Measurement of Suspended-Sediment Concentration and Particle Size in Laboratory Flumes

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ABSTRACT

Acoustic techniques have been used successfully to measure suspended sediments in marine environments, but more research is needed for effective acoustic measurements in fluvial environments. The high concentrations and wide size distributions of suspended-sediment in fluvial systems present difficult challenges. Multi-frequency particle sizing is necessary before a reliable instrument with no particle size bias can be fielded. Experiments have been under way with the goal of improved hardware and software for acoustic sediment measurement and particle sizing. Time series of backscatter data 1.8 hours long were collected from a fixed position. Cross-sectional suspended-sediment concentration variation was measured acoustically by repeatedly traversing a transducer across a laboratory flume, producing cross-sectional data at discrete time intervals. Multi-frequency acoustic techniques were used to size suspended-sand particles in a specialized jet tank.

INTRODUCTION

The results of corrective actions on fluvial systems, assessment of soil erosion losses, and reservoir sedimentation can all be determined using suspended sediment data (Vanoni, 1975; Edwards and Glysson, 1999). The highly variable nature of suspended-sediment concentration makes accurate measurements difficult to obtain (Lapointe, 1992, 1993, and 1996; Hay and Bowen, 1994; Kostachuk and Villard, 1996; Thorne et al., 1996). The use of automated methods for the measurement of suspended-sediment is necessitated by the difficulty of obtaining data during the storm events that produce much of the sediment movement in most streams and rivers. Danger to field personnel and high costs make manual data collection during these events problematic. Acoustic backscatter techniques, due to their non-intrusive nature and comparatively low cost, may prove to be a viable alternative to manually collected samples of the water/sediment mixture.

The use of acoustics to measure suspended-sediment concentrations has been under investigation at least as early as the early 1980's, with most of the work focused on marine environments (Young et al., 1982; Hay, 1983; Hess and Bedford, 1985; and Lynch 1985). The simplest form of measurement, using a single acoustic frequency, requires a known sediment concentration at some range from the transducer (Lee and Hanes, 1995 and Thorne and Taylor, 2000). Multi-frequency particle sizing techniques are more complicated but have the potential to be valuable tools (He and Hay, 1993; Crawford and Hay, 1993; and Hay 1991).

The main goal of this work is an independent, multiple-frequency acoustic system and associated processing algorithms to take continuous acoustic measurements at field sites and convert the measurements into suspended-sediment concentration data.

METHODS AND EQUIPMENT

Experimental data was collected in the 30 meter flume at the USDA-ARS-National Sedimentation Laboratory and in a jet tank at the National Center for Physical Acoustics (NCPA). Two different acoustic data collection systems were used to collect the data: (1) a proprietary system owned by the National Sedimentation Laboratory called the Bed And Sediment Imaging System (BASIS) and (2) a system made up of off-the-shelf components from the NCPA. Three different types of experiments are reported here: (1) longitudinal time series of bed topography and suspended-sediment concentration with pumped reference samples collected at one range from the acoustic transducer, (2) cross-sectional traverses of bed topography and suspended-sediment concentration and (3) multi-frequency particle sizing. The following sections detail the flume specifications, hydraulic parameters, and equipment used in the experiments.

Flume and jet tank

The flume, located at the USDA-ARS-National Sedimentation Laboratory in Oxford, Mississippi, has a channel that is 30 m long, 1.2 m wide, 0.6 m deep and has an adjustable longitudinal slope. Flow rate in the flume was measured using a pressure transducer connected to a Venturi meter in the return pipe. All sediment and water were recirculated. The jet tank (Figures 1 and 2) was built for the purpose of collecting acoustic backscatter data. The tank is made of clear polycarbonate to aid in observing experiments and is equipped with a pump that recirculates the water/sediment mixture in an arrangement similar to that of Hay (1991). The speed of the pump can be varied to obtain optimal jet conditions. Rails on the top of the tank allow for precise alignment of transducers, samplers, etc.

Figure 1. Jet tank plan view.

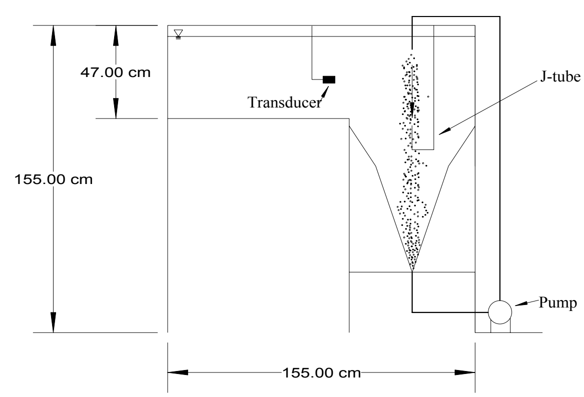

Figure 2. Jet tank diagram.

Hydraulic parameters

The mean flow velocity in the 30 meter flume was approximately 0.53 m/s, with a mean depth of 0.13 meters, a Froude number of 0.53, and a water surface slope of 0.003. The sediment used in the experiments had a median size of 0.52 mm and a standard deviation of 1.54 mm. These parameters resulted in a dune bed configuration. The suspended-sediment samples and acoustic backscatter data were collected 23.8 m downstream of the channel inlet tank.

Pump sampling
Except for the traversing experiment, ground truth sediment concentration data was collected with an isokinetic pump sampler. Samples were collected approximately 0.04 m downstream of the acoustic probes using an L-shaped 4.8 mm inside diameter bronze tube connected to a vacuum pump. Concentrations were determined by weighing each fluid-sediment sample, decanting the sample, and washing the sediment into pre-tared pans that were oven dried. The pans were weighed to obtain the dry weight of sediment in each sample. This type of sample will be referred to as a pump sample throughout the text.

Acoustic Equipment
BASIS system. The BASIS is a proprietary unit owned by the National Sedimentation Laboratory. It is a 2-channel, computer-controlled, high-resolution pulse/echo system that records bottom echo and sediment backscatter information. All of this information is collected in near real-time and can be stored to disk for later retrieval and analysis. Two 2.5 cm, 1 MHz transducers were used. The BASIS collects 30 profiles per second for each of its two channels (Derrow, 2001).

NCPA system. The NCPA system consists of off-the-shelf components. A PCI based oscilloscope controlled with custom-written software is used to collect the data. Transducer excitation is supplied by a PCI based arbitrary function generator whose signal was amplified to approximately 300 Vpp by a high voltage gated amplifier. One broadband transducer with a center frequency of 2.25 MHz was used. In order to produce 3 frequencies, a composite waveform made up of 1.4, 2.25, and 2.8 MHz was generated by the arbitrary function generator. Figures 3 and 4 show a tank wall echo of the composite waveform and its spectral content.

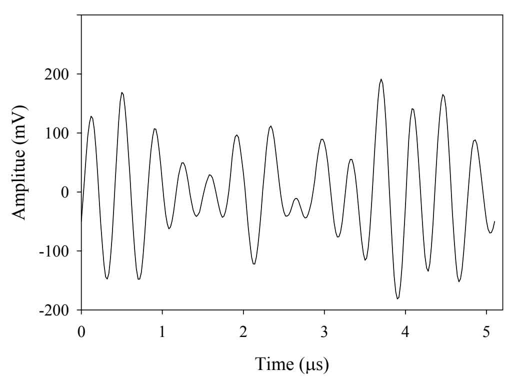

Figure 3. Tank wall echo return from composite waveform.

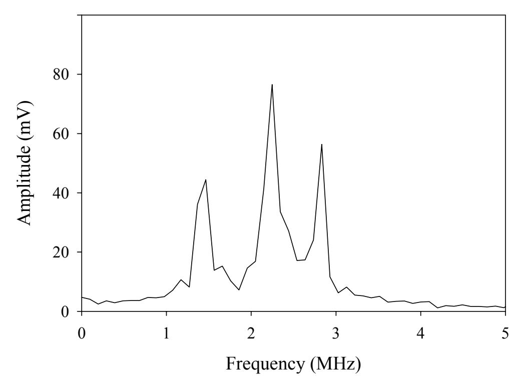

Figure 4. Spectral content of multifrequency waveform.

Longitudinal time series
The BASIS system was used to collect continuous records of dune topography and suspended-sediment backscatter for approximately 1.8 hours per run with pump samples collected every two minutes. The conversion of backscatter voltage values to suspended-sediment concentration was aided by using pumped sediment/water samples to measure the concentration at a given range from the transducer at various time intervals.

Traversing experiments
The BASIS was used to collect backscatter signal amplitudes and bottom surface profile data in two cross-sections of the flume (Figure 5). Backscatter data were converted to suspended-sediment concentration using concentration to voltage conversions established with data from the longitudinal time series work. Each traverse of the flume took about 13.6 seconds, for a speed of 8.8 cm/s. During this time, for an average range to the bottom of 0.13 meters, the round-trip time for sound was 0.17 milliseconds and the transducer moved about 15 µm. There are 412 vertical profiles in each traverse and 52 traverses (for both channels) were collected. Both the length of the experiment and the speed of the traverses were limited by the screw-type linear actuator. Even at relatively low speeds, it got very hot and began to emit a high pitched squeal, forcing an end to the experiment. For additional work of this type, a belt-driven linear actuator designed for high speed traverses will be required.

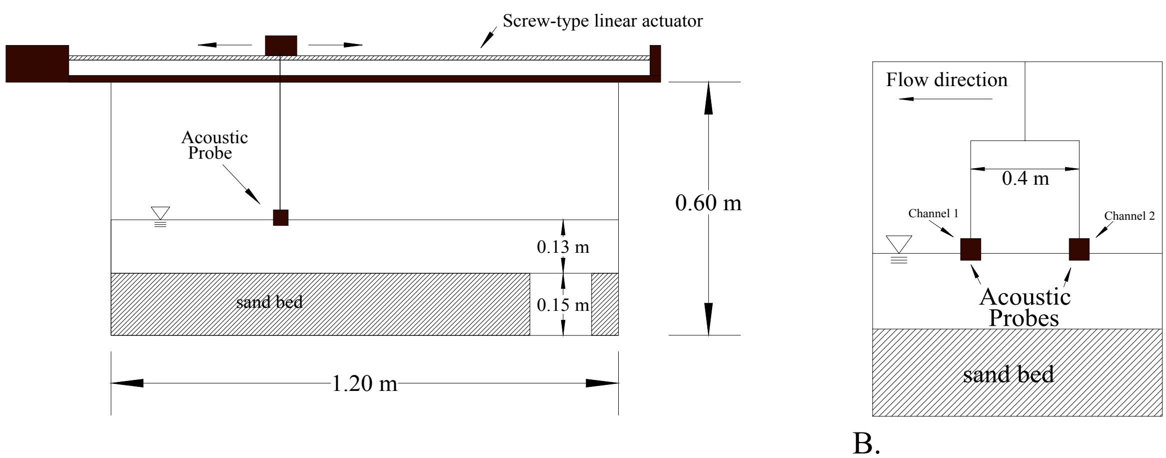

Figure 5. 30 meter flume with traversing apparatus. (A)Cross-section (B) Side view.

Particle Sizing
Due to space limitations, only a very superficial description of the particle sizing method will be included here. The jet tank shown in Figures 1 and 2 was used to create a steady-state concentration of suspended sediment in a vertical jet. The multifrequency signal was propagated across the sediment jet and backscattered signal data was collected. Using this arrangement, particle sizes with D_{50}=165 µm-780 µm corresponding to standard U.S. Sieve size designations and concentrations ranging from 0.01-5.4 g/L were tested. Particle sizes were estimated by combining the backscatter information from the three different frequencies (He and Hay 1993; Crawford and Hay 1993). Particle size distributions were generally limited to the width of sieve size intervals. However, two natural sand distributions with D_{50}'s around 0.5 mm were also used.

RESULTS

Longitudinal time series
A simple regression equation was found to provide a good fit to the backscatter versus concentration data (Figure 6). Backscatter voltages were converted to concentration values and then mapped (Figure 7). Since pump samples were only collected at one range, vertical error analysis was not possible in this experiment. Even assuming a large error in absolute concentration, the spatial variability information is still of value.

Error for one range at different times was found by averaging the backscatter returned from the range of the sampler nozzle during the pumping period of each physical sample. The following equation was used: %Error=|100*(measured-predicted)/measured|, resulting in an error of 36% for run 21, 28% for run 25, 20% for run 29, and 51% for run 33. Runs refer to data collected in different sampling sessions. Some of the error in the experiment is due to the fact that, in this experiment, no particle size data was available.

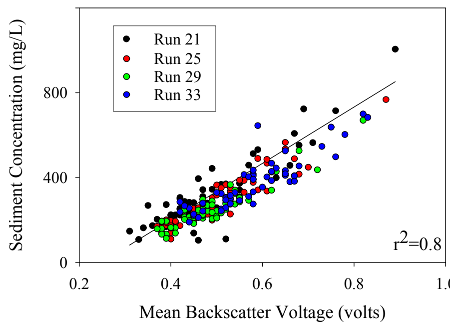

Figure 6. Regression plot for longitudinal time series. Runs represent data taken on different days.

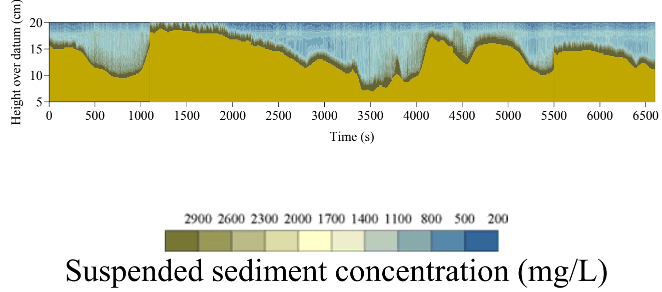

Figure 7. Selected contour graph from longitudinal time series data.

Traversing experiment

Figure 8 shows cross-sectional maps of suspended-sediment concentration collected at the times noted above each plot. Plots at equal times for Channels 1 and 2 were collected simultaneously and channel 2 was 40 cm upstream of channel 1. Comparing plots allows examination of temporal and spatial changes in concentration. Visually comparing frames collected simultaneously reveals little or no correlation in concentration or bed topography over the 40 cm longitudinal separation between the transducers. Series such as these have also been combined to create short animations of the suspended sediment in the cross section. This data is valuable in visualizing suspended-sediment behavior and in cross-sectional flux calculations. The use of this data in flux calculations is a possible future use.

Particle Sizing

Acoustic particle sizing over a broad range of sediment sizes is a difficult task and is currently under active development. The material presented here represents current progress that will likely be improved in the future. The results of the particle size measurement work can be seen in Figure 9. The sizing process works reasonably well over much of the size range, and less well with the broader size classes, which show more scatter in the size estimate. It is possible that this is due to particle sorting in the jet. It is expected that this will be less of a problem in the field since the entire range of particle sizes in bottom sediments is unlikely to be suspended in large amounts. Experiments to test this assumption and the overall performance of the technique are planned first in a standard horizontal laboratory flume, and then in a field deployment along with several other sensors. The concentration error, using these estimated sizes, is shown in Figure 10. For most particle sizes, the concentration is estimated with a good degree of accuracy, although the estimates are generally low.

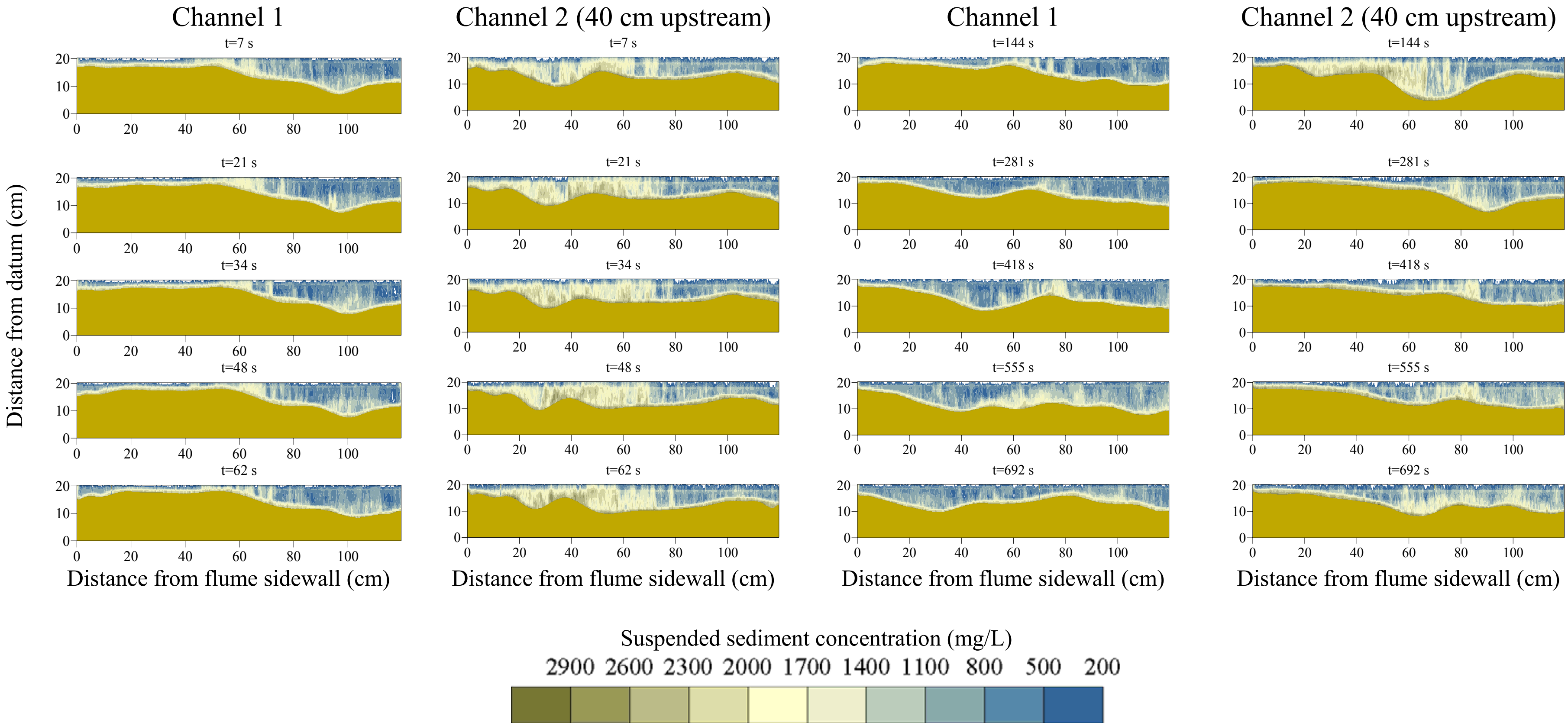

Figure 8. Traverse concentration data collected simultaneously in two positions at selected times. Flow direction is out of the page. Channel 2 data was collected 40 cm upstream of channel 1.

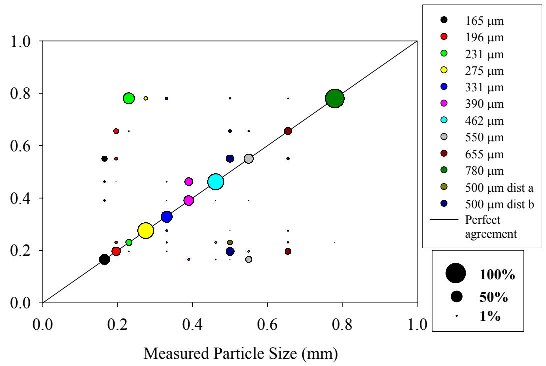

Figure 9. Multi-frequency particle size measurement accuracy.

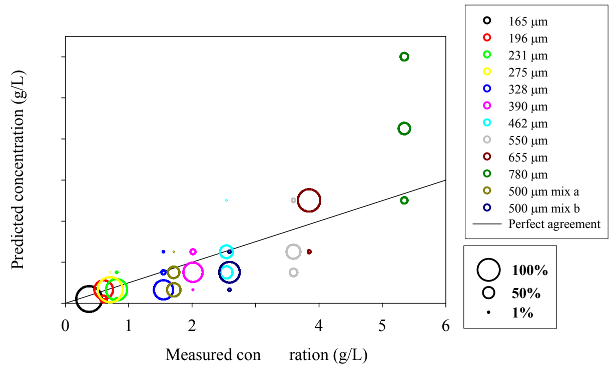

Figure 10. Multifrequency concentration measurement.

CONCLUSIONS

A simple linear regression method was used to convert acoustic backscatter data to suspended-sediment concentration values. This technique works fairly well for calculating sediment concentration at the same range as a pump sample, but caution is advised in using the regression approach at other ranges. It was found that the distance from the transducer at which the pumped reference sample is collected plays a major role in the accuracy of the backscatter voltage/concentration value relationship. However, this simple conversion process yields data on concentration variability that is useful for visualization of sediment movement. The use of a motor-driven carriage allowed for the creation of contour maps of the flume cross section that can be combined to form animations of sediment movement and eventually to calculate flux through a flume cross section. Visual inspection of such records collected simultaneously with a streamwise separation of 40 cm showed little correlation. Early work on multi-frequency particle sizing over a broad range of particle sizes and concentrations shows promise. More work will have to be done to improve accuracy, particularly with wide particle size distributions.

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