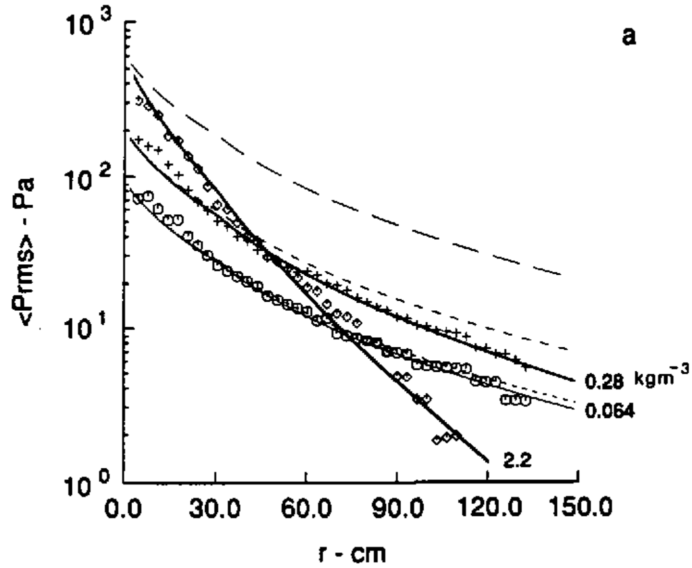
Most of the sediment measurements in the present work have been conducted on the sediment collected from the site of the marine measurements. The sediment consisted of well sorted fine to medium sand with $<a_s>$=82μm. Since the expressions given in equations (2) and (3) represent mean results, and there is some uncertainty in the accuracy of the predictions for the form function and normalised total scattering cross section for a particular sedimentary material it was considered judicious to measure these parameters before comparing predictions with observations. Measurements of the attenuation were obtained by recording the signal level measured using a hydrophone placed at the top of the tower. The value obtained for χ_a was 0.16±0.03, which compares with a value obtained from equation (3) of χ=0.12. The form function was estimated from readings taken at low concentration when the effect of α_s was not significant. This was carried out by rearranging equation (4) and making f the dependent variable on the backscattered pressure. This resulted in a measured value of f=0.74±0.11, with equations 2a and 2b respectively giving f_1=0.55 and f_2=0.51. The predicted and measured values for f_a and χ_a are comparable, although the predicted values under estimate the measured data. Further experimental studies of f and χ are required to examine the variability or consistency for varying sediment types. In the 3.0 MHz study the measured values for the form function and the normalised total scattering cross section were utilised.

Figures 2a and 2b show predicted and measured backscatter results obtained at 3.0 MHz using a suspension of sediments taken from the field site[9]. The variation in the range dependence of P_{rms}, for a number of concentration levels is shown in figure 2a. In all cases there is seen to be a steady fall off in pressure with range arising from a combination of spherical spreading and attenuation due to absorption by the water and suspension scattering. It is readily seen that as the concentration level rises and the distance increases the effect of the suspension attenuation becomes particularly significant. The highest concentrations is seen to give the lowest signal levels beyond about 60cm. Two theoretical curves calculated using equation (4) are compared with the data. The dashed line was calculated with sediment attenuation neglected, ie $\alpha_s=0$, and the solid line with sediment attenuation included. It can readily be observed that even at moderate concentration levels the presence of the suspension introduces sufficient attenuation that significant errors can be introduced into the calculations if α_s is neglected. Retaining the sediment attenuation when evaluating equation (4) significantly improves the agreement between prediction and observations. Figure 2b shows the variation of backscattered signal with concentration at the ranges, 7.5, 22.5, 52.5, and 92.5 cm from the transceiver. There are two curves shown for each range, and these again correspond to P_{rms} computed with and without the sediment attenuation. For low concentrations and close ranges there is seen to be a linear dependence of P_{rms} on $\sqrt{M}$, however, as the integrated effect of the attenuation accumulates there is a departure from the linear response. It can be seen that for the further ranges from the transceiver for increasing concentrations, the backscattered pressure actually begins to decrease. The effect of the sediment scattering attenuation more than offsets the signal increase due to the linear dependence on $\sqrt{M}$ and begins to dominate the backscatter response. This non-linear response of P_{rms} upon $\sqrt{M}$ with range and concentration demonstrates the difficulty in trying to obtain an empirical calibration for an acoustic backscatter device to estimate suspended sediment parameters.

Only a limited number of laboratory measurements have been conducted using the triple frequency system. An example of the results is shown in figure 3. The trends in the predictions compare favourably with the observed data, however, there is a degree of difference in absolute level. This is almost certainly due to experimental problems associated with sensitivities of the transducers which began to occur during the sediment measurements which followed the field observation. There is no reason to believe there were transducer problems during the marine measurements. However, this said, the comparability of the prediction and observations in figure 2b indicates the correctness of the characterisation of the backscattering.

3.2 Marine observations

Two field experiments have been conducted over floods at Springs. Both were conducted in the River Taw estuary in North Devon in August 1988 (Taw88) and in April 1991 (Taw91). In the Taw88 experiment the single frequency 3.0 MHz was used, while in the Taw91 experiment the triple frequency setup was employed. The bed consisted of well sorted fine to medium sand, $<a_s>=82\mu m$, and the area was dominated by sandwaves which typically had a wavelength of around 20m with an amplitude of the order of 0.8m. The estuary is subject to strong rectilinear turbulent currents which mobilise suspended sediments. At low water the site was dry and readily accessible for arranging the experiment. At high water the depth was approximately 6m. Measurements of the suspended load were taken above the bed at 0.1, 0.2, 0.4 and 0.8m using pumped sampling. Profiles of the suspended



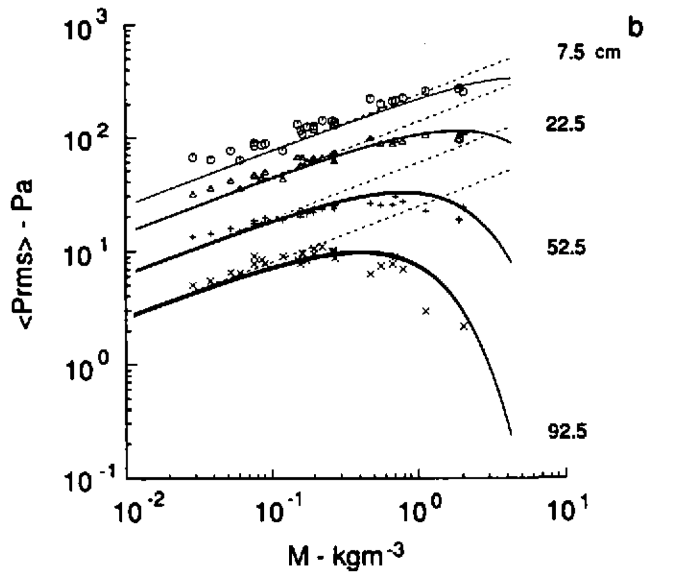


Fig. 2. a) Variation of the backscattered pressure with range for o 0.064, + 0.28, and ◊ 2.2 Kgm^{-3}. b) Variation of the backscattered pressure with concentration at ranges from the transceiver of o 7.5, Δ 22.5, + 52.5, and x 92.5 cm. ----- Equation (4) with α_s=0. —— Equation (4) including sediment attenuation.

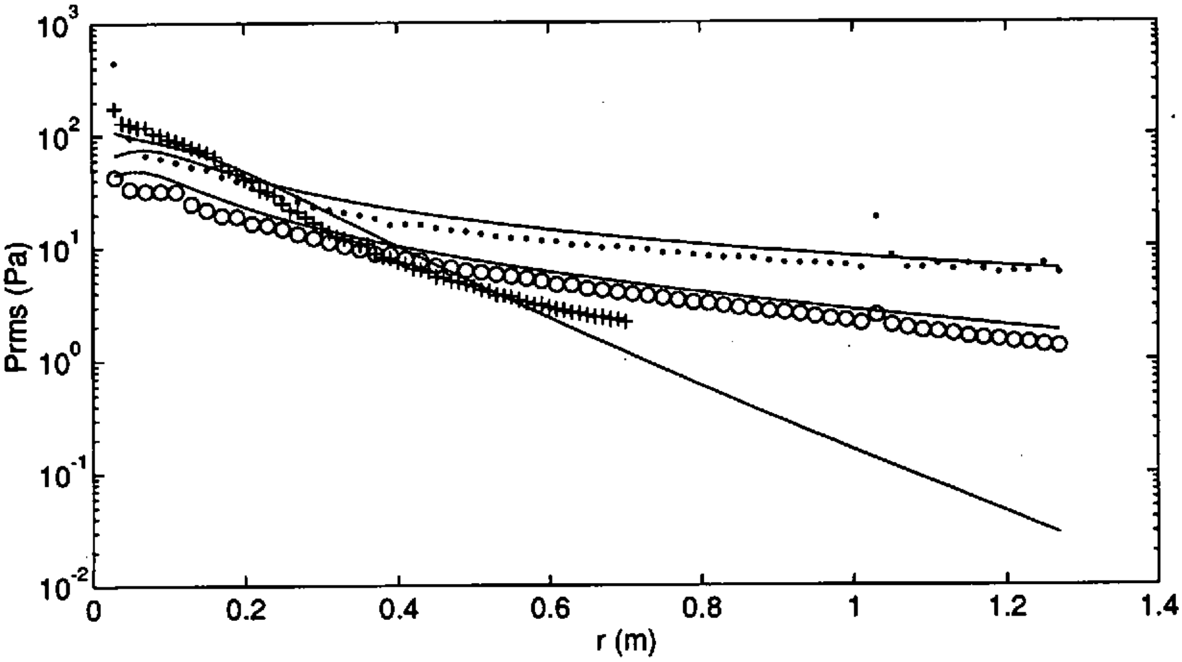


Fig. 3. Multifrequency frequency measurements of the backscattered pressure with range. · 1.0, o 2.5, and + 5.0 MHz. —— Equation (4).

load were obtained using acoustic backscattering, and these estimates of suspended load are compared with the pumped sample data.

The Taw88 experiment[9] was conducted using the single frequency transceiver mounted downward looking from 1m above the bed. The acoustic backscatter profiles were collected on a logging system having 256 contiguous range bins with profiles being obtained at a rate of 3.6 each second. The profiles had a vertical spatial sampling interval of 0.525cm, and a spatial resolution of 0.9cm, determined by the 12μs pulse length. Pumped samples were obtained at 5min intervals, and therefore each height was sampled every 20min. To obtain acoustic estimates of the suspended load, equation (5) was computed. K_t was obtained from the absolute system calibrations. K_s was calculated from in-situ measurements of $<a_s>$, f_a, and ρ_s. $<a_s>$ was obtained from the pumped sampled data, this was nearly uniform with height above the bed, and was therefore taken as constant in the present calculations. The form function, f_a, was estimated using five pumped sampled values from one of the flood periods, when sediment attenuation was relatively low, this gave f_a=0.88±0.1. This is higher than the value obtained from equation (2) but comparable to the laboratory measurements. To obtain the normalised total scattering cross section a similar number of high concentration samples were used to adjust χ_a until the acoustic and pumped sample concentrations coincided. This gave a value of χ_a=0.11±0.03, which compares favourably with the value calculated from equation (3) though less than the laboratory observations. Therefore all the parameters were known to enable an absolute acoustic measurement of the suspended load.

Using the in-situ values for f_a and χ_a results for the acoustic measurements of the suspended sediment concentration were computed for three consecutive days over floods periods, and these are compared with the pumped sample data in figure 4a. For comparison with the pumped sample data the acoustic estimates of concentration were averaged over the same 60s period as the pumped sample data. The data were also spatially averaged over ±2.6cm at the pumped sample heights. This gave 660 independent measurements of the backscattered pressure which resulted in an estimate error of 4% in the mean concentration due to the statistics of the backscattered echo. The comparison of the acoustic concentration estimates with the pumped sample data is seen to show good agreement. The gradient of the experimental data is close to unity, and positioned about the line M_A=M_p. These data show that acoustics can be employed to obtain accurate measurements of the suspended concentration. There is some divergence of agreement at the lower concentrations, and this is in part probably due to both the accuracy of the pumped sampled data and the signal to noise ratio of the backscattered signal. There is also an indication that the acoustic data are overestimating the suspended load. This is probably associated with an error in the value of K_s and/or K_t, errors of the order of 10% for either parameter would not be surprising, and this could account for the overestimate observed. However, the main outcome of this analysis is the generally good agreement between acoustic and pumped sampled observations of the suspended load. The similarity of the pumped sampled data, and the acoustic estimates of concentration provide confidence in the accuracy of the acoustic technique. However, unlike the pumped sample data which provide relatively limited spatial and temporal resolution, the acoustic data can provide the full suspension profiles with sub-centimetre resolution, and produce updated profiles in less than a second. The acoustic data can therefore be employed to investigate turbulent and within-wave processes. An illustration of the data which can be obtained is given in figure 4b. The data cover a period of 80s. Figure 4b shows the suspended concentration profile, with the mean concentration subtracted and only values above the mean displayed. These higher concentration features are seen to vary over periods of seconds, although there appears to be structures present, and these are vertically coherent over the height of the profile. It is these fluctuations and structures in the concentration profile which are uniquely obtained acoustically, and it is expected that these type of detailed observations will improve predictions of sediment transport.

The success of the single frequency results stimulated the development of a more comprehensive system. The triple frequency system was developed to investigate the use of multiple frequencies for examining the consistency of concentration profiles obtained at different frequencies, to look at the frequency response to examine the use of acoustics for sizing the suspended material and to possibly utilise the spatial separation of the devices to examine the spatial coherency of the suspended material[13,14]. The system used the three transceivers operating at 1, 2.5, and 5.0 MHz. The spatial resolution of these devices was 1cm, and 128 cells were recorded. The backscattered signal was amplified by a logarithmic amplifier capable of operating over a dynamic range of 80 dB, and the output data were digitised with 11 bit resolution. The system averaged 32 backscatter profiles each quarter of a second, at each of the three frequencies, and the 0.25s averaged profiles were stored for

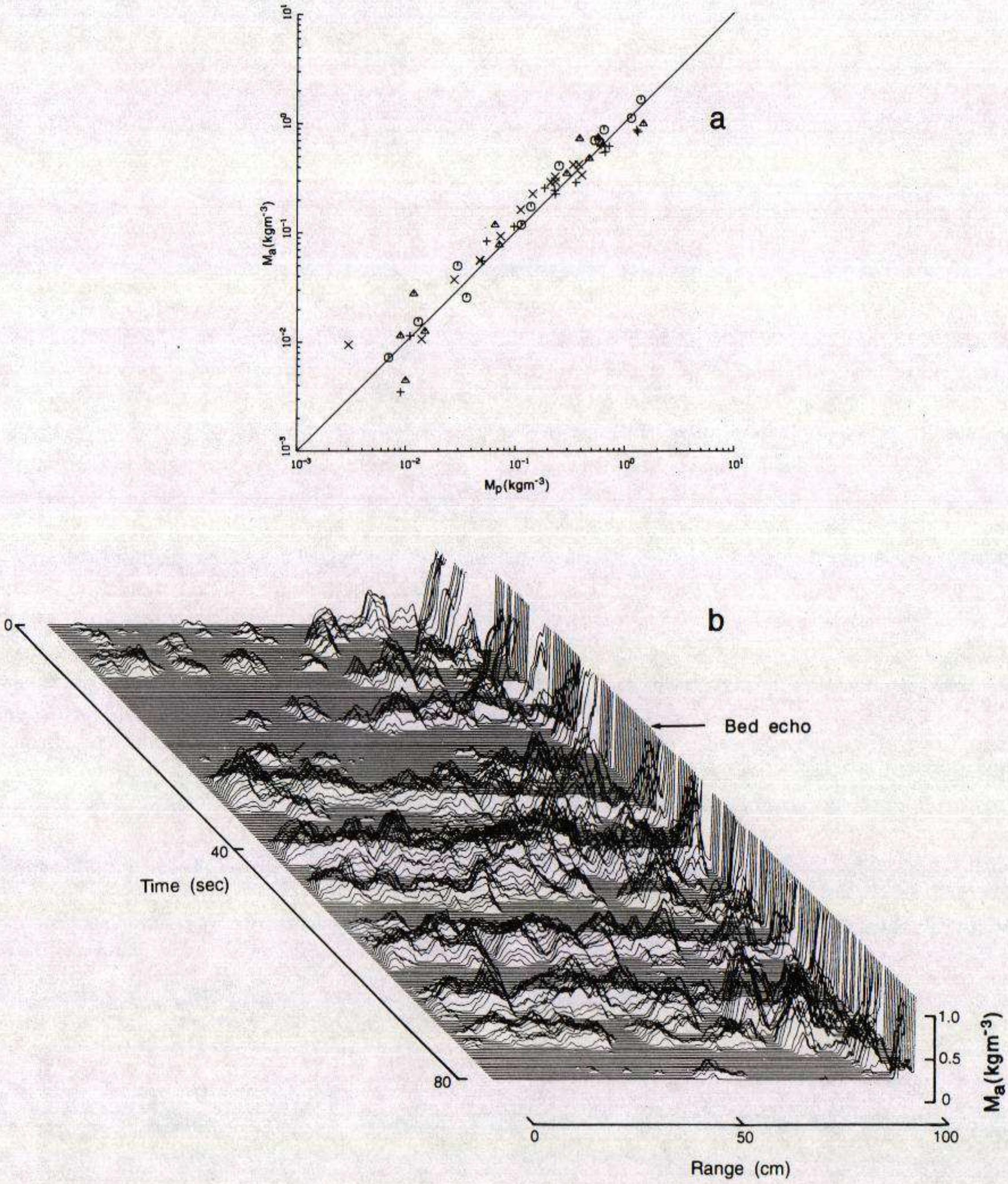
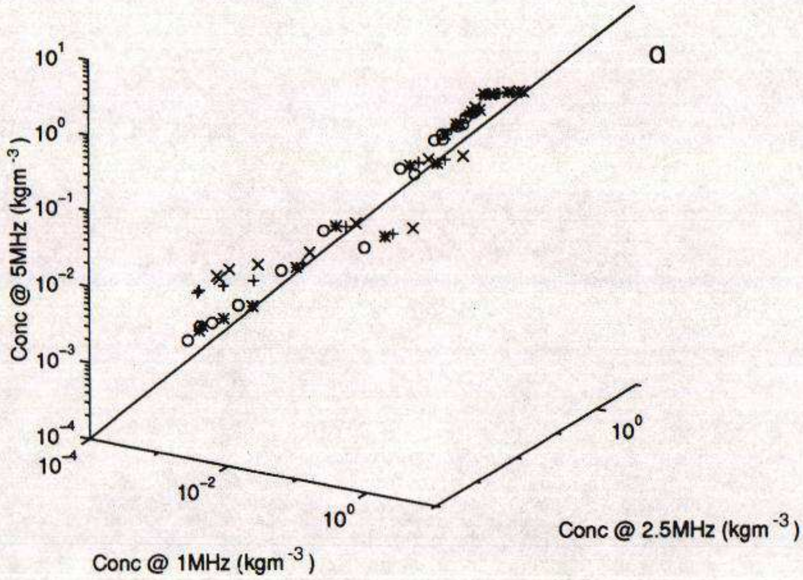


Fig. 4. a) Comparison of the 3.0 MHz Taw 88 acoustic estimates of suspended concentration with pumped sample measurements. o 10, Δ 20, + 40, and x 80 cm above the bed. b) High resolution acoustic estimates of the suspended load with the mean concentration subtracted and only values greater than the mean displayed.

further analysis. The system therefore collected profiles at each frequency over thirty time faster than the single frequency system, and thereby provided a significant advance in temporal resolution. As with the 3.0 MHz system the triple frequency system was fully calibrated, and therefore it was possible to obtain acoustic estimates of particle size and concentration independent of the insitu sampling. As in the previous single frequency study, pumped sample data were obtained, and these have again been employed to assess the acoustic data. In the present case pumped sample measurements were taken at each height simultaneously every ten minutes.

Initially to assess the internal consistency of the triple frequency acoustic observations suspended concentrations were computed using equation (5) for each frequency over one flood period. As with the 3.0 MHz analysis these calculations used $\langle a_s \rangle$=82um, and a constant value with height above the bed. Apart from the size input the acoustic results have not been calibrated by the pumped sample measurements, and they represent three independent observations of the suspended sediments. Also for the triple frequency calculations equation (2b) and (3) were used to obtain f_a and χ_a. Figure 5a shows a plot of the acoustic estimates of suspended sediment concentration at 10, 20 40, and 80 cm above the bed. Each data value used to construct the plot was generated by averaging 2048 0.25s profiles. The principal point to note is that it can readily be seen that the acoustic results are internally consistent. They generally show the same suspended sediment concentration. There is a degree of scatter about the ideal line of conformity particularly at low concentration (again probably due to the signal to noise ratio) though the general picture to first order is of consistency. To evaluate the accuracy of the acoustic estimates of concentration, comparison of the multifrequency acoustic values, averaged over the three frequencies, is shown with the direct pumped sampled measurements in figure 5b. This figure shows time series plots of the concentration at the four heights above the bed. As can be seen the acoustic and pumped sample results display extensive agreement. Both the variation with time, and the values at the different heights above the bed show concentration values which are comparable. These results explicitly show that multiple frequency acoustically computed estimates of suspended sediment concentration can be obtained which are internally compatible and compare very favourably with the bench mark of pumped sampling. Therefore on the tidal time scale the results are consistent. As with the 3.0 MHz case full advantage can now be taken of the temporal and spatial resolution offered by the acoustic technique to examine the details of suspended sediment transport, and the consistency of the mulitifrequency observations on a fine time scale.

Figure 6 shows three highly detailed images of suspended sediment advecting beneath the instruments. These figures indicate the passage of a large cloud of suspended sediment. Within this cloud a particularly high concentration event at about 20s into the record can be observed. A somewhat weaker event is also seen at about 35s into the record. These events could possibly be visualised as being associated with a package of relatively low velocity high sediment concentration fluid being ejected from the bed, and lifting sediment well up into the water column. The coherency of the three independent images lends credence to the reality of the structure seen in the figure 6 and provides confidence that these images are not contaminated with any acoustic artifacts but are a measure of the fluctuations in the suspended sediment concentration field. Figure 6 therefore provides unambiguous confirmation of the correctness of the detailed images, and provides sedimentologist with accurate observations of the features associated with sediment transport under turbulent tidal currents.



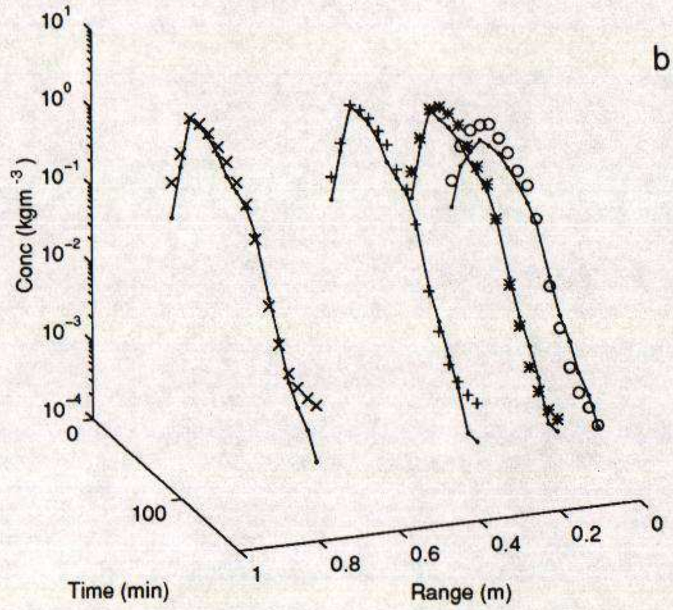


Fig. 5. a) Intercomparison of independent acoustic estimates of suspended concentration obtained at 1.0, 2.5, and 5.0 MHz. Ranges used o 10, * 20, + 40, and x 80 cm. b) Comparison of the acoustic data with the pumped sample data, ·-·.

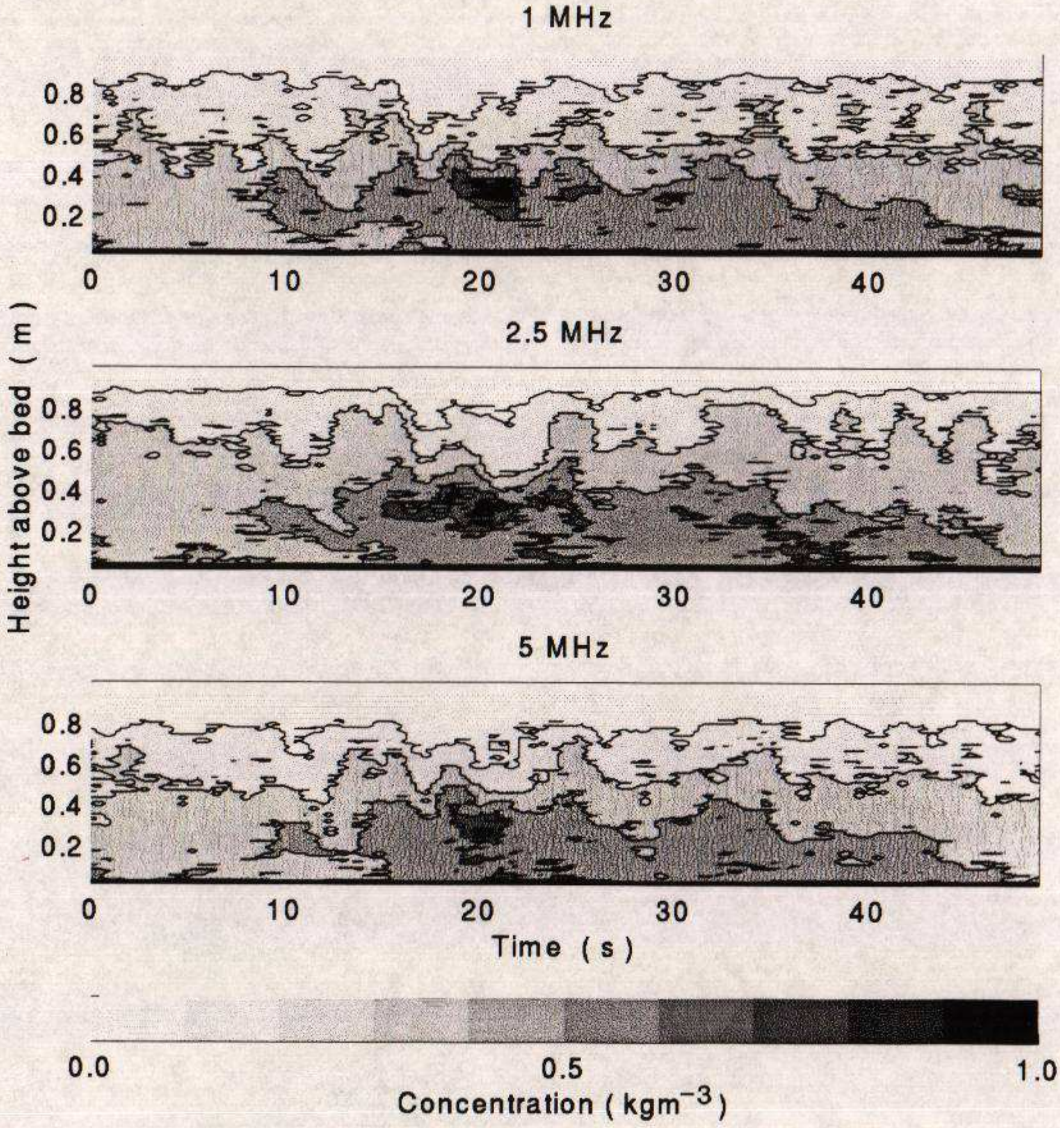


Fig. 6. Detail images of the suspended concentration.

Although to date the main analysis has been conducted to obtain suspended concentration level by inputing a mean estimate for the particle size obtained from pumped samples, initial calculations have been carried out to obtain the particle size using equation (6). The provisional outcome of these results are shown in figure 7. This shows a plot of the variation of the mean particle size over approximately a one hour period near maximum flow. The results indicate a relatively constant value, though increasing towards the bed, which was at a range of just over 1m. The particle size estimates

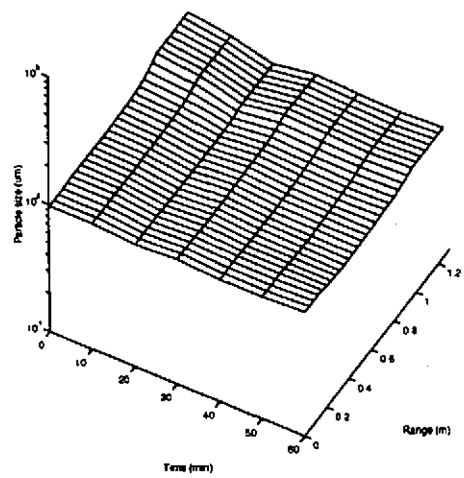


Fig. 7. Acoustic estimates of particle radius.

of approximately 100 μm are of the order of 20% greater than the insitu pumped sample measurements. However, these particle size estimates are a first approximation, and the initial results look promising.

4. CONCLUSIONS

Laboratory results have been presented which show the measured variation of the backscattered pressure with range and concentration. To predict these values the backscattered pressure was computed using a form function description derived from scattering by single irregularly shaped particles and the measurements of ref[6]. The single frequency 3.0 MHz results show close agreement between predictions and observations and effectively demonstrate the correctness of the approach. The triple frequency results are somewhat less convincing and as mentioned in the text there were some problems with transducer stability which impacts on the absolute levels. However, it can be seen that the form of the predicted curves are consistent with the observation which is indicative of the basic description being correct.

The laboratory results were used to primarily look at the forward problem; for the field measurements the inverse solution was required. The Taw88 experiment provided single frequency estimates of the concentration which compared favourably with the pumped sample data, and indicated the temporal resolution which can be obtained using acoustic backscattering. The Taw91 system provided significantly improved temporal resolution, provided multiple estimates of the concentration, and supplied the opportunity to extract particle size. To ascertain the internal integrity of the acoustic inversion the backscattered data was used to obtain three independent estimates of the suspended concentration. These calculations were conducted using $<a_s>$=82 µm. The outcome of the intercomparison showed results which are generally consistent, and compared well with the pumped sample data. Also detailed independent representations of the fluctuations in suspended concentration showed internally consistent results, and this compatibility provides confidence that the acoustic approach can provide unambiguous high resolution images of suspended sediments. Finally provisional results have been shown of acoustic estimates of the suspended particle size. These are of the correct order of magnitude, but overestimate the size by around 20%. Further work is still continuing on the Taw91 data set to try and resolve some of these latter differences.

5. ACKNOWLEDGEMENTS

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