# HIGH-RESOLUTION MEASUREMENTS OF SUSPENDED-SEDIMENT CONCENTRATION AND GRAIN SIZE IN THE COLORADO RIVER IN GRAND CANYON USING A MULTI-FREQUENCY ACOUSTIC SYSTEM

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**Abstract**

Computation of accurate sediment loads in rivers where the transport of suspended sediment is at least partially regulated by changes in the upstream sediment supply requires high-resolution measurements of suspended-sediment concentration that are collected independently of water-discharge data. To meet this objective, a multi-frequency acoustic system has been developed and tested on the Colorado River in Grand Canyon, Arizona, USA. This system consists of an array of three single-frequency sideways-looking acoustic-Doppler profilers. Acoustic attenuation is used to measure suspended-silt and clay concentration, and the acoustic backscatter in each frequency is used to measure the concentration of suspended sand in a discrete grain-size range. The median grain size of the suspended sand is then calculated by logarithmic interpolation between the acoustically computed concentrations in each grain-size range. This approach to measuring sediment loads has been shown to be as or more accurate than using conventional sampling methods alone.

**Keywords:** acoustic backscatter, acoustic attenuation, suspended sediment, grain size.

## INTRODUCTION

The grain-size distribution of suspended sediment in the regulated Colorado River below Glen Canyon Dam is broad and typically bimodal, with a silt and clay mode (dominated by clay-sized particles) and a sand mode (dominated by 0.10-0.13 mm particles). Transport of both modes is limited by episodic resupply from tributaries. Transport of the sand mode is regulated by both the discharge of water and short-term changes in the grain size of sand available for transport. Changes in sand grain size caused by changes in the upstream supply can result in several orders of magnitude change in suspended-sand concentration within hours, with little to no corresponding change in water discharge. This prohibits the computation of sand-transport rates using stable relations between water discharge and sand transport, and therefore requires a continuous method for measuring sediment transport. A multi-frequency acoustic system for measuring the concentration and grain size of suspended sediment every 15 minutes has therefore been designed to monitor sediment transport in the Colorado River in Grand Canyon. This investigation was conducted at the Colorado River near Grand Canyon, Arizona, gaging station (U.S.

Geological Survey station 09402500) located 166 km downstream from Glen Canyon Dam in Grand Canyon National Park, Arizona, USA (Figure 1).

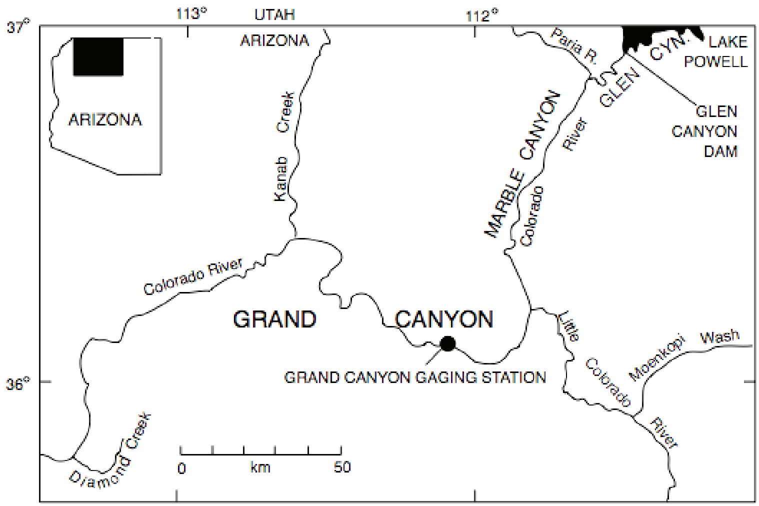



**Figure 1.** Map of the study area showing the location of the Colorado River near Grand Canyon, Arizona gaging station, hereafter referred to simply as the Grand Canyon gaging station.

## PURPOSE AND SCOPE

The purpose of the paper is to describe the development and testing of a three-frequency array of sideways-looking acoustic-Doppler profilers for use in measuring the concentration of suspended-silt and clay, and the concentration and median grain size of suspended sand.

## BACKGROUND

Theory and measurements of underwater acoustics indicate that, at a given frequency of sound, broad grain-size distributions of suspended sediment can be segregated into two acoustic size classes: (1) a finer acoustic size class in which increasing concentration (or decreasing grain size at a constant concentration) results mainly in increased attenuation of sound due to viscous losses (Urick, 1948; Flammer, 1962; Lohrmann, 2001; Gartner, 2004; Topping et al., 2004, 2006; Wall et al., 2006), and (2) a coarser acoustic size class in which increasing concentration (or increasing grain size at a constant concentration) results mainly in increased backscatter of sound (Thorne and Campbell, 1992; Thorne et al., 1993; Lohrmann, 2001; Thorne and Hanes, 2002; Gartner, 2004; Topping et al., 2004, 2006; Wall et al., 2006). For a given frequency of sound, the finer acoustic size class comprises the grain-size range occupying the viscous loss region in the sediment attenuation coefficient curves of Flammer (1962) and the coarser acoustic size class comprises the grain-size range occupying the left half of the scattering loss region (Figure 2a).

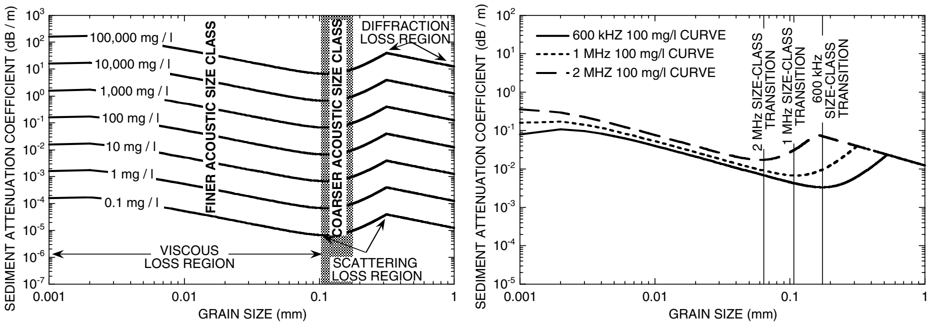



**Figure 2.** Sediment attenuation coefficient curves after Flammer (1962). **(a)** Curves calculated for a frequency of 1 MHz and a water temperature of 10° C over the sediment concentration range from 0.1 mg/l to 100,000 mg/l. The viscous, scattering, and diffraction loss regions are indicated. The transition between the two acoustic size classes occurs at the transition between the viscous and scattering loss regions; coarser acoustic size class indicated by gray shading. **(b)** Curves calculated at sediment concentration of 100 mg/l and a water temperature of 10° C for frequencies of 600 kHz, 1 MHz, and 2 MHz. The transitions between the two acoustic size classes are indicated for the three frequencies of sound (~0.0625 mm at 2 MHz, ~0.105 mm at 1 MHz, and ~0.177 mm at 600 kHz).

Within the scattering loss region, most of the scattering is propagated backward when the sound wavelength is much greater than $\pi D$, where $D$ is the grain size (Flammer, 1962). At each frequency of sound, the maximum grain size comprising our defined coarser acoustic size class is about 40% of this limit. Therefore, most of the scattering resulting from particles in the coarser acoustic size class is backscattering. The threshold grain-size between the two acoustic size classes of sediment occurs at the minima in the sediment attenuation curves and is negatively correlated with the frequency of sound (Figure 2b). Thus, at progressively lower frequencies of sound, progressively coarser sizes of sediment contribute to the attenuation of acoustic energy owing to viscous losses. Similarly, progressively lower frequencies of sound will return proportionately more backscatter from coarser sediment than from finer sediment.

For a wide range of conditions, increases in the acoustic attenuation due to sediment are related linearly to increases in the concentration of the finer acoustic size class, whereas increases in backscatter are related nonlinearly to increases in the concentration of the coarser acoustic size class. Our experiments in the Colorado River, however, indicate that increases in the concentration of the finer acoustic size class also contribute to small increases in acoustic backscatter when: (1) concentrations of the finer acoustic size class are large, and (2) the proportion of the finer acoustic size class relative to the coarser acoustic size class is large.

## INSTRUMENTS TESTED AT THE GRAND CANYON GAGING STATION

The principal instrument test site for this study is the left-bank gage at the Grand Canyon gaging station (Figures 1 and 3a). At this test site, the three-frequency sideways-looking acoustic-Doppler profiler array is mounted on a cart attached to a vertical H-beam bracket anchored to a vertical concrete wall at the base of the gaging station stilling well (Figure 3a). The cart is stationary at the base of the bracket during periods of data collection, and is raised to the surface (Figure 3b) to perform maintenance. The three acoustic-Doppler profilers mounted on this cart are a 1 MHz Nortek EZQ, 2 MHz Nortek EZQ, and a 600 kHz Nortek Aquadopp (Note, that use of trade, product, and firm names is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey). These instruments were initially set to sample 13 out of every 15 minutes to conserve power; they are now set to sample 4 out of every 15 minutes.

a)



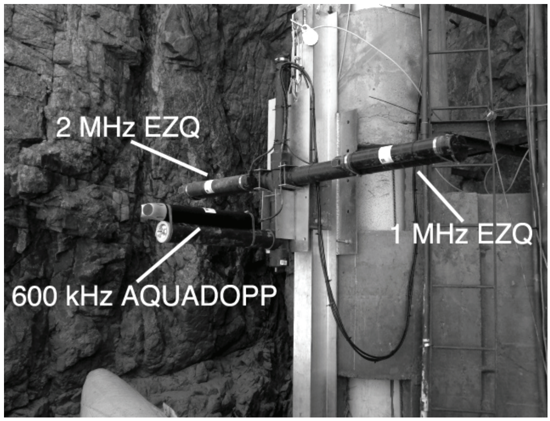
b)



**Figure 3. (a)** Locations of instrument deployments at the Grand Canyon gaging station. **(b)** Three-frequency acoustic-Doppler profiler array on cart (out of water).

In addition to the acoustic-Dopper profilers, other instrumentation at this test site include: a Sequoia Scientific LISST (Laser In-Situ Scattering and Transmissometry)-100 type C laser-diffraction instrument, a Sequoia Scientific LISST-25X type C laser-diffraction instrument, and an ISCO 6712 automatic pump sampler. Tests of these other instruments have been previously described by Melis et al. (2003) and Topping et al. (2004, 2006). Communication between the office and the instruments at this site occurs over the internet via a two-way-broadband satellite system installed at the site.

## DATA USED FOR INSTRUMENT CALIBRATION

Acoustic measurements of suspended-sand concentration were calibrated to the corresponding velocity-weighted cross-sectionally averaged values measured at a cableway (200 m downstream of the gage pictured in Figure 3a with either a D-96-A1 or D-96 depth-integrating sampler (Davis, 2001; Federal Interagency Sedimentation Project, 2003) deployed using the Equal-Discharge-Increment (EDI) method (described in Edwards and Glysson, 1999). Prior to April 2003, the principal sampler used at this site was a D-77 bag sampler (Szalona, 1982); tests have shown that the D-77 bag sampler and D-96 samplers collect comparable data at this site. The 1 MHz EZQ data were calibrated using 345 EDI measurements made between February 12, 2003, and September 19, 2005, the 2 MHz EZQ data were calibrated using 74 EDI measurements made between September 30, 2004, and September 19, 2005, and the 600 kHz Aquadopp data were calibrated using 65 EDI measurements made between September 19, 2004, and September 19, 2005. Acoustic measurements of suspended-silt and clay concentration were calibrated using both the EDI measurements and additional measurements made using the ISCO automatic pump sampler (triggered by the LISST-100 to sample at higher concentrations of silt and clay). This allowed many more measurements of silt and clay concentration to be included in the calibrations. Silt and clay concentrations measured using the pump sampler have a tight 1:1 relation with the EDI-measured silt and clay concentrations at the site; thus, little additional error was introduced by using the pump measurements.

Analysis of the errors associated with use of depth-integrating samplers deployed using the EDI method at this site (analysis conducted using a combination of P-61 point-integrating samplers, D-77 and D-96-A1 depth-integrating samplers, and the P-61 sampler operated in the depth-integrating mode) indicates that the mean EDI error in suspended-silt and clay concentration is ±10%, the mean EDI error in suspended-sand concentration is ±22%, and the mean EDI error in suspended-sand median grain size is ±12%. The EDI error in suspended-silt and clay concentration is random, whereas the EDI errors in suspended-sand concentration and median grain size are a combination of mostly random errors and some systematic biases. The random errors arise because depth-integrating samplers do not collect time-averaged data, and the systematic biases arise from inadequate sampling of the spatial structure in the sediment flux through the cross-section and/or bed contamination of the suspended-sediment sample.

**MULTI-FREQUENCY APPROACH**

This approach to using multi-frequency acoustics to measure suspended-silt and clay concentration, and suspended-sand concentration and grain size is a four-step approach in which the following operations are conducted for each of three frequencies. The first two of these operations are conducted using a form of the sonar equation of Urick (1975):

$$B = 0.43A + 20\log(R) + 2\alpha_w R + 2\alpha_s R\,, \qquad (1)$$

where $B$ is the range-normalized backscatter, dB; $A$ is the amplitude of the signal strength, in counts; $R$ is the distance, m along the beam, $\alpha_w$ is the water absorption coefficient, dB/m; and $\alpha_s$ is the sediment attenuation coefficient, dB/m.

In the first step, the two-way transmission losses associated with beam spreading (the second term in equation 1) and $\alpha_w$ are removed (Figure 4a). $\alpha_w$ in a river (where salinity and depths are typically small) varies mainly as a function of water temperature (Schulkin and Marsh, 1962; Urick, 1975). Then, in the second step, we solve for $\alpha_s$ using linear regression (Figure 4b) resulting in $B$ being essentially constant along each beam (Figure 4c). From theory (Urick, 1948; Flammer, 1962), $\alpha_s$ is related linearly to the concentration, $C_F$, of sediment in the finer acoustic size class, which at 2MHz is sediment less than about 0.0625 mm, at 1 MHz is sediment less than about 0.105 mm, and at 600 kHz is sediment less than about 0.177 mm. Because $\alpha_s$ is dominated by the attenuation arising from the finest particles (e.g., the attenuation coefficient for clay $\alpha$-sized particles is an order of magnitude larger than that for coarse-silt-sized particles, Figure 2), for simplicity, we equate the finer acoustic size class with silt and clay (Figure 5).

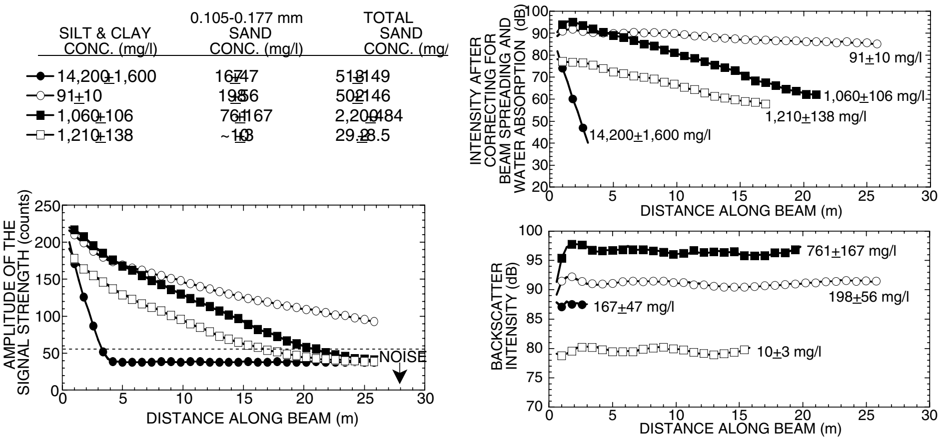



**Figure 4.** Example of first two steps in approach.

Data are from the 1 MHz EZQ at four different sediment-concentration and grain-size conditions. First two cases are from very different concentrations of the finer acoustic size class (silt and clay), but comparable concentrations of the coarser acoustic size class (0.105-0.177 mm sand). Second two cases are from comparable concentrations of the finer acoustic size class, but very different concentrations of the coarser acoustic size class. **(a)** Raw data (in counts); noise level is at about 55 counts. **(b)** Data (in dB) after correcting for spherical beam-spreading losses and water absorption; data below noise level have been removed. Note that changes in the concentration of the finer acoustic size class mainly affect the slopes of the profiles, whereas changes in the concentration of the coarser acoustic size class mainly shifts the profiles up and down. For each case, $\alpha_s$ is now determined by linear regression to be 1/2 of the profile slope. **(c)** Backscatter intensity, *B*, in dB, after correcting the data in (b) for sediment attenuation. Note that, for each case, *B* is constant along the beam and is proportional to concentration of the coarser acoustic size class (indicated in the graph)

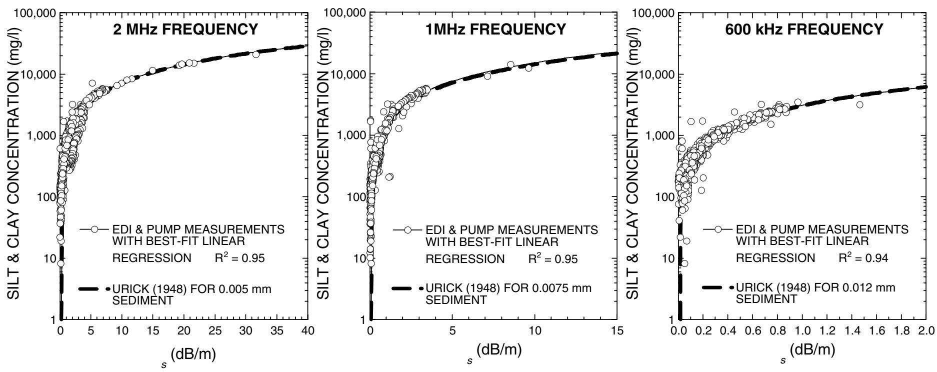



**Figure 5.** Linear relations between $\alpha_s$ and suspended-silt and clay concentration at sound frequencies of **(a)** 2 MHz, **(b)** 1 MHz, and **(c)** 600 kHz

Also shown for each frequency is the Urick (1948) theoretical relation for the computed grain size that gives best agreement with the empirical best-fit linear regression. As expected, these grain sizes are inversely related to the sound frequency. These computed grain sizes agree well with the known grain sizes that dominate the suspended-silt and clay in the Colorado River. Based on 40,213 in-situ LISST-100 measurements at the Grand Canyon gaging station and additional laboratory analyses, the average median grain size of the silt and clay is 0.012 mm, and the average mode of the silt and clay is 0.0014 mm.

In the third step, we compute relations between $B$ in each cell and the EDI-measured concentration of sand in a discrete size range (i.e., the coarser acoustic size class corresponding to a given frequency). At low concentrations of the coarser acoustic size class (<100 mg/l), concentration is related to backscattered sound pressure (in Pa) increased to the second power (Thorne and Campbell, 1992; Thorne et al., 1993), or backscattered sound intensity (in dB) increased to the fourth power. At higher concentrations of this second acoustic size class, however, substantial deviation from the power of two relations between backscattered sound pressure and sand concentration occurs. For example, power-law curves fit to the theoretically derived relations in Thorne and Campbell (1992, Figure 8) have exponents >10. For each frequency, the best form of the relation between the concentration (over the widest range) of the coarser acoustic size class and $B$ is the log-transformed relation based on the equation for sound scattering from small particles (Gartner, 2004):

$$\log(C_C) = k + mB\,, \qquad (2)$$

where $C_C$ is the EDI-measured concentration of the coarser acoustic size class and $k$ and $m$ are regression-determined constants; $k$ varies between different instruments and grain-size ranges, whereas $m$ is approximately constant at 0.1 (Figure 6).

The grain-size ranges used for the coarser acoustic size class in these relations are: 0.0625-0.105 mm at 2 MHz, 0.105-0.177 mm at 1 MHz, and >0.177 mm at 600 kHz. Scatter about these relations is due to: (1) the ~22% EDI-measurement error in suspended-sand concentration and (2) the effect of higher concentrations of silt and clay contributing to some additional backscatter.

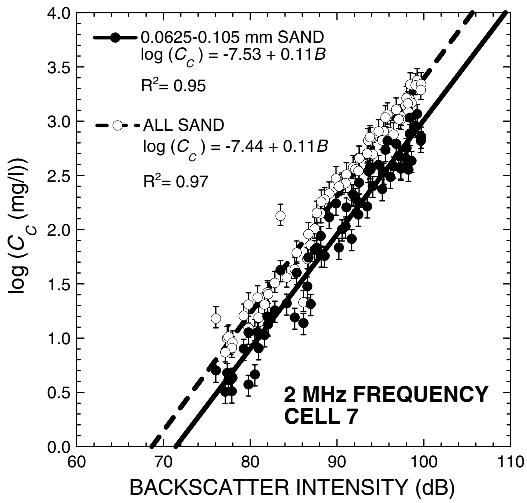



**Figure 6.** Example of a typical relation between $B$ and the EDI-measured concentration of the coarser acoustic size class, $C_C$. This example relation is between $B$ measured at a frequency of 2 MHz in cell 7 (1.6 m from the instrument). Shown are the relations with the coarser acoustic size class set equal to 0.0625-0.105 mm sand and total (i.e., 0.0625-2.0 mm) sand. Error bars indicate the ~22% EDI-measurement error in suspended-sand concentration.

At any given sand concentration, there is a tendency for higher backscatter intensities to correspond to higher silt and clay concentrations. Therefore, in the fourth step, a correction is applied to remove this effect. This correction is most important at silt and clay concentrations in excess of 100-200 mg/l and when silt and clay comprises most of the suspended sediment. When sand concentrations are higher than about 800-1000 mg/l, this correction does not need to be applied. The form of this empirical correction is:

$$S = a + b\log\left(C_F / C_C\right) + c\left(\log\left(C_F / C_C\right)\right)^2 , \tag{3}$$

where $S$ is the correction in dB that needs to be applied to the backscatter intensity in each cell, and $a$, $b$, and $c$ are regression-determined constants. The concentration of suspended sand in each grain-size range is then computed by averaging among all cells the recomputed $C_C$ based on the corrected values of $B$. The total suspended-sand concentration is then computed by summing the computed concentrations of sand in each grain-size range and the median grain size of the suspended sand is computed by logarithmic interpolation between the acoustically computed concentrations in each grain-size range. Examples of the application of this approach beyond the calibration time period are shown in Figure 7.

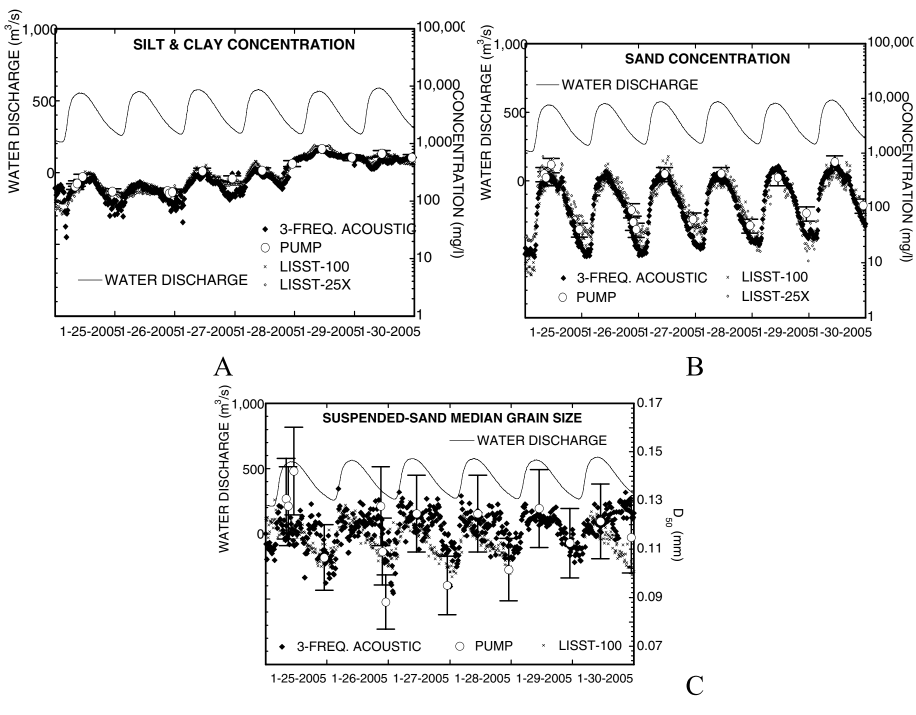



**Figure 7.** Comparisons from beyond the period of calibration of the three-frequency acoustic, calibrated pump (with error bars), LISST-100, and LISST-25X measurements of **(A)** suspended-silt and clay concentration, **(B)** suspended-sand concentration, and **(C)** suspended-sand median grain size ($D_{50}$). No EDI measurements were made from the cableway during this 6-day period.

## CONCLUSIONS

An approach that relates acoustic attenuation to the concentration of suspended silt and clay, and acoustic backscatter to the concentration of suspended sand in discrete frequency-dependent grain-size ranges has been developed. This approach yields silt and clay concentrations over the range from less than 10 mg/l to at least 20,000 mg/l (Figure 5), and yields sand concentrations over the range from about 10 mg/l to at least 3,000 mg/l (Figure 6) that are within 5% of the values computed using conventional data. Three-frequency-acoustic measurements of the median grain size of the suspended sand are typically within 10% of the values of the median grain size measured by conventional methods. This result, in conjunction with the fact that orders of magnitude more data can be collected each day by the three-frequency acoustic-Doppler profiler array, indicates that a much more complete, and therefore more accurate record of sediment transport can be collected by multi-frequency acoustics than by conventional sampling methods alone.

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# PROCEEDINGS OF THE TENTH INTERNATIONAL SYMPOSIUM ON RIVER SEDIMENTATION

## Effects of River Sediments and Channel Processes on Social, Economic and Environmental Safety

**August 1-4, 2007, Moscow, Russia**

**Volume III**

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Main theme of the 10th International Symposium on River Sedimentation is "The Effects of River Sediments and Channel Processes on Social, Economic and Environmental Safety". More than 300 papers have been received from 145 countries. They are accepted and printed in the following volumes.

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3. Volume III. Session III "River sediment yield estimation for studying and modeling river channel processes"
4. Volume IV. Session IV "Sediment yield in river mouths"
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