ACOUSTIC MEASUREMENT OF FINES

Wayne Carpenter, R&D Engineer I, University of Mississippi, University, MS, wocarpen@olemiss.edu; James Chambers, Research Scientist, University of Mississippi, University, MS, chambers@olemiss.edu; Daniel Wren, Hydraulic Engineer, USDA-ARS-NSL, Oxford, MS, daniel.wren@ars.usda.gov; Roger Kuhnle, Research Hydraulic Engineer, USDA-ARS-NSL, Oxford, MS, roger.kuhnle@ars.usda.gov; Jeffrey Diers, Hydrologic Technician, USDA-ARS-NSL, Oxford, MS, jeffrey.diers@ars.udsa.gov

Abstract Knowledge of sediment concentration is important in the study of streams and rivers. The work presented explores the appropriate frequency and transducer spacing for acoustic measurement of suspended particles in the range of 0.1 – 64 microns. High frequency (20 MHz) acoustic signal attenuation was used to measure the concentration of fine sediment particles in a laboratory environment. A small tank with a pitch-catch transducer configuration was used to measure the attenuation caused by kaolinite, bentonite, and silt concentrations over a range of distances (180 – 357 mm). The experimental data shows that increasing concentrations of suspended sediment causes increasing attenuation or decreasing signal levels across the entire range of concentrations considered. An increase in particle size diameter (i.e. silt particles are larger than kaolinite particles, which are larger than bentonite particles) also resulted in a decrease in signal level. As much as a 35 dB change in signal level was observed over a range of kaolinite and bentonite concentrations (1 – 14 g/L) and silt concentrations (1.5 – 5.5 g/L) over the 180 mm to 357 mm range. Additional measurements to assess the limits of detection of the setup were performed at 180 mm for kaolinite concentrations (0.01 – 0.7 g/L), bentonite concentrations (0.01 – 0.7 g/L), and silt concentrations (0.006 – 0.7 g/L). The data suggest that a fixed distance of 180 mm between the transducers was capable of measuring the widest range of concentrations considered. Transducer separations larger than this value were unable to observe any signals at the highest concentrations due to their large attenuation. The ultimate goal of this project is the fabrication and deployment of an autonomous instrument for field studies of fine sediments transported by streams and rivers. From this initial study, the 20 MHz acoustic system was able to measure signal loss over the entire range of concentrations considered at the 180 mm range.

INTRODUCTION

Suspended sediments are a global-scale pollutant whose yield has been estimated at 20 billion tons per year [Holeman (1968)]. In many streams, the majority of sediment moves during flood events caused by a few large storms per year [Nelson and Benedict (1950)]. These flood events are unpredictable and frequently occur at night, making the collection of physical sediment samples difficult and sometimes dangerous. Manual techniques yield samples that are widely spaced in time, small in number, and flow intrusive. To improve the spatial and temporal density of suspended sediment data, the continuing development of automated measurement systems is essential. Ultrasonic measurement systems can detect particles with a high degree of both spatial and temporal resolution, making them ideal for addressing the needs those who rely on sediment data [Shen and Lemmin (1996) and Thorne et al. (1995)].

Acoustic technology has great potential for improving the current state of suspended-sediment measurement technology; it can be relatively inexpensive, lends itself well to remote deployment, and is non-intrusive [Wren et al. (2000)]. Most acoustic systems have targeted sand sized particles (62-2000 µm) due to their heterogeneous distribution with depth as shown by Thorne et al. (1995). However, a large portion of the sediment load in a stream may be <62 µm, a size range that is well-distributed throughout the cross-section [Kuhnle et al. (2000) and Kuhnle et al. (2007)]. Lane (1940) and Yang et al. (2005) observed these fine sediment particle concentrations to be as high as 56% by weight.

This report describes experiments aimed at the development of a device that will use measurements of acoustic signal attenuation during propagation through water containing clay and silt particles to determine the particle concentration. The two clays, kaolinite and bentonite, were chosen for several reasons. In the sea floor, Eisma (1993) states that clays represent 40-80% of silicate minerals in pelagic sediments. Kowallis et al. (1984) and Marion et al. (1992) note a strong effect of kaolinite content on the acoustic properties in sedimentary rocks and unconsolidated mixtures. Bentonite at 0.2 µm and kaolinite at 5 µm represent a wide range of clay particle sizes. These two clays are also readily available from commercial sources. In a river with suspended sediment loads, silt concentrations may reach 10g/L or more. These high silt concentrations cause abrasion on the turbines. Staubli, Gruber, and Luescher (2006) suggest to shut down the turbines to prevent damage if particle concentration is higher than 5 g/L.

Previous work on acoustic attenuation by fine particles focused on fixed pitch/catch configuration distances. Greenwood et al. (1993) measured ultrasonic attenuation in a kaolin-water slurry (1 micron particles) from 0-0.2 volume fraction and utilized a frequency range of 0.5-3 MHz at a fixed distance of approximately 0.1016 m. At each frequency, they found that attenuation was a linear function of the volume fraction and had a linear dependence on frequency within the 0.5 – 3 MHz range. To measure kaolinite/water suspensions in near 40% solid-volume, Green and Esquivel-Sirvent (1999) used a bench-top 1L suspension chamber with two ultrasonic transducers (3.5 and 7 MHz) and a micrometer stage allowing adjustments in transmit/receive path length. The effect of the increasing frequency produced only a moderate increase in attenuation and a slight increase in the concentration of maximum absorption. The present work focuses on suspended sediment concentrations much smaller (0.010 – 14 g/L) than some of the aforementioned studies. These lower concentrations, which encompass what one would find in streams as noted by Kowallis et al. (1984), made it possible to neglect multiple scattering since the concentrations were below 10 g/L [Sheng and Hay (1988)].

METHODS AND EQUIPMENT

Experimental data were collected in a recirculation tank at the National Center for Physical Acoustics (NCPA) in collaboration with the USDA-ARS-National Sedimentation Laboratory. A 110 gallon (416.9 L) elliptical tank was used to recirculate and suspend the fine sediment particles as illustrated in Figure 1. The dimensions of the tank were 126 cm long, 85 cm wide, and 51.5 cm deep. The water and fine sediment particles were recirculated using a Weg Electric Corp. ½ hp 220V centrifugal pump. The tank had extruded aluminum rails mounted on its top to allow three-dimensional alignment of the transducers. A point gauge was mounted to the rails to verify that the same water level was used during the measurements.

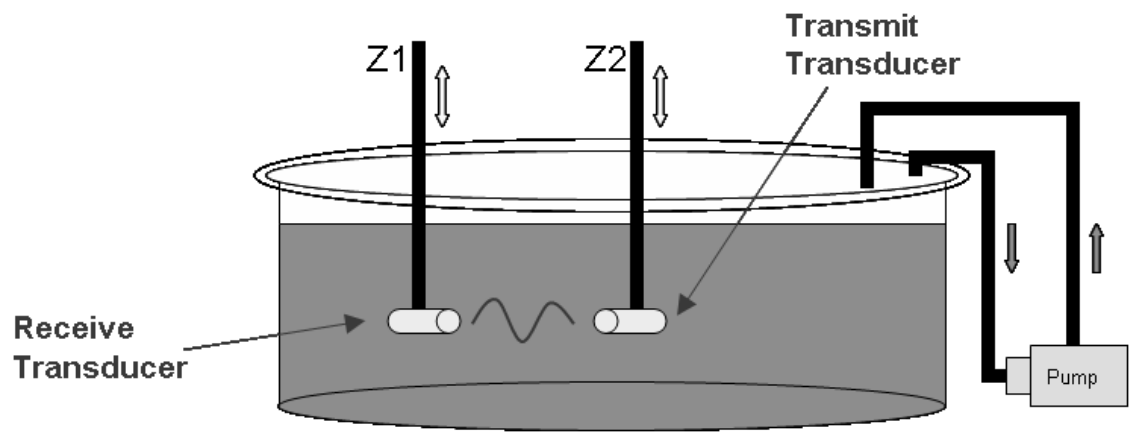

Figure 1 Recirculation tank.

Two 20 MHz immersion transducers were used in a pitch-catch configuration to send and receive acoustic signals as shown in Figure 2.

Figure 2 Pitch-catch transducer configuration.

The transducers were placed 4.5 cm under the water surface and separated by 2.8 – 36.0 cm in 2.54 cm increments. At each range setting, the transducers were aligned by adjusting their position until the maximum signal amplitude was achieved, thus ensuring that the active elements were aligned with one another. The data were collected and averaged for 1000 bursts per range setting. Each experiment was repeated three times and the results were averaged. Kinsler et al. (1982) note that averaging removed statistical variations due to the random relative motion of the scatterers.

The acoustic data collection system consisted of off-the-shelf components for transmitting and acquiring acoustic data. A custom written LabVIEW program was used to operate the instruments. A Hewlett Packard 3314A function generator transmitted the acoustic signal. The waveform tone burst was set to $10V_{peak}$, 100 cycles, and a 10 ms delay between bursts to allow the reverberant signal to completely dissipate. The signal was both sent and received with NDT

Systems IBHG202 20 MHz immersion transducers with a ¼" (3 mm) diameter active element. At 20 MHz, the generated acoustic wavelength in clear water is approximately 74 µm. The sediment particle size range was 0.1-64 microns. The near-field length, N, for these transducers is given as 136 mm and the half angle beam width is 0.365^{o}. Thus, we expect to be well in the far field at a distance of 230 mm and not have any multipath effects from the surface. The received acoustic signal was amplified by an Olympus 5682 500 KHz - 25 MHz preamplifier, and then captured with a National Instruments 2-channel, 8-bit, 1GS/s per channel oscilloscope card (NI PXI-PCI-5152).

Kaolinite and bentonite with concentrations of 0.01 – 24 g/L and silt with concentrations of 0.006 – 24 g/L in tap water (70 – 72 ˚F) were used in the experiments. The kaolinite particles had a particle diameter range of 2 – 5 µm. The bentonite particles had a particle diameter of 0.2-1µm. The kaolinite particles stayed well separated due to the recirculation pump, but the bentonite particles tended to flocculate. Therefore, prior to adding the bentonite to the circulation tank, sodium hexametaphosphate, a deflocculant, was added in a 1:100 ratio and allowed to completely dissolve. The silts had a particle diameter range of 45 – 60 µm. The silt particles were separated, but required more mixing time to insure all particles were suspended.

Duplicate 1-L pump samples were taken in pre-tared pyrex flasks at each concentration. Samples of the fluid/sediment mixture were used to verify that a uniform distribution of particles in the tank was achieved. The physical samples were obtained using a vacuum pump connected by a hose to a small bronze tube near the receive transducer. Concentrations were determined by weighing each fluid/sediment sample, decanting the sample, and placing the sediment into pre-tared pans that were oven dried at 60˚C for approximately 48 hours. Then, the flasks were re-weighed to obtain particle mass and sediment concentration.

THEORETICAL MODEL

In the following expression, Hay (1991) shows that the received voltage as a function of range and concentration is determined by both spherical spreading and absorption due to either pure water or the water-sediment mixture.

$$V = \frac{V_0 R_0}{R} e^{-\alpha (R - R_0)} \tag{1}$$

The reference voltage, V_0, is recorded at the reference position, R_0. The reference data point V_0R_0 must be selected outside of the near-field of the transducer. The reference distance used in these experiments is 230 mm. The measured voltage, V, corresponds to the position, R. The total sound attenuation coefficient, α, is a function of water temperature and suspended-particle concentration. It should be noted that the purpose of the work is not to determine the attenuation of the sediment from scattering theory as done by Hay (1991), but rather to determine if the presence of suspended particles in concentrations that commonly occur in streams will cause enough signal attenuation to be usable for field measurements.

To estimate the absorption coefficients for each of the concentrations, the clear water reference voltage and associated distance is compared to the measured voltage resulting from the fine

sediment particle concentration. The resulting attenuation values are averaged over all distances for each concentration. This provides an absorption coefficient for each concentration.

EXPERIMENTAL FINDINGS

Figure 3 shows the results for signal loss in the estimated far-field past 180 cm for both pure water and kaolinite mixtures. The geometrical spreading curve shows the 6 dB loss per doubling of distance (6 dB/DD) associated with simple spherical spreading while the data shows the significant contribution of attenuation to signal loss from both tap water and suspended sediment mixtures. For the purpose of prediction and evaluation of an absorption coefficient, the data at a range of 230 mm was used as the start of the far field as the data closer than this shows the residual effect of the near field. The absorption coefficient for the water used in these experiments was found to be 8.3 Np/m, which is comparable to the 8.7 Np/m one can calculate for distilled water at 72˚F. B is an empirical constant with a value of $3.38\text{x}10^{-6}$ Np/m. Schulkin and Marsh (1962) show the following expressions:

$$\alpha = B \cdot \frac{f^2}{f_T} \tag{2}$$

$$f_T = 21.9 \times 10^{\left(6 \cdot \frac{1520}{T+273}\right)} \tag{3}$$

Any discrepancy, perhaps due to specific water chemistry, would be present for both the reference clear water and water-sediment mixtures both in the lab experiment and ultimately field measurements. Figure 3 also shows the signal level changes with range for kaolinite concentrations ranging from 1.4 – 13.6 g/L. As the concentration increases, absorption increases and the signal level decreases. Using Equation 1, the absorption coefficient was estimated for each concentration of kaolinite using a best fit to the data and is shown in Table 1.

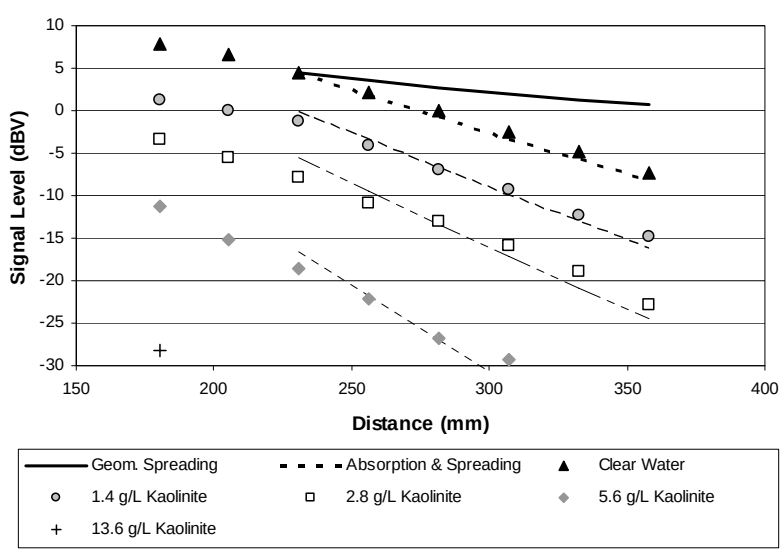

Figure 3 Signal level (dBV) for kaolinite concentrations (1.4 – 13.6 g/L).

Table 1 Kaolinite concentrations and calculated absorption coefficients.

Concentration (g/L)	Absorption (Np/m)
1.4	11.2
2.8	13.7
5.6	19.6

Figure 4 shows the signal level changes for bentonite with concentrations ranging from 1.7 – 13.4 g/L. Figure 4 also shows the signal level for geometrical spreading and absorption in clear and sediment laden water at pre-determined distances for data past 230 mm. Similar to the kaolinite measurements, as the concentration increases, absorption increases and the signal level decreases. However, the signal levels for the bentonite mixtures are higher and the absorption is lower than in the kaolinite mixtures. Kaolinite particles are larger than bentonite, and should be expected to scatter and attenuate more signal than a similar concentration of bentonite particles. The calculated attenuations for the bentonite mixtures are shown in Table 2.

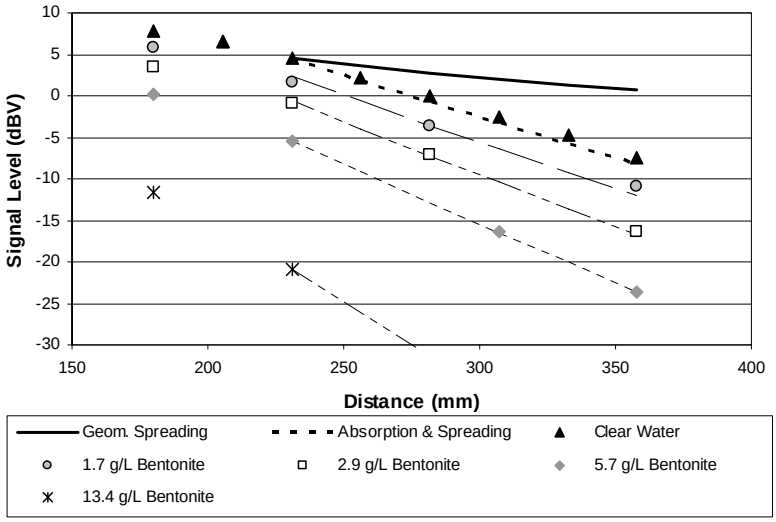

Figure 4 Signal level (dBV) for bentonite concentrations (1.7 – 13.4 g/L) at pre-determined distances.

Table 2 Bentonite concentrations and calculated absorption coefficients.

Concentration (g/L)	Absorption (Np/m)
1.7	9.5
2.9	11.2
5.7	13.0
13.4	20.6

Figure 5 shows the signal level changes for silt with concentrations ranging from 1.5 – 5.5 g/L. Additional measurements at higher concentrations could not be determined, because the signal to noise ratio was extremely low (20 mV_{pp}). Similar to the previous plots, Figure 5 shows the signal level for geometrical spreading and absorption in clear water at pre-determined distances. As the silt concentration increases, absorption increases and the signal level decreases much more rapidly than the aforementioned clays. Correspondingly, the signal levels for the silt concentrations are lower than bentonite and kaolinite, because the absorption due to spherical spreading is higher. Recall the silt particles are 10 orders of magnitude larger in diameter than the kaolinite bentonite particles. The calculated attenuations for the silt mixtures are shown in Table 3.

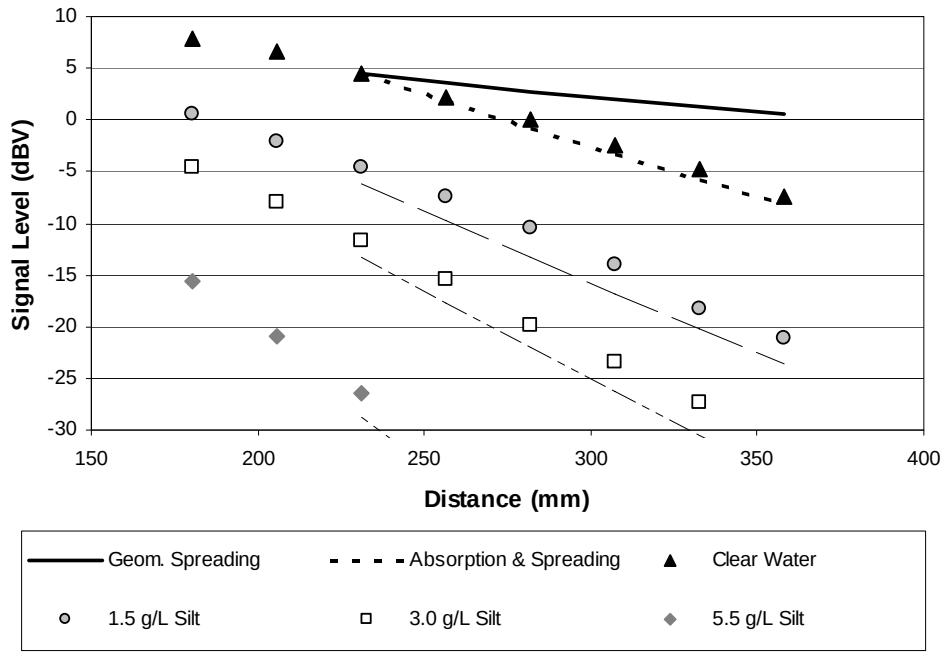

Figure 5 Signal level (dBV) for silt concentrations (1.5 – 5.5 g/L) at pre-determined distances.

Table 3 Silt concentrations and calculated absorption coefficients.

Concentration (g/L)	Absorption (Np/m)
1.5	12.3
3.0	15.8
5.5	23.5

For kaolinite and bentonite concentrations within the range of approximately 13 – 23 g/L, attenuation measurements were recorded in the near field at pre-determined distances from 28 – 180 mm in 2.54 cm increments. Attenuation of silt concentrations in the near field were recorded in the range of 5.5 – 24.4 g/L. Figures 6, 7, and 8 show the near field measurements of kaolinite, bentonite, and silt concentrations, respectively.

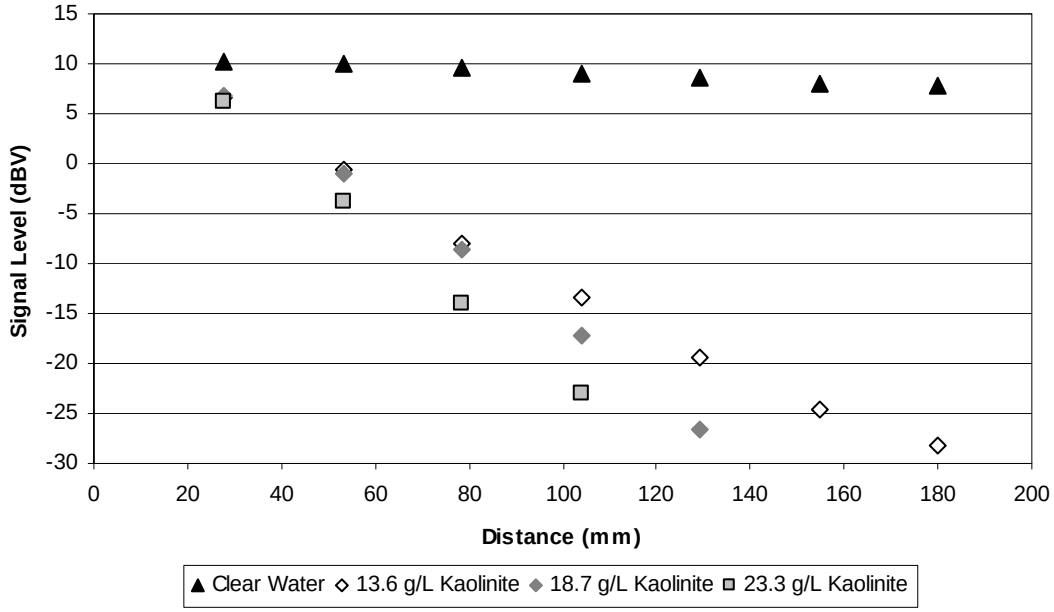

Figure 6 Signal level (dBV) for kaolinite concentrations (13.6 – 23.3 g/L) at pre-determined distances in the near field.

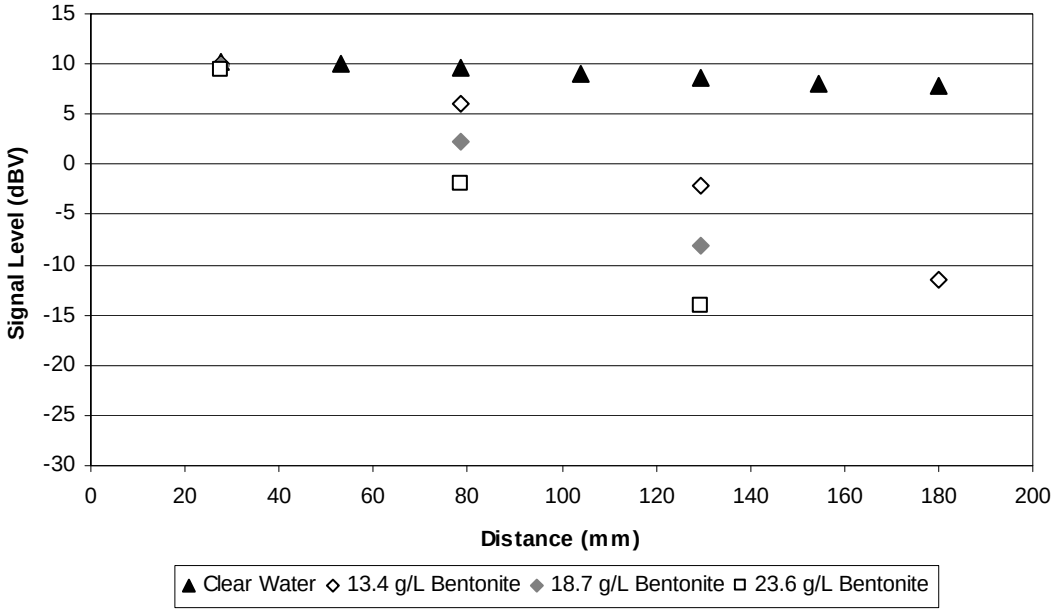

Figure 7 Signal level (dBV) for bentonite concentrations (13.4 – 23.6 g/L) at pre-determined distances in the near field.

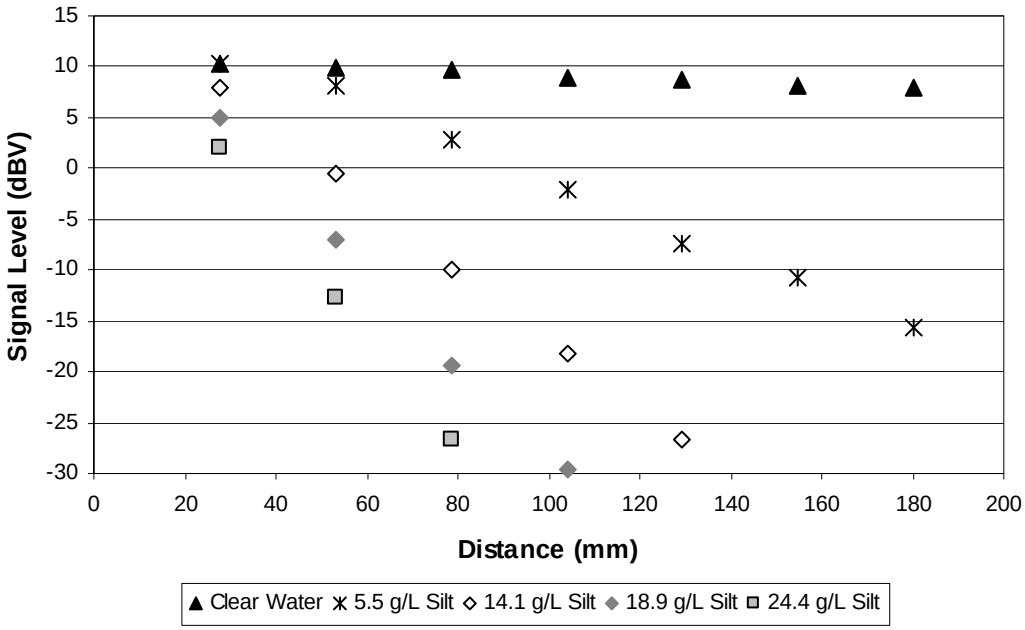

Figure 8 Signal level (dBV) for silt concentrations (5.5 – 24.5 g/L) at pre-determined distances in the near field.

While we have performed calculations to investigate the attenuation beginning at 230 mm and beyond, the data at 180 mm has significance in that we are able to investigate the full range of sediment concentrations considered. At distances greater than 180 mm, the attenuation caused by high concentrations is greater than the dynamic range of our instrumentation and the signal is lost in the noise. Conversely, at ranges closer than 180 mm (data not presented) it was difficult to distinguish the attenuation of lowest sediment concentrations from that of clear water.

Figure 9 shows signal level relative to clear water for various kaolinite, bentonite, and silt concentrations at 180 mm. The tested concentration range was 1.4 – 14.1 g/L for kaolinite, 1.7 – 13.4 g/L for bentonite, and 1.5 – 5.5 g/L for silt. The signal level loss due to water attenuation (approximately 8dBV) has been subtracted from this data to show the effect of increasing particle concentration. As indicated in the plot, an increase in suspended sediment concentration resulted in a corresponding decrease in signal level. An increase in particle size diameter (i.e. silt particles are larger than kaolinite particles, which are larger than bentonite particles) also resulted in a decrease in signal level. The 20 MHz acoustic system was able to measure signal loss over the entire range of concentrations considered at the 180 mm range.

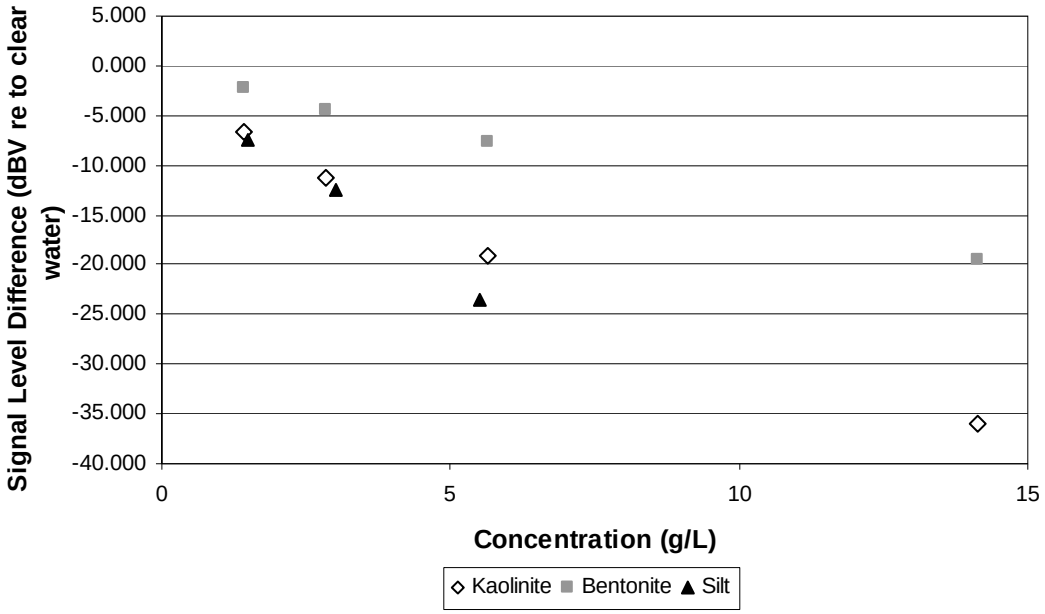

Figure 9 Signal level (dBV) for kaolinite, bentonite, and silt concentrations at a distance of 180 mm signal level of clear water subtracted from measurements.

Additional measurements to assess the low concentration measurement limits of the setup were performed at 180 mm for kaolinite and bentonite concentrations (0.01 – 0.7 g/L) and silt concentrations (0.006 – 0.7 g/L). Note kaolinite and bentonite concentrations at 0.006 g/L were undetected.

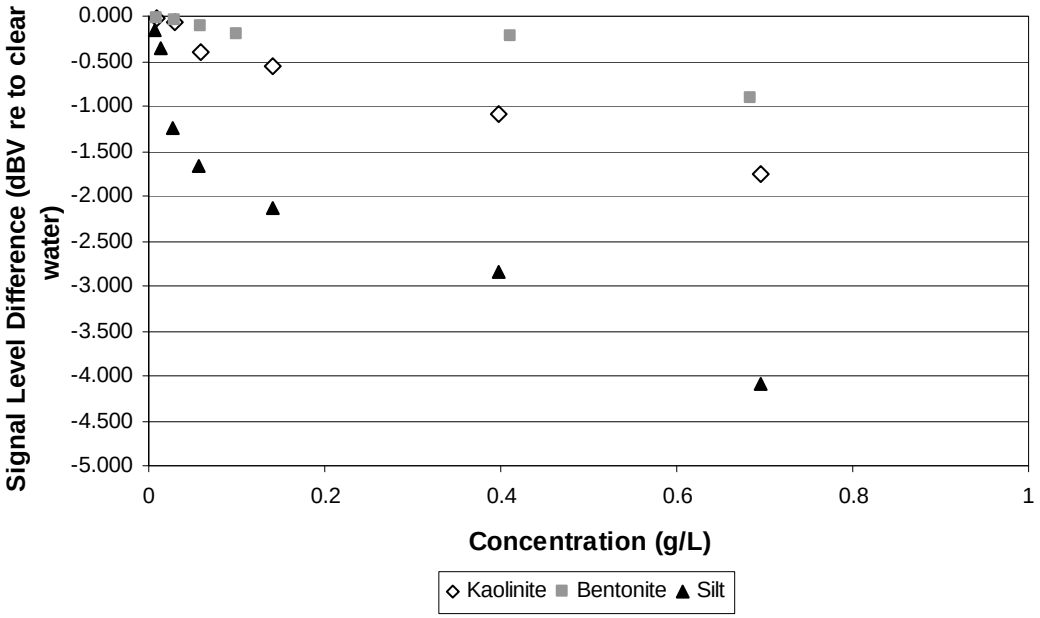

Figure 10 Signal level (dBV) for kaolinite, bentonite, and silt concentrations at a distance of 180 mm signal level of clear water subtracted from measurements.

It is evident from Figures 9 and 10 that similar concentrations of different fine materials can cause different levels of signal attenuation. This will present similar challenges to the measurement of sand sized particles with respect to the effect of particle size on the accuracy of concentration measurement. It may be possible to make educated assumptions to narrow down the range of possible particle sizes, or to use a combination of attenuation/backscatter to constrain the problem. These issues will be explored more fully in future work; however, the work reported here establishes an important baseline that will be used in the design of new experiments and instrumentation.

CONCLUSION

The feasibility of measuring particle concentration using the attenuation of high frequency acoustic waves traversing a suspension of fine particles in water was investigated in a series of laboratory experiments. The data showed that as concentration increased, attenuation increased and signal level decreased over a distance and using a frequency that are physically reasonable for field measurements. The use of a 20 MHz pitch/catch transducer arrangement to measure the concentration of 5 micron particles, or smaller, suspended in water appears to be practical at a range of distances from 180 mm to 357 mm. In the 180 – 357 mm range, the tested concentration range was 1.4 – 13.6 g/L for kaolinite, 1.7 – 13.4 g/L for bentonite, and 1.5 – 5.5 g/L for silt. Near field measurements in the 28 – 180 mm range had a tested concentration range of 13.6 – 23.3 g/L for kaolinite, 13.4 – 23.6 g/L for bentonite, and 5.5 – 24.4 g/L for silt. At the 180 mm range, the pitch-catch configuration was capable of detecting concentration ranges of 0.01 – 13.6 g/L for kaolinite, 0.01 – 13.4 g/L for bentonite, and 0.006 – 5.5 g/L for silt. This work suggests that fixed distance measurements of approximately 180 mm can be used to evaluate the broad range of concentrations expected in the field.

REFERENCES

Eisma, D. (1993). Suspended Matter in the Aquatic Environments. Springer-Verlag, Berlin.

Green, D. H., and Esquivel-Sirvent, R. (1999). "Acoustic behavior at the fluid/solid transition of kaolinite suspensions," Journal of Geophysics, 64(1), p 89.

Greenwood, M. S., Mai, J. L., and Good, M. S. (1993). "Attenuation measurements of ultrasound in a kaolin-water slurry: A linear dependence upon frequency," Journal of Acoustical Society of America, 94(2), pp 908–916.

Hay, A. E. (1991). "Sound scattering from a particle-laden, turbulent jet," Journal of Acoustical Society of America, 90(4), pp 2055–2074.

Holeman, J. N. (1968). "The sediment yield of major rivers of the world," Water Resources Research, 4, pp 737–747.

Kinsler, L. E., Frey, A. R., Coppens, A. B., and Saunders, J. V. (1982). Fundamentals of Acoustics, 3rd ed. Wiley, New York, p 161.

Kowallis, B., Jones, L. E. A., and Wang, H. F. (1984). "Velocity-porosity-clay content: Systematics of poorly consolidated sandstones," Journal of Geophysics, 89, pp 10355–10364.

Kuhnle, R. A., Bennett, S. J., Alonso, C. V., Bingner, R. L., and Langendoen, E. (2000). "Sediment transport processes in agricultural watersheds," International Journal of Sediment Research, 15, pp 182–197.

Kuhnle, R. A., Wren, D. G., and Chambers, J. P. (2007). "Prediction of the grain size of suspended sediment: Implications for calculating suspended sediment concentrations using single frequency acoustic backscatter," International Journal of Sediment Research, 22, pp 1–15.

Lane, E. W. (1940). "Notes on limit of sediment concentration," Journal of Sediment Petrology, 10, pp 95–96.

Marion, D., Nur, A., Yin, H., and Han, D. (1992). "Compressional velocity and porosity in sand-clay mixtures," Journal of Geophysics, 57, pp 554–563.

Nelson, M. E., and Benedict, P. C. (1950). "Measurement and analysis of suspended loads in streams," Transactions of the American Society of Civil Engineers, Proceedings, No. 31, Paper No. 2450, pp 891–918.

Schulkin, M., and Marsh, H. W. (1962). "Sound absorption in sea water," Journal of Acoustical Society of America, 34, pp 864 – 865.

Shen, C., and Lemmin, U. (1996). "Ultrasonic measurements of suspended sediments: A concentration profiling system with attenuation compensation," Measurement Science and Technology, **7**, pp 1191–1194.

Sheng, J. Y., and Hay, A. E. (1988). "An examination of the spherical scatterer approximation in aqueous suspensions of sand," Journal of Acoustical Society of America, 83, pp 598–610.

Staubli, T., Gruber, P., and Luescher, B. (2006). "How much silt is acceptable for the acoustic discharge measurement," Hydrographic Conference, Porto Carras, Greece, pp 1–6.

Thorne, P. D., Holdaway, G. P., and Hardcastle, P. J. (1995). "Constraining acoustic backscatter estimates of suspended sediment concentration profiles using the bed echo," Journal of Acoustical Society of America, 98(4), pp 2280–2288.

Wren, D. G., Barkdoll, B. D., Kuhnle, R. A., and Derrow, R. W. (2000). "Field techniques for suspended-sediment measurement," Journal of Hydraulic Engineering, 126, pp 97–104.

Yang, C. T., and Simoes, F. J. M., (2005). "Wash load and bed-material load transport in the Yellow River," Journal of Hydraulic Engineering, 131(5), pp 415–416.