Calibrating multi-frequency acoustic backscatter systems for studying near-bed suspended sediment transport processes

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Abstract

The utilisation of sound backscattered from sediments in suspension, to measure profiles of near-bed particle size and concentration, has been gaining increasing acceptance and usage by sedimentologists and coastal engineers over the past two decades. To obtain the sediment parameters from the backscattered signal requires an inversion to be conducted on the signal and this necessitates a system calibration. The calibration can be carried out by detailed acoustic and electronic measurements, or alternatively by measuring the backscattering from suspensions with known scattering characteristics. Here we explore the latter approach and describe in some detail the calibration of a triple frequency acoustic backscatter system. The aim is to provide coastal scientists involved in using acoustics as a tool for sediment transport research, with a clear exposition of the calibration process. Suspensions of glass spheres of varying particle size were used as the calibration scatterers. To interpret the signal backscatter from the suspension of glass spheres a simple model for sphere scattering is presented. The results show that consistent calibration results can be obtained in a relatively simple and robust manner.

I Introduction

The processes of near-bed sediment transport can be thought of as dynamic feedback interactions between the bed, the flow and the mobile sediments. In recent years acoustic instrumentation has been increasingly used to measure, co-located and simultaneously, these three components of this inter-related sediments triad. Acoustics has gained this role because of its capability to profile non-intrusively, with high temporal and spatial resolution, the three components. A review by Thorne and Hanes, 2002, detail some of these applications. In the present study we focus on the use of multi-frequency acoustic backscattering for measuring near-bed profiles of suspended particle size and concentration and in particular the calibration of such systems. To extract the suspended sediment parameters from the backscattered signal necessitates an inversion to be conducted on the acoustic signal. To carry out the inversion requires a calibration of the acoustic backscatter system. While there is a wide variety of publications (Hay and Sheng 1992, Hampton et al 1998, Vincent and Hanes 2000, Rose and Thorne 2001, Green et al 2004, Dohmen-Janssen and Hanes 2005 and recent commercially available systems Smerdon 2006) on the use of acoustic backscatter systems, ABS, to measure profiles of sediment concentration and size, there is little published literature on how to perform the calibrations of these systems. It was therefore considered appropriate and timely to examine the calibration of such systems. The aim here is to provide coastal engineers and scientist, who are increasingly using such instruments as a tool for sediment studies, with a clear description of the calibration process, so that data collected with an ABS can be accurately and correctly interpreted.

The calibration of a multi-frequency ABS can be carried out by measuring the electronic response of the system, in conjunction with measurements of the transmit and receive sensitivities and beam patterns of the acoustic transducers, Thorne and Hardcastle, 1997. These are time consuming operations and the acoustic component of the calibration requires specialist equipment that would not normally be readily available in most sedimentary laboratories. The alternative to such a calibration is to measure the backscattering from a suspension with known scattering characteristics. Such a measurement automatically incorporates both the electronic and acoustic components of the calibration. The choice of scatterers in suspension for the calibration is crucial. It might be considered that natural sandy sediments would be an appropriate choice, given that ABS's have generally been deployed above sandy beds in the marine environment, however, this is not the case. If, for example, natural sediments were used, the measured system calibration constant would only be valid for that particular sediment site and size distribution. This is because of the detailed variable scattering characteristics due to the precise shape and mineralogy of natural sediments. (Schaafsma and Hay 1997; Thorne and Buckingham 2004). This is not to say there is no theoretical framework for the interaction of sound with suspended sediments, there is, see Thorne and Hanes 2002. It is the sandy sediment scattering characteristics given in such papers which are used in the multi-frequency ABS inversion to obtain profiles of particle size and concentration. However, the description of the interaction of sound with sandy suspensions is not as precise as that of spheres, and never will be, because of the uncertainty introduced by the particles being non-spherical and irregular in shape. Therefore in the present study the calibrations were conducted using suspensions of spheres. The scattering properties of spheres are well documented and an exact solution exits (Gaunaurd and Uberall, 1983). Spheres provide the correct value for the system constant, because their scattering properties are precisely know and therefore the system constant can be decoupled from the scattering properties of the suspension. As will be seen below, the exact sphere solution is moderately complicated, however, here we present a new simple approximation to the exact solution, which can be easily evaluated and used for ABS calibration purposes.

Many sedimentary laboratories have facilities for generating suspensions for instrument calibration and for studying suspended sediment processes. Therefore the approach adopted here should have broad appeal. For the present study a homogeneous suspension of sediments were generated in a sediment tower constructed for calibration and sediment scattering studies. The tower provided a homogeneous suspension over about one metre. Calibration of a triple frequency ABS was carried out by measuring the backscattered signal from a suspension of sediments. The sediments used were glass spheres; these are inexpensive and readily obtained. Their scattering properties have been measured and good agreement obtained with theoretical predictions; Hay 1991, Thorne et al 1992, Schaafsma and Hay 1997. Here results are reported on calibrations conducted in a sediment tower on suspensions of glass spheres with particle sizes ranging in radius from 50-400 μm. The procedure for the calibration is explained in some detail so that the approach can be readily understood. The outcomes from the measurements are discussed and an assessment of the accuracy of the calibration is considered.

II Theory

Here we provide the background theory to incoherent scattering from a suspension of sediments and how this is used to obtain the system constant, from a series of simple backscattering measurements. The description of the backscattering from suspended sediments is now well developed (Sheng and Hay 1988, Hay 1991, Hay and Sheng 1992, Thorne and Campbell 1992, Thorne et al 1993, Thorne and Hardcastle 1997) and the root-mean-square backscattered signal, V_{rms}, from a homogeneous suspension can be written as

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

$$K_s = \frac{f}{\sqrt{\rho_s a_s}}, \qquad \alpha = \alpha_w + \frac{3\chi M}{4 a_s \rho_s}$$

The term K_s contains the sediment backscattering properties; ρ_s is the sediment grain density, a_s is the particle radius of the sediment in suspension and f is known as the form function and describes the backscattering characteristics of the particles in suspension. The term α_w is the attenuation due to water absorption, M is the concentration of sediment in suspension, r is the range from the transducer, ψ accounts for the departure from spherical spreading within the transducer near-field (Downing et al 1995) and χ is known as the normalized total scattering cross-section and describes the scattering attenuation characteristics of the suspension. For fixed settings K_t is a system constant and its measurement is the focus of this paper. It is necessary to establish the value of K_t, as a prerequisite, for the interpretation of backscatter data collected in the marine environment. If the system is operating in its linear region, that is the recorded signal is linearly proportional to the backscattered pressure, and if account has been taken of any time varied gain applied to the system, then a calibration can be obtained by a single measurement using a suspension of known particle size and concentration. By simply rearranging equation (1) and considering measurements made in the far-field of the ABS transducers, that is where $r>A/\lambda$, giving $\psi=1$, and where A is the area of the transducer radiating aperture, we obtain

$$K_t = \frac{V_{rms} r}{K_s M^{1/2}} e^{2r\alpha} \qquad (2)$$

V_{rms} is the measured backscattered signal at range r, a_s can be measured by sieving the sediments in suspension, ρ_s can be readily measured and f, for spheres, is given below in equation (3a), hence K_s is known. The attenuation in the exponent, α, is made up of two components; α_w which can be taken from tables (eg Kaye, and Laby, 1986.) and χ which is given by equation (3b). M can be obtained by direct sampling of the suspension. Hence all the parameters are known on the right hand side of equation (2) for the evaluation of K_t.

The exact solutions for f and χ, for sphere scattering, are given by

$$f = \left| \frac{2}{ix} \sum_{n=0}^{n=\infty} (-1)^n (2n+1) b_n \right| \qquad (3a)$$

$$\chi = \left| \frac{-2}{x^2} \sum_{n=0}^{n=\infty} (2n+1) \mathrm{Re}(b_n) \right| \qquad (3b)$$

Where b_n is a moderately complex function composed of spherical Bessel and Hankel functions of the first kind and their derivatives (Gaunaurd and Uberall,1983), Re denotes taking the real part of the complex expression and $x=ka_s$ where $k=2\pi/\lambda$ and λ is the wavelength of the sound in water. Shown in Figure 1, and represented by the dashed lines, are calculations for f and χ, obtained using equation (3), for a suspension of glass spheres of uniform particle size. The values used in the calculation for the glass spheres were; compressional and shear wave velocities respectively of 5550 ms^{-1} and 3545 ms^{-1}, with a density of 2500 kgm^{-3}**.** For water the values used for density and sound velocity were 1000 kgm^{-3} and 1480 ms^{-1}. As can be seen in figure 1, f is quite variable in form above x=5, with a series of sharp dips associated with spherical resonances of the spheres in suspension. Alternatively χ is relatively simple in structure. The solid lines in figure 1 were calculated for a suspension with a ¼φ ($\phi=-\log_2 d$ were d is the particle diameter in millimetres) size fraction. The size range covered by ¼φ sieves is nominally $a_s \pm 0.09a_s$. Introducing even this relatively narrow size range into the suspension significantly reduces the dips in f, with the result that its structure is somewhat simplified. The impact of the size range on χ is essentially minimal. The simplification in the form of f allows the suspension scattering characteristics to be represented by the following easily evaluated expressions.

$$f = \frac{\varsigma x^2}{1.17 + 0.95x^2} \qquad (4a)$$

$$\varsigma = (1 - 0.5e^{-((x-1.5)/0.5)^2})(1 + 0.4e^{-((x-1.5)/3.0)^2})(1 - 0.5e^{-((x-5.9)/0.7)^2})$$

$$\chi = \frac{0.24\varphi x^4}{0.7 + 0.3x + 2.1x^2 - 0.7x^3 + 0.3x^4} \qquad (4b)$$

$$\varphi = 1 - 0.4e^{-((x-5.5)/2.5)^2}$$

Figure 2 shows comparisons of equation (4), which is a simplified empirical expression representing the solid lines in figure 1, with the measurements (Thorne and Buckingham 2004, Schaafsma and Hay 1997) conducted on suspensions of glass spheres sieved into ¼φ size fractions. It can readily be seen that for the range of x considered, x=0-8, the above simple equations accurately describes the scattering characteristics for ¼φ sieved suspensions of glass spheres. If suspensions other than ¼φ sieved were used, equation (4) would have to be modified. In the rest of the paper it is equation (4) which is used to calculate f and χ for the evaluation of the equation (2) to obtain K_t.

III Instrumentation

(i) Tower

Figure 3 shows the sediment tower used for the calibration measurements. It primarily consisted of a 2.15 m transparent Perspex vertical tube, with a diameter of 0.3 m and with mixing and re-circulating units. The main objective of the tower's design was to generate a homogenous suspension of sediments over about a metre in length, which remained constant over time, and did not contain micro-bubbles, since the latter are significant acoustic scatterers in their own right. Once the tower was filled with a suspension, bilge pumps were used to extracted water and sediment from the bottom of the tower and deliver it back to the top of the tower through a 0.05 m diameter pipe. Two bilge pumps, pumping side by side, operating at approximately 50% of their maximum capacity were chosen for this function. Operating in this mode prevented pump cavitation and thereby reduced the possibility of introducing air into the system through the pumping mechanism. Also the two pumps generated sufficient flow in the return pipe to ensure the sediments extracted with the water from the bottom of the tower were returned to the top. At the top of the tower the suspension was re-introduced below the upper water surface, open to the atmosphere, through a mixing chamber, designed to homogenise the suspended sediments within the tower, without the entrainment of air. The upper mixing arrangement provided a degree on homogeneity, however, further mixing was required to obtain uniformity over a metre. Through a method of trial and error a rotating mixing unit composed of a turbulence grid, impeller and propeller which generated an upward mixing turbulent flow was arrived at. This combination of mixing elements provided a bubble free uniform suspension over the central portion of the tower.

Intermittently the tower required cleaning and was refilled with water from the mains supply. In such cases, due to the presence of micro-bubbles in the fresh water, a period of hours to days was allowed to elapse, with the system running, but with no sediment present, to vent off the air in the water to the atmosphere through the open top of the tower. When the backscatter background signals reduced to levels comparable with the electronic noise floor of the ABS, degassed wetted sediments were introduced into the system. Typically suspended sediment backscatter recordings of about one hour were used to obviate the impact of any short term fluctuations in the suspended concentration and to obtain accurate values for V_{rms}. The backscattered signal has an amplitude that is Rayleigh distributed (see Thorne et al 1993) with a standard error in V given approximately by $V_{rms}/(2\sqrt{n})$, where n is the number of independent backscatter measurements. Therefore if the aim is to achieve 1% accuracy in V_{rms}, 2500 independent profiles have to be collected and the root-mean-square average formed.

(ii) Acoustic backscatter system

The system calibrated was a triple frequency ABS with the transducers operating in transceiver mode at 1.0 MHz, 2.0 MHz and 4.0 MHz, having nominal -3dB half beamwidths respectively of 2^o, 2^o, and 1^o and a transmitted pulse length of 0.02 m. The transducers were mounted near the top of the tower and their beams were directed vertically downwards. The system measured the amplitude envelope of the backscattered signal at 0.01 m intervals over a range of 1.28 m. Although in the marine environment the ABS system interleaved the three frequencies with a pulse repetition frequency of 128 Hz, to obtain high temporal resolution measurement of the suspended sediments, for the acoustically reverberant environment of the tower the pulse repetition frequency was reduced to 4 Hz, to allow sufficient absorption of the sound pulse, by the water, to prevent interference between consecutive transmissions.

(iii) Sediments

The suspension used for the calibration was composed of glass spheres sieved into ¼φ size fractions and covering a particle size range of a_s=50-400 μm. The glass was soda glass and had the physical characteristics given in the 'Theory' section above. Figure 4 shows a typical scanning electron micrograph of the sediment. The glass spheres can be seen to be nominally spherical in shape, although it can readily be seen that there was some departure from sphericity and with odd nodules and paired particles being present in the batch. However, even though the glass spheres were not perfectly spherical, the data presented in figure 2 shows the scattering behavior of suspensions of glass particles is well represented by a sphere scattering model.

(iv) Suspension homogeneity

As shown in figure 3, to generate a homogeneous suspension a combination of recirculation using pumps and stirring was employed. To assess the homogeneity of the suspension in the tower experiments were conducted using suspensions of glass spheres with a_s=115, 137 and 195 μm. Siphoned samples of the sediments were collected between 0.3-0.8 m below the transducers, and located on the central vertical axis of the tower, at 0.07 m from the axis, and at 0.14 m from the axis, the latter was within 0.01m of the tower wall. Known volumes of water were extracted, passed through a 10 μm aperture net filter, and the retained sediments dried and weighed. The concentration was then calculated as the dried mass divided by the volume of water extracted. The resultant measured concentrations are given in figure 5. The data clearly show the suspended sediments were homogeneous both across the tower and vertically. There was no significant difference with sediment size and the individual pump samples were generally within about ±10% of the mean concentration of the suspension.

IV Measurements and results

Backscatter measurements were collected on suspensions of glass spheres sieved into ¼φ size fraction over a range of particle radii between a_s=50-400 μm. The concentration in the tower was kept relatively constant for each size fraction and was normally in the range 0.4-0.6 kgm^{-3}. The normal experimental procedure was to take background readings for several minutes in clear water, add wetted and degassed sediment to the tower, allow the mixture to homogenise over a period of about one hour, record data for of the order of one hour, take pumped samples to assess the concentration and homogeneity and then remove the sediment from the tower using a conical fine nylon mesh, of aperture size 20 μm, placed in the top of the tower. The tower was then ready for another experiment and the whole procedure was repeated.

A typical example of the relative root-mean-square backscatter signal, V_{rms}, is shown in figure 6. This data was collected using M=0.58 kgm^{-3} and a_s=115 μm. The first 0.1 m data is not shown because this was contaminated by crosstalk between the transmitter and receiver during transmission. The results show a decreasing backscattered signal with range due to the r^{-1} term in equation (1) and with increasing signal reduction with frequency due to increasing water absorption and sediment attenuation. To obtain backscatter profiles as smooth as shown in figure 6, 5000 independent profiles were collected and the root-mean-square average formed.

Using the type of data shown in figure 6, equation (2) was evaluated for a number of different ¼φ size fractions using the sphere scattering model given by equation (4). Ideally the value calculated for K_t should be independent of range, particle size and concentration, since it is a system constant and not dependent upon the suspension. Figure 7 shows profiles of K_t with range between 0.1-1.1 m (0.2-1.1 m for the 1.0 MHz due to crosstalk) for three different particle sizes. The error bars were derived from repeating experiments on the same particle size. Although there are differences in the results between the different particle sizes, they are comparable with those obtained by carrying out repeat experiments on the same size particle; therefore there was no systematic variation with particle size. As can be seen, essentially the same is true with range; the value for K_t does not have any significant trend with range. The latter also supports the conclusion drawn from figure 5 that the suspension was homogeneous; since if this were not the case, K_t would not be constant with range. Although not shown here for brevity, measurements made of K_t with another multi-frequency ABS showed no trends with concentration. To assess all the data sets, the values for K_t were averaged over the range 0.2-0.8 m and the results for all the particle sizes are plotted in figure 8. The solid line in the figures is the K_t value averaged over the all the size fractions and the dashed lines are 10% values about this line. As can be seen, in keeping with figure 7, there is no systematic variation of K_t with a_s, which is exactly what should be the case if equation (4) accurately represents the acoustic scattering properties of a suspension of glass spheres sized into ¼φ fractions. In general the data do lay between the 10% dashed lines. There does seem to be somewhat more variability in the measurements above a_s=250μm and this is ascribed to the difficulty in maintaining the sediment in suspension for the larger size fractions, however, even in this regime the results remain consistent. For the smaller size fractions, below a_s= 200 μm, with the odd exception, for example 164 μm at 2 MHz, the results are very consistent. It is not readily apparent why the odd outliers occur, since the discrepancies are not consistent across the three frequencies. The values for K_t were recomputed using the exact solutions of equation (3) with account taken of the size range within a ¼φ; however, there were no significant differences in the resulting K_t values. Therefore the simplified sphere model was not introducing any significant errors. At present, these relatively small discrepancies, in what is generally a consistent calibration series, cannot be explained other than due to experimental error.

V Discussion and conclusion

The application of acoustic backscattering to the measurement of suspended sediment concentration and particle size has become a relatively common technique. The development of ABS systems from their initial development by and for academic institutions, to the production of commercially developed systems is allowing for the broader application of this acoustic technology. To fully take advantage of multi-frequency ABS and obtain accurate quantitative measurements of particle size and concentration requires calibration of the system. As noted in the introduction the calibration can be carried out by measuring the electronic and acoustic response of the system. This requires specialised equipment for the acoustic component of the calibration and such equipment would not normally be available in a sedimentary laboratory. However, such laboratories often have systems to generate suspensions of sediments, both for instrument calibration purposes and for the study of sediment transport processes. Therefore the approach adopted in the present paper has been to utilise the scattering from suspensions of sediments to calibrate an ABS.

As discussed in the 'Introduction', it could be thought that natural sediments should be used for the calibration, however, this essentially leads to a calibration only applicable to the sediments used for the calibration. Therefore the material used for the suspensions was glass spheres. These are readily obtained in the size range required and are inexpensive. The scattering properties of glass spheres have been well documented and are in accord with the general theory of sphere scattering given in equation (3). For all practical circumstances when suspensions are being generated in the laboratory for calibration, the glass spheres will be divided into separate size fractions by sieving. Therefore the approach adopted here was to take advantage of the impact a spread of particle sizes in suspension had on the complicated resonances associated with equation (3), and provide very simple expressions for the backscattering and attenuation of suspensions of glass spheres sieved into ¼φ size fractions. Equation (4) essentially provides the non-specialist in acoustics with readily usable scattering expressions for calibrating an ABS system. The veracity of the equation (4) was assessed with published laboratory measurements and good agreement was obtained. To carry out the calibration a sediment tower was constructed, this used a mixture of pumping and mixing to generate a homogeneous suspension. The construction of the tower was not particularly complicated and its use is straightforward. Using a range of sediments in the tower, with ¼φ size fractions between 50-400 μm, a series of measurements of K_t were collected. The results showed that profiles of K_t were nominally constant with range and particle size and the deviations from the ideal single value were generally close to the limits of the accuracy of the measurement technique. The K_t values for the individual size fractions were generally within ±10% of the global mean obtained by averaging over all the size fractions. The final average value for the normalized standard error, $\sigma_e(K_t)/K_t$, for each frequency, was close to 2%. Improvements to achieve further accuracy are not warranted for the acoustic inversion because the scattering properties of marine sediments are not known to this level. Indeed using three fractions reasonably well separated in size should be adequate; this provides a standard error for K_t of about 5% and the three sizes offers some protection against an erroneous K_t value which could possibly arise if only one size fraction was used.

On a final note, although the calibration of acoustic Doppler velocity meters, ADV's and higher frequency short range acoustic Doppler current profilers, ADCP's, is not the focus of the present paper, the methodology of using homogeneous suspensions of spherical scatters can be used to obtain a similar calibration constant for such systems (Deines 1999). However, since the calibration present here is for a linear system, appropriate accounting for any logarithmic amplification and/or time varying gain used in such systems is required to derive the correct K_t value.

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Figure captions

Figure 1. Predictions for f and χ with x, calculated using equation (3), for a suspension of uniform particle size (---) and with a ¼φ size fraction (─).

Figure 2. Comparison of f and χ with x, calculated using equation (4), with measured values (●) obtained using ¼φ size fractions.

Figure 3. Diagram of the sediment tower used for the calibrations.

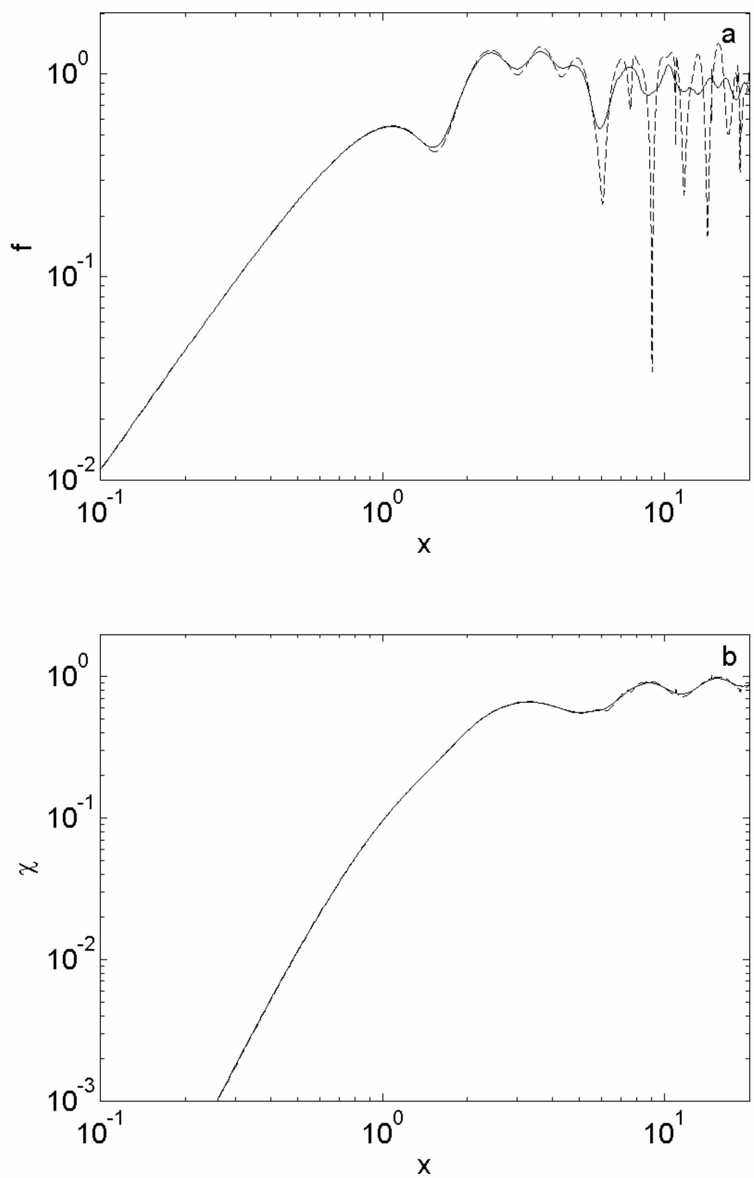
Figure 4. Scanning electron micrograph of the glass sphere sediments used in the calibration study.

Figure 5. Measurements of the variation of concentration across the tower and with range; for a_s= o-115 µm, x-137 µm and +-195 µm.

Figure 6. Measurements of the relative backscatter signal with range in the tower; (●) 1.0 MHz, (o) 2.0 MHz and (x) 4.0 MHz for a_s=115 µm and M=0.58 kgm^{-3}.

Figure 7. Measurements of K_t with range for a_s= 68 (●), 115 (o) and 195 (+) µm, at a) 1.0 MHz, K_{t1}, b) 2.0 MHz, K_{t2} and c) 4.0 MHz, K_{t4}.

Figure 8. Mean values for K_t between 0.2-0.8 m for ¼φ size fractions between 50-400 µm. The solid line is the K_t value averaged over the all the size fractions and the dashed lines are ±10% values about this line. a) 1.0 MHz, K_{t1}, b) 2.0 MHz, K_{t2} and c) 4.0 MHz, K_{t4}.



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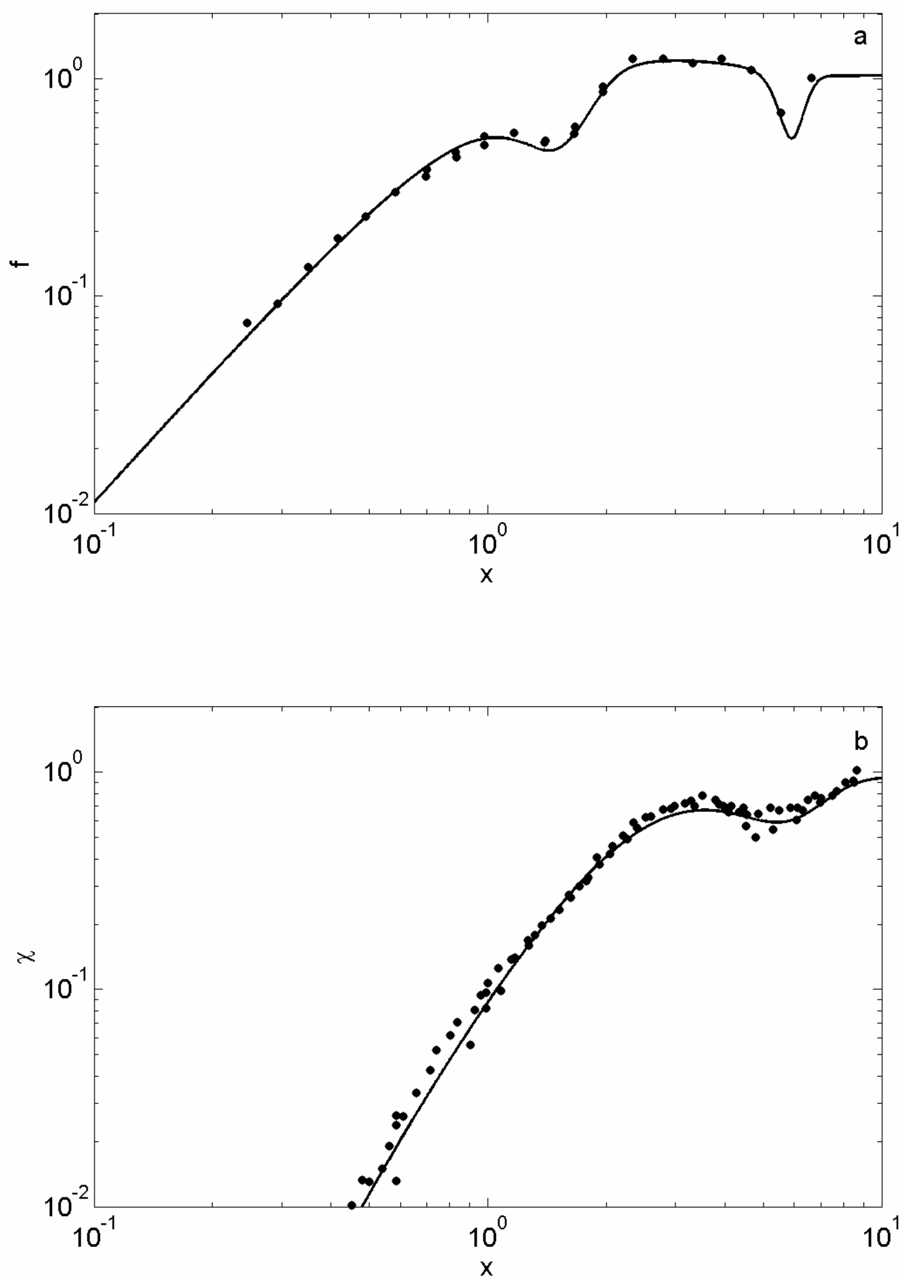

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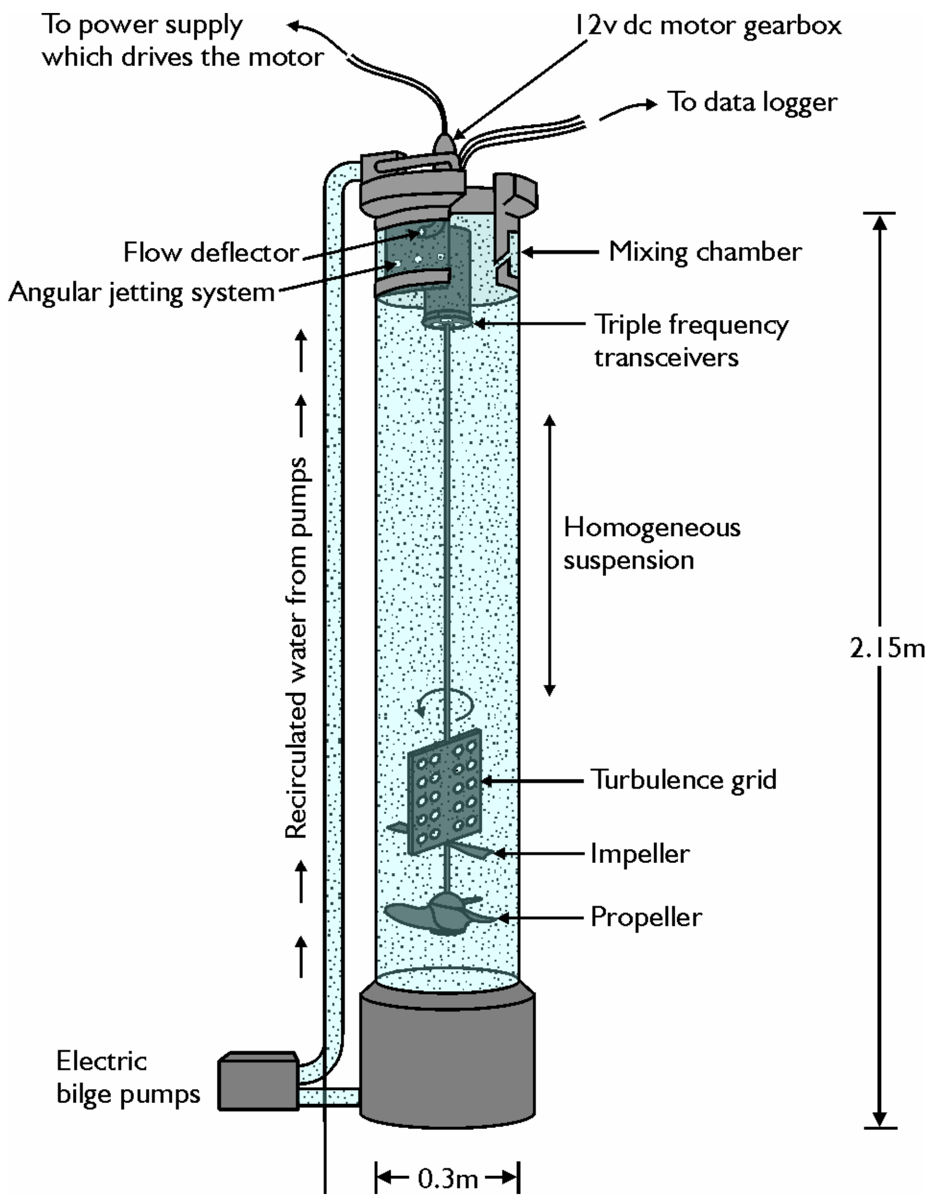

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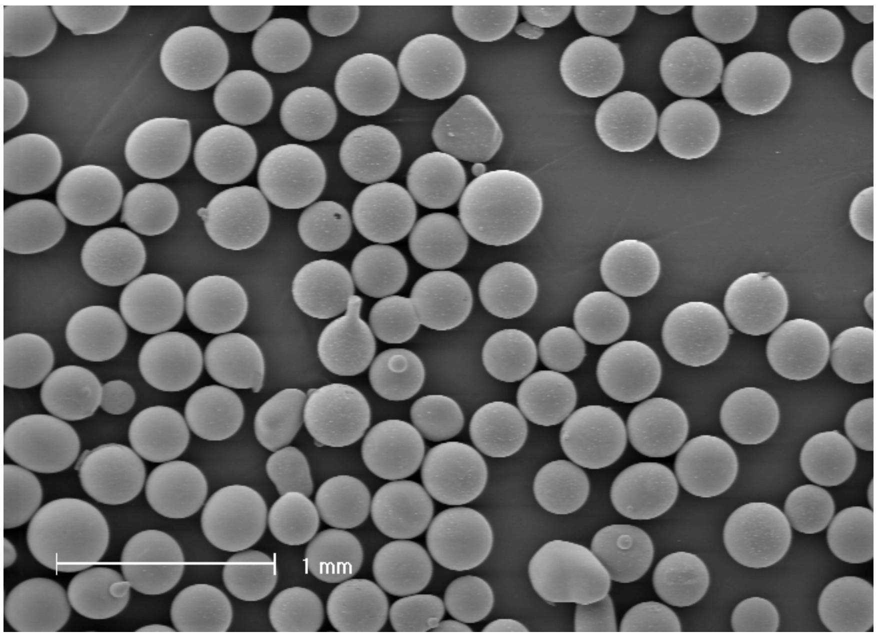

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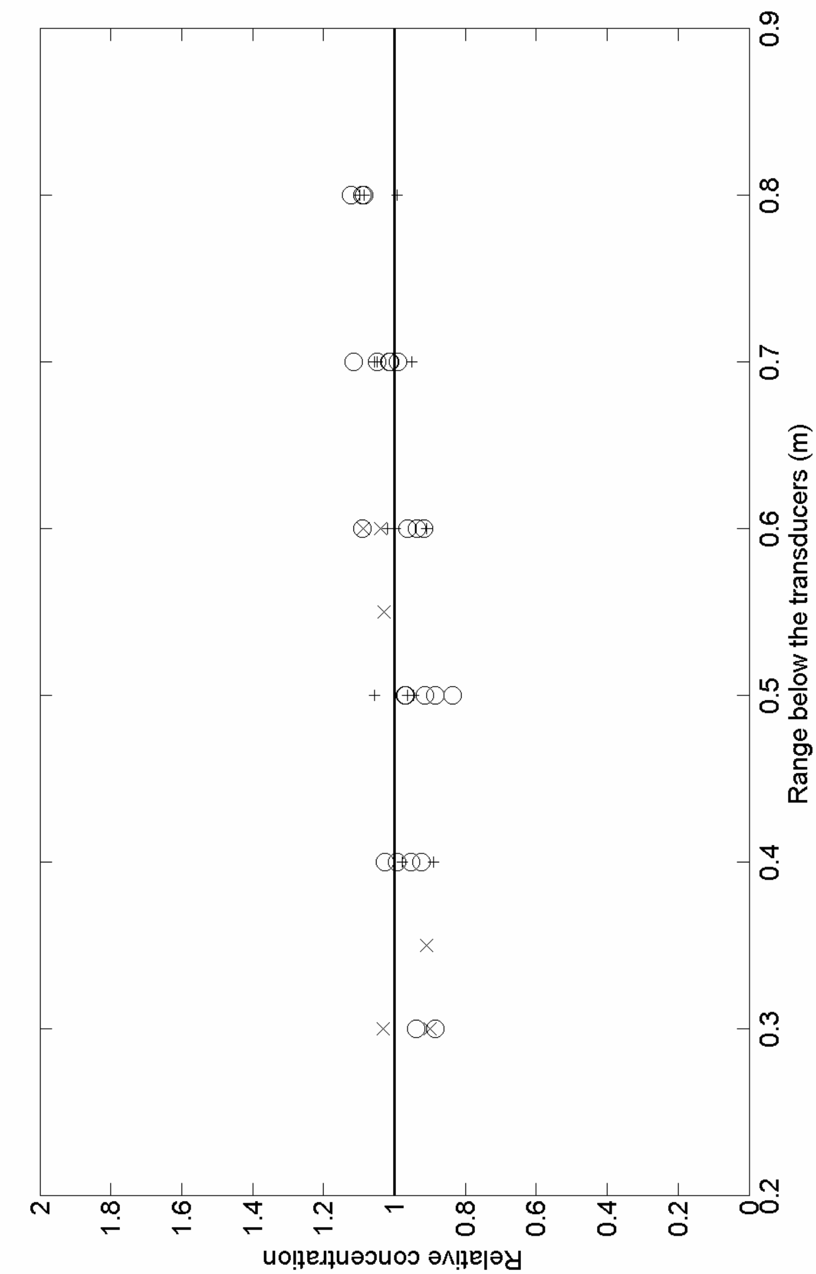

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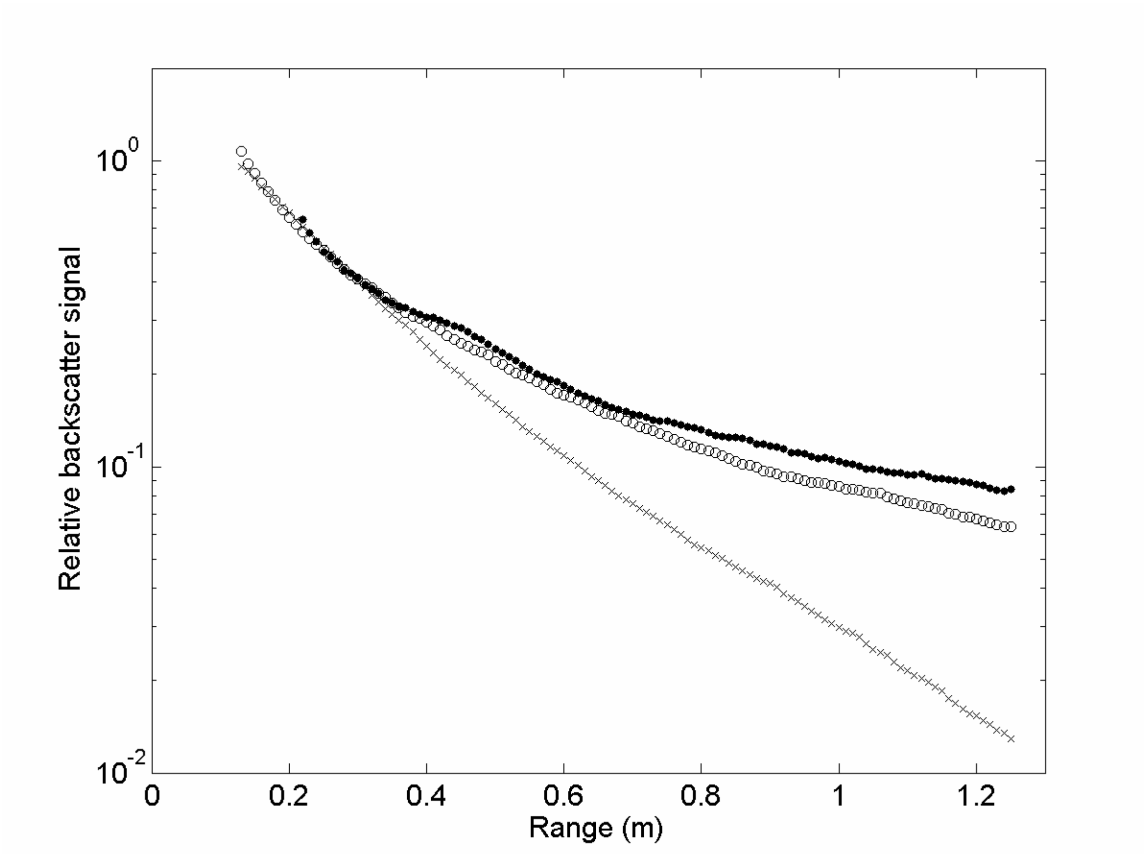

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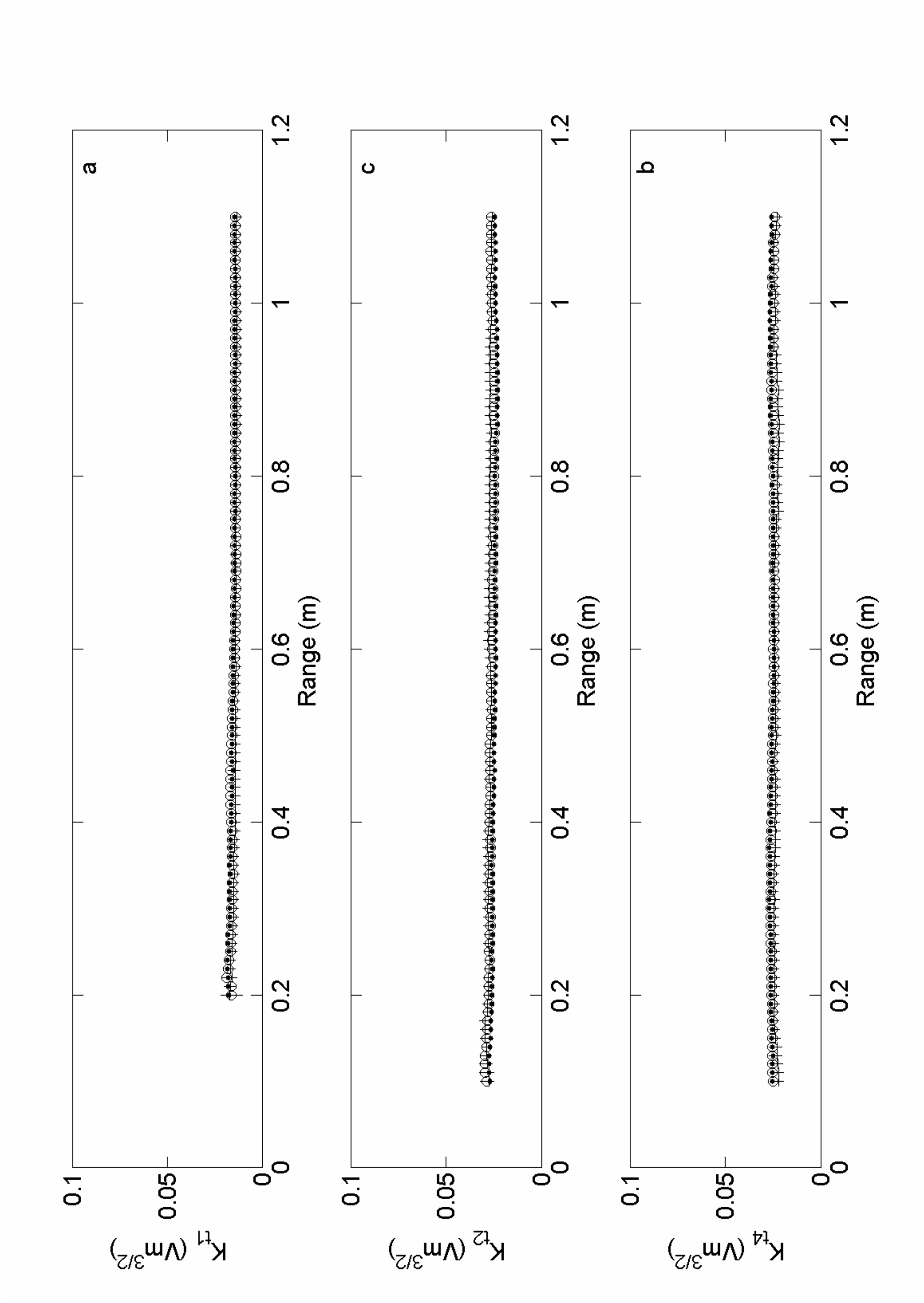

Fig 7 n:\mat5work\labscatter\sam\balsed\bprogs\samspherekt1.m

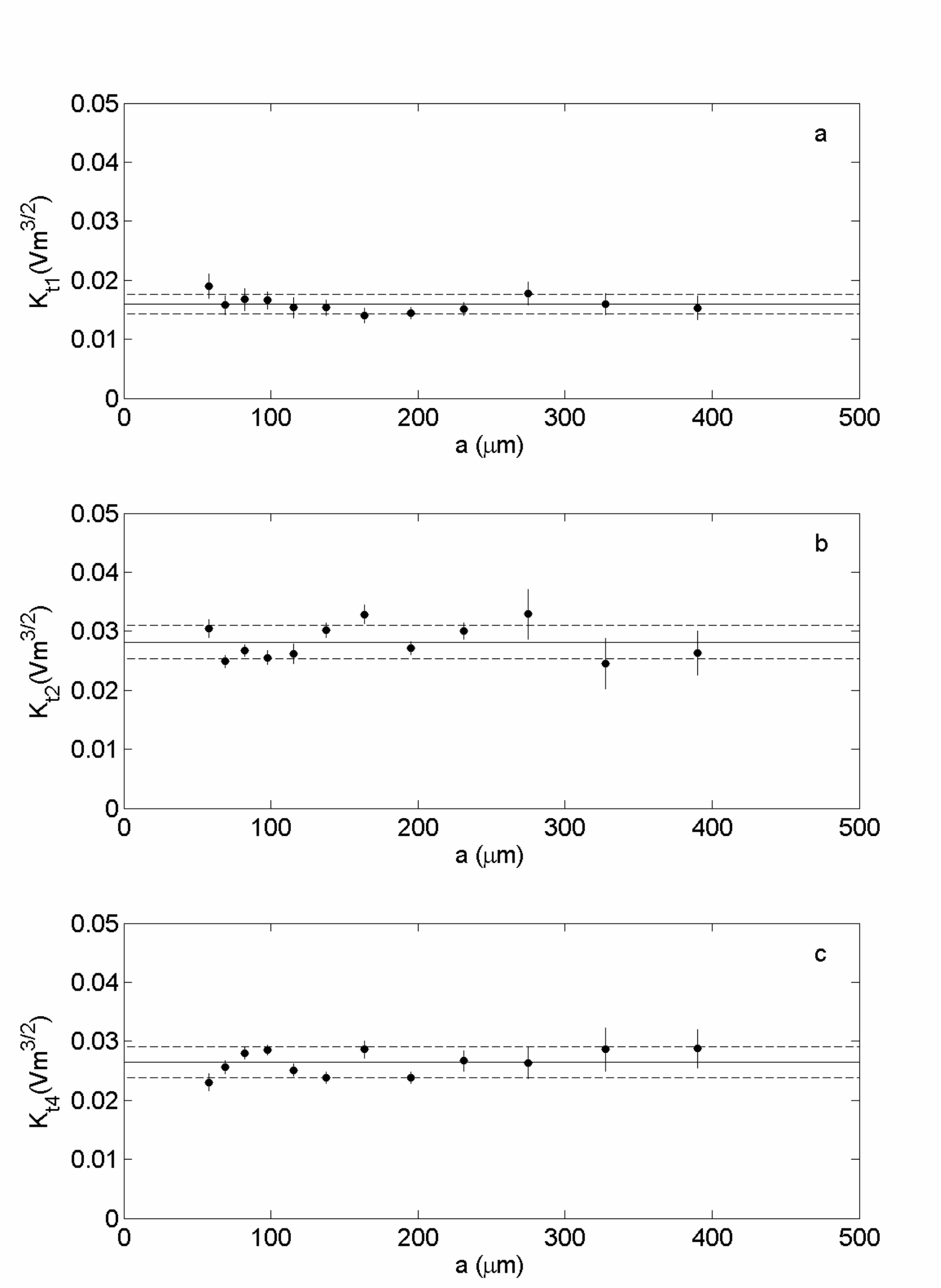

Fig 8 n:\mat5work\labscatter\sam\balsed\bprogs\samspherekt1.m