Estimating Colloidal Concentration Using Acoustic Backscatter

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***Abstract*—Interest has grown for using acoustic Doppler current profilers (ADCPs) to measure suspended solids concentrations (SSC) in aqueous environments because of the ability to make simultaneous unobtrusive long-term multipoint measurements with high spatial and temporal resolutions. The acoustic backscatter intensity (ABS) measured by ADCPs is a function of the particle size distribution, concentration, and incident acoustic signal strength and thus provides the theoretical basis for measuring SSC. The applicability of using ABS from a 2400-kHz ADCP to estimate SSC in units of volume concentration over variable particle size distributions is evaluated in a controlled laboratory study. Results from this research show a log-linear relationship between ABS and volume concentrations over variable size distributions. Volume concentrations predicted from the sonar equation using measured ABS and empirically derived response coefficients compare well with the measured concentrations over the full range of concentrations and particle size distributions tested. The ABS response is shown to be linear with the theoretical Rayleigh scattering target strength, calculated from the empirical particle size distribution, and thus explains the observed linearity over a variable particle size distribution. These results indicate that ABS can be used to provide meaningful volume concentration estimates for characteristically variable colloidal suspensions.**

***Index Terms*—Acoustic backscatter, ADCP, LISST-100, suspended solids.**

I. Introduction

Many contaminant transport processes in aqueous systems may be described by particle transport mechanisms. It is documented that the most widespread pollutants affecting United States (U.S.) streams are silt and adsorbed contaminants [1], [2]. Additionally, non-aqueous phase hydrocarbons can exist as colloidal suspensions subject to aggregation and subsequent sedimentation processes [3]–[6]. Similarly, many hazardous materials including heavy metals, pesticides, and polychlorinated biphenyls (PCB) will preferentially adsorb to suspended sediments in the water column [7], [8]. The particulate nature of these contaminants opens the possibility for surrogate detection methods. For example, optical suspended sediment measurements are being used in a real-time monitoring system to track PCB transport in the Hudson River, NY [9].

Conventional suspended sediment data collection relies heavily on gravimetric analysis of water samples collected either manually or by automated devices [10]. Deficiencies in these conventional methods include high unit data cost, potential for significant risk to personnel when collecting samples in adverse conditions, and the need to interpolate data from a relatively small data set to estimate concentration values for periods lacking data [11]. Furthermore, the number of sites at which the U.S. Geological Survey (USGS) has collected daily sediment data has declined approximately 75% between 1981 and 2008 primarily due to budget limitations [1]. These statements suggest the existing monitoring networks are inadequate to provide data necessary to accurately describe sediment conditions in U.S. waterways. However, the use of an appropriate surrogate technology for suspended sediment analysis may provide data of sufficient quality at a low unit data cost allowing implementation at the required spatial and temporal resolutions. Another benefit provided by in-situ surrogate detection systems is the capability for continuous monitoring during extreme episodic events that significantly impact the ecosystem [12].

Acoustic sensors have been developed to measure both physical and chemical parameters in harsh environments with applications in industry, pollution control, and biomedicine [13]–[16]. Surrogate methods developed to measure suspended sediments using acoustic backscatter have gained recent attention [1], [17]–[19], [21]–[23]. The capability of Acoustic Doppler Current Profilers (ADCP) has been extended by combining stream flow data with ABS inferred suspended sediment concentration to estimate sediment flux [17], [23]. Further, rapid developments in ADCP technology have led to increased use by the USGS for stream flow measurements [24], [25]. These advances in stream flow and suspended solids measurement methodologies represent a significant unit data cost reduction which is necessary to develop comprehensive environmental monitoring networks such as the River and Estuary Observatory Network (REON) in the Hudson River watershed [26]–[28].

With acoustic methods, suspended solids are measured as a function of the target strength echoed and scattered back to an acoustic receiver by the suspended particles. This target strength is a function of the particle concentration, size distribution, shape, density, compressibility, rigidity, and acoustic wavelength [17]. The received echo intensity represents the

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integrated signal from all scattering particles in the volume, thus it is not possible to distinguish whether changes in echo intensity are the result of variations in particle concentration or size distribution when using a mono-frequency instrument [18], [29]. Methods have been developed that combine both optical and acoustic backscattering methods to determine suspended sediment particle size information [30]. The ability to determine mean suspended particle sizes has been demonstrated with multiple acoustic frequencies [31]. Researchers have also shown good correlations between ABS attenuation and high particle concentrations in the range of g/l [21], [29], [32]. Extending the work by previous researchers who evaluated ABS responses to suspended particle mass concentrations, this study determined the ABS response to standard clay suspensions as a function of volume concentration. Further, this study evaluated the ABS response over a variable particle size distribution. The measured particle size distribution was used to calculate the ABS intensity predicted by the Rayleigh scattering model. The model predicted ABS values were then compared to the measured ABS values to validate suspended solids volume concentration estimates based on ABS-volume concentration response curves.

II. Theory

A. Acoustical Determination

Echo Intensity (EI) is a measure of the source acoustic signal that is reflected off small particles or plankton that exist in natural waters [33]. Rayleigh scattering describes the echo intensity strength (TS_R) as a function of acoustic wavelength, particle size and concentration and is expressed mathematically as

$$TS_R = 10 Log I_0 \left(\frac{\pi^2}{\lambda^4} \left(1 + \frac{3}{2}\mu\right)^2 \sum_{p=1}^{n} \left(\frac{4}{3} \left(\frac{d_p}{2} \right)^3 \pi \right)^2 \right) \quad (1)$$

where I_0 = ADCP source acoustic signal intensity minus the transmission losses due to beam spreading and water absorption, λ = acoustic wave length, n = number of particles, μ = cosine of angle between scattering direction and reverse direction of the incident wave, d_p = diameter of the individual particle [18], [34]. This relationship assumes that the particles are small rigid spheres whose ratio of circumference to wavelength is much less than unity. An important implication of Rayleigh scattering, with respect to this study, is that the signal strength is directly related to the particle size distribution.

Previous researchers demonstrated that ABS intensity can reasonably estimate suspended solids (*SSC*) mass concentrations when particle suspensions are characteristically uniform with respect to the particle size distribution using the sonar equation

$$Log_{10} SSC_{measured} = A * ABS + B \quad (2)$$

where A and B are the empirically derived slope and intercept, respectively, of the semi-log regression of $SSC_{measured}$ versus the acoustic back scatter (*ABS*) [17], [19], [22]. However, in natural systems, particle suspensions can be diverse with respect to particle size distributions, particle geometry, density and rigidity. These characteristics can change both with respect to location and environmental conditions. To account for these differences, the researchers typically developed site-specific ABS response factors for variable suspended solids concentrations as it was acknowledged that mass concentration calibrations do not apply well when there are significant changes in the PSD. Further ABS corrections are required to account for signal attenuation resulting from beam spreading, water absorption, and sediment attenuation [17], [19]. These corrections allow a single response curve to be applied throughout the ensonified range of the ADCP. These corrections require that the ABS have units of decibels to allow direct application of calculated attenuation values to the measured ABS.

B. Optical Determination

PSDs and volume concentration can be measured with a LISST-100 (Sequoia Scientific, Inc., Bellevue, WA) particle size analyzer using small-angle forward scattering to determine the particle size distribution over 32 ring detectors that correspond to log-normally-distributed particle diameters [35]. Each ring detector measures a scattering intensity that scales typically to the fourth power of the particle radius and weighted by the number density. Scattering intensity from a particle ensemble can be expressed using the Mie solution $I(\theta) = \int K(a, \theta) n(a) da$, where $K(a, \theta)$ is the scattering Kernel describing the intensity contribution from a particle of radius a at a scattering angle θ [35]. Comparison of Rayleigh scattering and the Mie solution shows that both may be calculated as the integral of the particle size distribution while their intensities differ proportionately by a factor of a^2. Additionally, the Mie scattering solution describes scattering by all particle sizes inclusive of Rayleigh scattering (i.e. when particle circumference is less than the wave length). Most particles in natural aquatic systems remain in the measurement size range of the LISST-100 (i.e., 1∼ 250 um) and follow the Rayleigh scattering assumption. Considering the similarities between acoustic backscatter and forward laser in-situ scattering suggest the basis for a strong correlation between the two SSC measurements.

III. Materials and Methods

A. Experimental Design

Echo intensity (EI) responses to standard clay particle suspensions were measured in a laboratory test tank using a 2400-kHz Teledyne RD Instruments StreamPro. Six EI depth profiles were collected during three experimental replicates, each with 6 experimental treatments including (a) no-clay control, (b) standard clay suspensions of 7.5, 15, 22.5, and 30 mg/L (nominal mass loads), and (c) following the addition of a flocculent aid to the maximum mass clay load (30 mg/L). The StreamPro was selected for this laboratory study due to its relatively short acoustic range, which alleviated tank wall interferences experienced with longer range units (i.e. 1200 kHz Workhorse Monitors, Teledyne RDI). The StreamPro was mounted in the Teledyne RDI Riverboat® with a down-looking orientation. Streampro transducers were positioned 5 cm below the water surface. Real time data collection was made with data acquisition and visualization software WinRiverII (Teledyne RDI) via a Bluetooth serial connection to a Dell Laptop computer with a Windows XP operating system. The StreamPro was configured in WinRiverII to collect echo intensity ensembles (profile samples) with the following parameters (6 pings/ensemble, time between pings = 0.2 seconds, interval between ensembles = 0 seconds, sampling frequency = 1.8 seconds/ensemble, depth bin size = 10 cm, number of depth bins = 15). All echo intensity values reported are the mean of all ensembles (minimum 50 ensembles) collected from each experimental treatment. To alleviate variations in incident signal strength resulting from variable power as described by Wall *et al.* [17], the StreamPro was connected to laboratory power supply with an operating voltage set to 12.5 VDC. This modification was required because unlike the 600 kHz ADCP used by Wall *et al.* [17], the StreamPro data output does not include the parameters transmit current and voltage which are required to make the required echo intensity corrections.

B. Test Tank Configuration

All tests were conducted during March 2010 at the Shoreline Environmental Research Facility located in Corpus Christi, Texas in a fiberglass tank (Inside Diameter 3.7m x Depth 1.7 m) and filled with potable fresh water. The tank bottom was lined with rubber mats (1.9 cm thick) to minimize acoustic signal reflection and subsequent interference with the ADCP. To mix the tank, a 1-Hp pool pump was plumbed to an octagonal PVC distribution manifold installed on the tank bottom. The manifold contained 32 equally spaced distribution ports (diameter = 0.7 cm) oriented to direct the water toward the tank center and along the tank floor that created an upwelling current in the tank center that was replenished with a down-welling current around the tank circumference. Pump intake was through a 3.7 cm (I.D.) plumbing fixture in the tank wall located 15 cm above the tank bottom. The tank was completely drained, cleaned, and refilled with clean water between each experimental replicate. A more detailed test tank description is available in [36].

C. Clay Standard Preparation

Cohesive fine-grained sediments including clays are ubiquitous to aquatic systems where they are subject to erosion and suspension during episodic events and commonly transported in a flocculated form [12], [37]. Bentonite clay (Volclay® 200, Univar U.S.A) was selected as the model suspended sediment used to prepare all standard clay suspensions. This material (dry) was passed through a #200 sieve (74 micron) with a dry density of 2.5 mg/μl and is comparable to typical natural suspended solids with fine particle dimensions of less than 62 microns [38]. Prior to each experimental replicate, 4 identical concentrated clay suspensions, each representing a standard test tank clay load of 7.5 mg/L, were prepared by adding 118 g clay to 9.5 L tap water followed by mixing with an electric hand held mixer coupled to a multi-vane impeller at 850 RPM until well dispersed (i.e. until no clay clumps were visible). Before adding the concentrated suspensions to the test tank, visible flocs would form and begin to settle. Therefore, the concentrated suspensions were remixed with the electric mixer immediately prior to addition to the test tank. For each experimental treatment, the entire volume of 1 concentrated suspension was then poured in the center of the mixed test tank 10 minutes prior to sampling to allow the suspension to become well distributed throughout the tank. Final nominal clay concentration in the test tank was determined as the sum of the sequential clay concentrate additions.

To evaluate the effect of variable particle size distribution on the ABS responses to a clay-suspension-standard it was necessary to vary the PSD while holding the mass concentration constant. Therefore, the maximum clay load in each experimental replicate (30 mg/L nominal load) was flocculated with the addition of a commercially available flocculent aid (Super Floc, Advantis Technologies, Inc., Alpharetta, GA). Optimal Super Floc dosage was determined to be 50 ml/16,000L using standard jar testing procedures [39]. This dosage was diluted in 1 L tap water prior to application. Following, flocculent aid addition, the tank was allowed to mix continuously for 30 minutes prior to sampling. Flocculated treatments are referred to as Floc+30 in the results and discussion.

D. Clay Suspension Characterization

Two analytical methods were used to characterize the clay suspensions including (1) volume concentration using optical instrumentation and (2) total suspended solids using gravimetric analysis. Details on each are provided as follows.

Suspended clay volume concentrations were optically measured in-situ with a LISST-100, Type B (Sequoia Scientific Inc., Bellevue, WA. U.S.A.) which measures 32 log-normally-distributed particle size classes with diameters ranging from 1.2 to 250 microns. The particle size analyzer was configured to collect 1 sample/ensemble with an ensemble sampling frequency = 1.74 Hz using the LISST MFC Application (Version 1.0.0.1). It was suspended on a chain in a horizontal orientation to reduce settling of suspended particles on the optical surfaces. All measurements were taken at 0.65 meters below the water surface. All volume concentrations and particles size distributions reported in this study are the mean of 30 ensembles.

Total suspended solids (TSS) mass concentrations were determined by standard gravimetric analysis for total suspended solids (EPA Method 160.2). Briefly, one 1 L grab samples for each experimental treatment (i.e. no-clay control, each clay standard concentration, and following flocculent aid addition) was collected at the control depth (0.65 m) in amber Boston Bottles. The samples were then stored at 3-5 °C until analyzed. A well-mixed sample was then passed through a GF/C filter (0.2 μm). The filter was then dried to a constant weight at 103-105 °C. Suspended sediment concentrations were calculated as the difference between the filter final and tare weights divided by the filtrate volume.

All sampling was performed sequentially in the following order; LISST-100, TSS grab sample, and finally ADCP Stream Pro. Sequential sampling was required to alleviate possible acoustic interference with the StreamPro caused by acoustic signal reflection off the particle size analyzer.

E. Estimating Suspended Sediment Concentration From EI

In the case of the 2400 kHz StreamPro, no factory-determined Received Signal Strength Indicator (RSSI) scale factors to convert raw EI counts to decibel units are provided. This is a deviation from the previous research using 1200 and 600 kHz ADCPs where the RSSI factors were provided by the manufacturer [17], [19]. Therefore, it was necessary to estimate the RSSI as the slope of the normalized echo intensity depth profile when plotted against the respective ABS signal attenuation due to beam spreading and water absorption [36].

F. Beam Normalization and ABS Corrections

The measured EI from the StreamPro for a given depth bin can vary as much as 90 counts between beams on the same instrument (Dan Murphy, Teledyne RD Instruments, oral communication, Jan, 2010). To account for this variability, EI values were normalized to a reference beam [17], [36].

The received acoustic backscatter attenuates with distance from the transducer due to beam spreading, water absorption, and sediment attenuation. These losses must be added back into the measured echo intensity prior to substitution into the sonar equation (Equation 2) used to estimate *SSC*. The corrected echo intensity or *ABS* is represented by

$$ABS_{k,corrected} = ABS_k + BS + WA + SA \tag{3}$$

where *BS* = beam spreading attenuation, *WA* = water absorption attenuation, *SA* = sediment attenuation, and k = depth bin [17]. *BS* was determined as a function of slant distance from transducer, transducer radius, acoustic wavelength [17], [40], [41]. *WA* was calculated as a function of salinity, temperature, and pressure as previously described [17], [19], [42]. The sum of both Beam Spreading and Water Absorption values were found to be negative at depth bins ranging from 0.15-0.85 meters which correspond to corrected slant line distances from the transducer face of less than 1 meter. The negative values are a function of the *BS* term (Equation 3) which calculates attenuation relative to a 1m reference distance. At slant line distances greater than 1 meter, the calculated attenuation values were positive. To remove the negative values, the total attenuation values (BS + WA) were normalized using the Bin 1 attenuation value as the reference. Sediment attenuation was calculated as a function of the acoustic wave length, particle density, fluid density, and kinematic viscosity of water integrated over the particle size distribution [19], [28], [43]. Sediment attenuation was evaluated in this study using a representative particle suspension PSD obtained from the maximum clay mass load (30 mg/L) prior to flocculent aid additions. Sediment attenuation calculated for this particle suspension over the acoustic signal range (1.25 meters) was less than the sum of beam spreading and water absorption attenuation by more than an order of magnitude and was therefore omitted from Equation 3.

G. Computation of Theoretical Target Strength Echo Intensity

The LISST-100 measures the particle volume concentration as a function of 32 discrete logarithmically distributed particle sizes. This particle size distribution may then be used to calculate the theoretical target strength *ABS* in a given depth bin using the Rayleigh scattering equation (Eq. 1). To apply the particle size distribution to Eq.1, it was necessary to calculate the number of particles in each particle size category and depth bin by

$$N_p = \frac{C_p}{T_p} V_k \tag{4}$$

where N = ensonified particle count, C = particle volume concentration (m^3/L), T = individual particle volume (m^3), p = particle size class, and k = depth bin. The bin volume, V_k, was calculated as the volume of a solid angle of a sphere

$$V_k = \frac{1}{4}\pi\varphi^2 L\left[r^2 + \frac{L^2}{12}\right] \tag{5}$$

where L = vertical bin size/cos (Janus angle), φ = two way two sided beam width in radians (1° for 2400 kHz ADCP), and r = distance to bin center/*cos* (Janus angle), and Janus angle = 20° (Gregory Rivalan, Teledyne RD Instruments personal communication, 2010). The summation term in Equation 1 is calculated as

$$\sum_{p=1}^{32}\left(\frac{4}{3}\left(\frac{d_p}{2}\right)^3\pi\right)^2 = \sum_{p=1}^{32} N_p \times \left(T_p\right)^2 \tag{6}$$

where p = particle size bins measured with the particle size analyzer. All length and volume terms have units of meters and meters cubed, respectively.

IV. Results and Discussion

A. Suspended Solids Characterization

Suspended solids measurements were made both gravimetrically and optically with the particle size analyzer to provided concentration data in units of mass and volume concentration, respectively. For experimental replicates, measured mass concentrations ranged between 87 and 93% with $R^2 = 0.999$ (data not shown) compared to nominal mass loads and suggests that some clay was lost in the system or the possibility of errors associated with tank volume determination. Clay mass loss may be attributed to unavoidable settling in the tank which was observed in the spaces between the PVC water distribution manifold and the tank wall. Measured volume concentrations also demonstrated linear increases to the measured mass concentrations, excluding the Floc+30 data points, with replicate R^2 ranging from 0.86 to 1.0 (data not shown).

Following addition of the flocculent aid, the volume concentrations increased from 103, 96, and 93 to 189, 192, and 168 μ l/L, for the March 14, 23, and 26, replicates respectively without an increase in the mass concentrations relative to final clay addition. This observed volume concentration increase with coincident mass conservation indicates fractal aggregation [6], [44]. This implies that the clay aggregates deviate from the Rayleigh scattering assumption of small rigid spheres. A modified Rayleigh equation considers cases where the particles do not adhere to the assumptions of the general equation (i.e. dense ridged spheres) where the term $\left(1+\frac{3}{2}\mu\right)^2$ in Equation 1 is replaced by

$$\left[1-\frac{k'}{k}+\frac{3\left(p'/p-1\right)}{1+2p'/p}\mu\right]^2 \tag{7}$$

where k and p are the compressibility and density of water, respectively. Prime denotes the same qualities for the particle [34]. When particle dimensions are large compared to the wave length ($2\pi a/\lambda \gg 1$) the target strength intensity is given as $TS = 10\log\left(\frac{a^4}{4}\right)$ [34]. Application of these alternative target strength expressions requires characterization of the fractal aggregate. Fractal aggregates are characterized by several parameters including fractal dimension, packing factor, primary particle dimensions, characteristic aggregate length, and shape factors [6], [44]. In addition to the LISST-100, procedures to measure the fractal solid volume distribution and fractal dimension used a Coulter Counter and flow-cytometer [6], [44]. The use of the Coulter Counter and flow-cytometer were not used to characterize the standard clay suspensions, thus precluding fractal aggregate characterization in the current study. Our experimental objective was to quantify the acoustic backscatter response to sediment suspensions with variable particle size distributions under ideal flocculation conditions where the observed conditions represented extreme test cases.

PSDs were generally conserved between replicate tests and standard additions with exception of the Standards 1 and 2 on March 14 which showed elevated volume concentrations at the upper end of the distribution (Figure 1 A). This deviation in PSD resulted in a subsequent reduction in linearity of the March 14 TSS vs. volume concentration ($R^2 = 0.87$) compared to the linearity observed during replicate tests on March 23 and 26, both with $R^2 > 0.99$ (data not shown). Following addition of Standards 3 and 4, the PSDs of all three replicates were similar (Figure 1 A-C). The PSD's represented in Figure 1 show an obvious shift toward larger particles following flocculent aid additions. Corresponding analysis of the mean particle diameters obtained using the LISST operating software, showed mean particle size = 55 microns ($\sigma = 13$) for the 4 clay standards over all experimental replicates. A mean diameter = 120 microns ($\sigma = 1.4$) was measured 30 minutes after the flocculent aid was added. In the case of the standard clay additions the PSDs showed that the clay particle diameters resided within the Rayleigh size limitation (i.e. <206 μm) as indicated by the right hand tail of the PSD (Figure 1). The LISST-100 particle size limitation of 230 μm does not capture the upper PSD of the clay flocs resulting after flocculent aid addition (Figure 1). Thus, indicating that the actual mean particle diameter of the Floc+30 clay suspensions exceeded the mean 120 μm diameter measured with the particle size analyzer. It is important to note that only the largest measured diameter (size bin 230 μm) exceeds the Rayleigh limit. However, Agrawal *et al.* [45] showed that laser diffraction can overestimate the size of natural particles by 20-40%, due to bias resulting from a departure from spherical geometry. Therefore, the measured

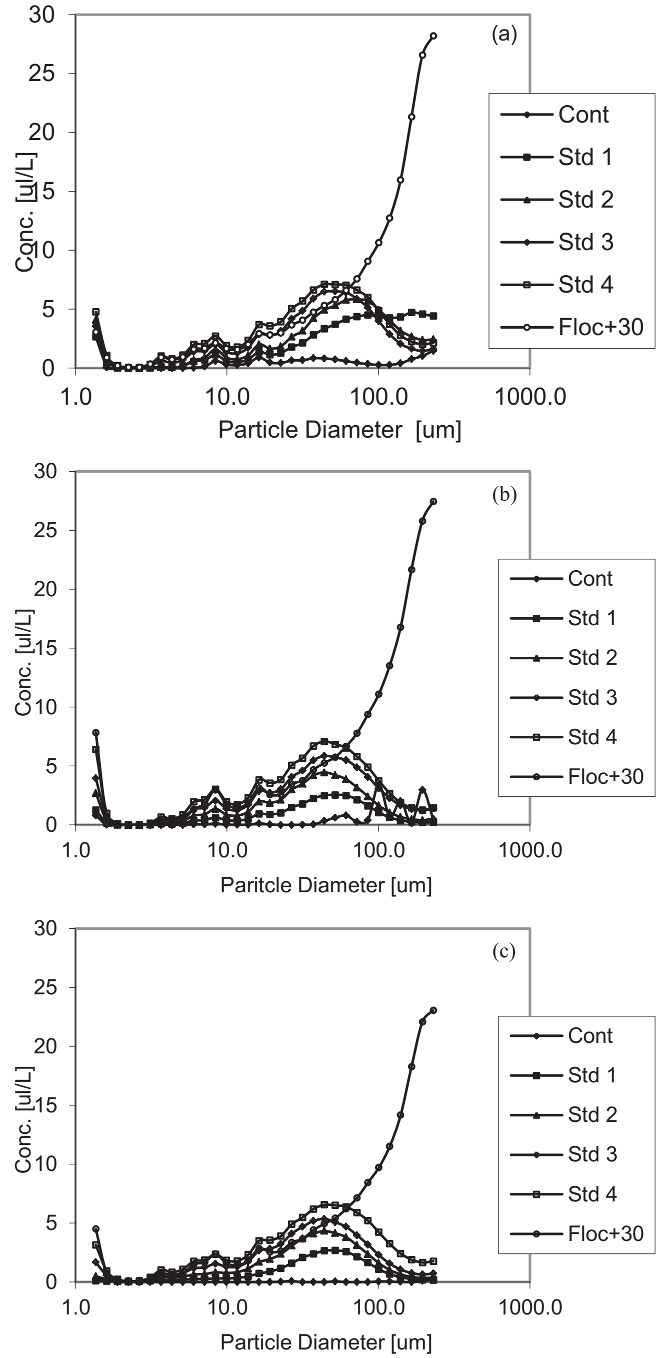

Fig. 1. PSD inferred from LISST 100. (a) March 14. (b) March 23. (c) March 26.

total particle volume concentration is comprised primarily of particles falling within the Rayleigh size limit.

B. Acoustic Backscatter Depth Profiles

ABS depth profiles for each test condition were corrected for beam spreading and water absorption attenuation (Equation 3) to evaluate the applicability of ABS as a surrogate method to measure particle suspension depth profiles as previously described by Wall *et al.* [17]. In homogeneous suspensions the ideal corrected ABS depth profiles would show equal ABS values in all depth bins. Depth profiles of suspended

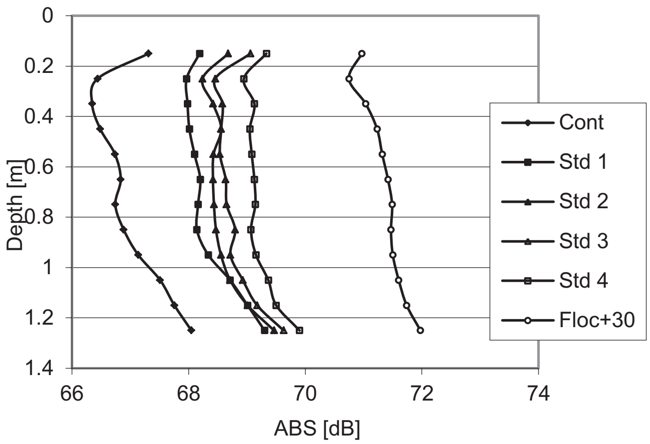

Fig. 2. Representative ABS depth profiles from March 14, 2010 replicate.

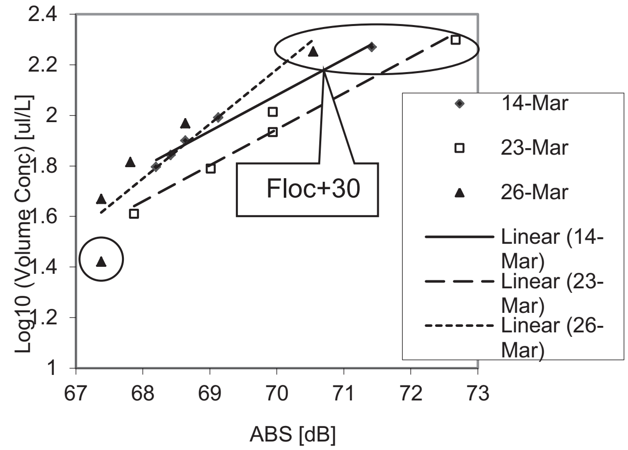

Fig. 3. ABS responses to Log(10) volume concentrations at 0.65 m depth.

sediment concentration were not measured by gravimetric or optical methods. However, it was assumed that there were no vertical particle concentration gradients in the tank based on the high correlation between the measured and nominal mass concentrations and visual observations that clearly indicated the suspension of clay particles within the tank. Deviation from ideality is indicative of the error associated with beam spreading and water absorption corrections. A characteristic ABS depth profile generated from the May 13 replicate is plotted in Figure 2. Inspection shows that corrected ABS generally increased with depth, suggesting that the beam spreading and water absorption corrections may overestimate actual attenuation. Further inspection shows that the ABS values of the no-clay control treatments varied the most across all depth bins, compared to all clay standard and Floc+30 treatments. The greatest depth variability was observed in the no-clay-control treatment during the March 26 replicate (data not shown) which had the lowest control volume concentration $= 1.2\ \mu$ l/L compared to 13 and 28 μ l/L for March 14 and 23 replicates, respectively. This is consistent with reduced ADCP range observed during occasions when scatterers were lacking in the water column and indicates that a minimum threshold particle concentration is required to obtain valid acoustic backscatter responses [33]. Due to the variability observed in the no-clay-controls, they were omitted from the response curves used to determine the calibration coefficients A and B in Equation 2.

C. ABS Response to SSC (Volume Concentration)

Representative ABS-volume concentration response curves at the 0.65 m depth bin for each test replicate are shown in Figure 3. Evaluating the Pearson correlation coefficients (Table 1) indicates log-linear acoustic backscatter responses to increasing volume concentration, including the 4-standard clay additions and the Floc+30 suspensions, for all depth bins and test replicates. Within each replicate, slopes and y-intercepts were comparable across depth bins as indicated by average covariance values of 4.7 and 6.0%, respectively. Considerable variability was observed between replicates as indicated by slope and y-intercept covariance values of 16.9 and 20.2 %, respectively (Table 1). The relatively high covariance across replicates is due to the March 26, 2010, STD 1 (circled point, Figure 3), where the ABS response was high with respect to the measured volume concentration. This observation cannot be explained by the PSD nor was there any indication in the data set that validated its exclusion as erroneous data. The Cook's distance $(D_i) = 0.72$ for the questionable data point was lower than the critical D_i value 0.8 $(2p/n$, where $p =$ number of parameters evaluated (ABS and $\mathrm{Log_{10}VC}$) and $n =$ sample size) and therefore failed to validate exclusion of the suspect data as an outlier [46]. However, the calculated D_i was greater than 0.5 indicating that it strongly influenced the regression [46]. To evaluate the influence of STD 1(March 26, 2010) data point, it was omitted from the regressions for Bins 3, 6, 9 resulting in mean slope and y-intercept of 0.169 and −9.65, respectively. Omission of the suspect datum showed improved agreement across experimental replicates with lower coefficient of variances for slope and y-intercepts of 11.7 and −15%, respectively.

The volume concentrations $(C_{predicted})$ were predicted as a function ABS by substituting the empirically derived slope and y-intercepts for each replicate and depth bin (Table 1) into their respective coefficients A and B (Equation 2). The percent error of $C_{predicted}$ was calculated as

$$\%_{error} = \left| \frac{C_{measured} - C_{predicted}}{C_{measured}} \right| \times 100 \qquad (8)$$

where $C_{measured}$ is the volume concentration measured with the LISST-100. The mean error evaluated across all replicates and depth bins (3, 6, and 9) was 14%. When the Mar 26 2010, STD 1 datum was omitted from the regressions, the average error was reduced to 8.7%. These errors are well within the suspended solids suggested acceptance criteria ± 15-50% [47]. Further, these errors are less than the reported 35-40% variation between ABS estimates and OBS mean values of estuarine suspended solid concentrations [19]. Considering that ABS volume concentration measurements spanned a factor $\sim$ 2x increase in both volume concentration and mean particle diameter between the STD 4 and Floc+30, with no change in mass concentration, demonstrates the capability of ABS methods to estimate particle volume concentrations.

TABLE I
REGRESSION STATISTICS FOR ABS RESPONSE CURVES

	Slope	y-intercept	Pearson Correlation (r)	%Error
14-Mar-10				
Bin 3	0.152	-8.54	0.997	2.8
Bin 6	0.138	-7.57	0.988	4.8
Bin 9	0.139	-7.66	0.984	5.9
23-Mar-10				
Bin 3	0.189	-11.3	0.982	11
Bin 6	0.174	-10.3	0.973	12
Bin 9	0.190	-11.5	0.964	15
26-Mar-10				
Bin 3	0.204 (0.163)[a]	-12.0 (-9.23)[a]	0.906 (0.976)[a]	24 (9.7)[a]
Bin 6	0.208 (0.167)[a]	-12.4 (-9.54)[a]	0.910 (0.985)[a]	24 (7.9)[a]
Bin 9	0.219 (0.176)[a]	-13.3 (-10.2)[a]	0.920 (0.978)[a]	23 (9.3)[a]
Average	0.179	-10.5	0.958	14(8.7)
STDEV	0.0303	2.12	0.0360	8.4(3.8)
COVAR %	16.9	-20.2	3.76	62(44)

r_{critical}=0.648, n=5, $df = n$-2, α=0.05 [48]
[a] Values in parenthesis represent regression statistics calculated with suspect data point (STD 1, 26-Mar-10) omitted.

The primary incentive to conduct this study was to extend the capacity of the ADCP by developing ABS response factors that may be applied to estimate volume concentration through the entire water column with variable particle size distribution. To make this evaluation, the ABS responses from all valid depth bins were plotted against the respective Log(10) Volume concentration (Figure 4). A one-tail t test: Paired Two Sample for Means (Microsoft Excel) was performed to evaluate the error associated with predicting the volume concentration (dependent variable) from the ABS (independent variable). The null hypothesis was assumed (i.e. volume concentration is not dependent on ABS). The calculated $t = 600$ was within the critical region defined by $t_{critical} = 1.65$ ($\alpha = 0.05$, $df = 179$, [48]). Therefore, the null hypothesis was rejected indicating that it is appropriate to predict the volume concentration over the depth bins and particle size distributions evaluated by applying the acoustic backscatter response to the log-linear regression (Figure 4).

The maximum SSC in this study was limited by the maximum detection limit of the particle size analyzer. Therefore it was not possible to empirically define the maximum SSC detection limit using the ABS response. However, the maximum ABS response of 93 dB was estimated as the sum maximum ABS value, obtained from the reflected signal off the tank bottom, plus the signal attenuation due to beam spreading and water absorption. Substitution of the estimated

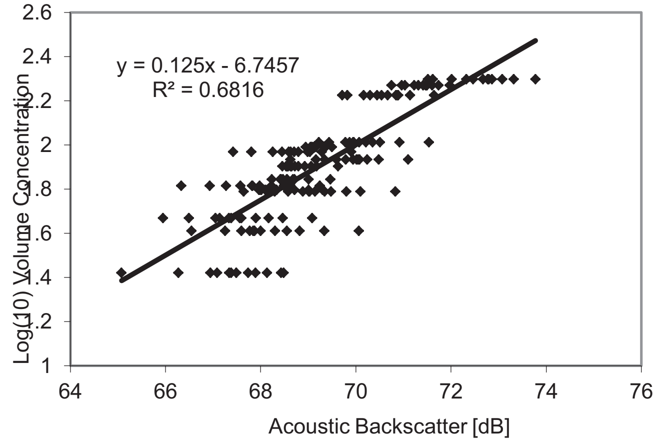

Fig. 4. Cumulative ABS responses from all replicate tests, depth bins, and standard clay loads.

max ABS into linear the regression provided in Figure 4 suggest a maximum acoustic backscatter SSC detection limit of $\sim 10^5$ μ l/L, a 10% solids suspension. Minimum ABS responses obtained from no-clay controls averaged 62 dB at a mean volume concentration = 1.4 μ l/L. These values suggest an ABS SSC detection range spanning 5 orders of magnitude. However, at high SSC concentrations signal attenuation due to sediment absorption would become significant, requiring additional corrections for signal attenuation. The increased signal attenuation resulting from elevated SSC concentrations would also reduce profiling range. It is hypothesized that the volume concentration response curves can be applied over various particle size distributions since the ABS responses are defined by the Raleigh scattering equation. To test this hypothesis, the correlation between the Rayleigh scattering model and the observed ABS with respect to increasing suspended clay volume concentrations was evaluated. This evaluation required that the target strength ABS (TS_R) be calculated with Eq.1 using the particle size distribution for each experimental treatment. For this exercise, I_0 = intensity of source signal is assumed to be unity. The ensonified volume was calculated using Equation 5 for depth bin 6 (0.65m). Plotting TS_R vs. measured ABS for the representative bins, cumulative across all replicate tests, demonstrated a linear correlation in all depth bins evaluated (Figure 5), as indicated by $r = 0.7928$-0.8512 ($r_{\text{critical}} = 0.194$, $\alpha = 0.05$, $df = 13$, [48]), over a variable PSD that was characterized by doubling of the mean particle diameter. This shows that the Rayleigh scattering solution applies to ABS measurements and that it is applicable to estimating volume concentrations. Further, this correlation explains why ABS shows such a strong correlation to volume concentration over a variable PSD.

The correlation between acoustic backscatter and inferred volume concentration should be anticipated considering the theoretical similarities between the measurements. Acoustic backscatter is based on the Rayleigh scattering equation while the LISST-100 utilizes the Mie scattering approximation to infer particle size distribution. Mie scattering applies to particles of all sizes; however when the particle circumference is less than the wavelength, the equation reduces to the Rayleigh

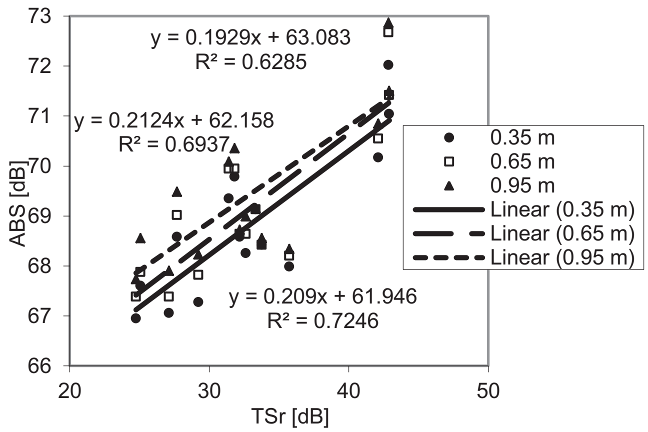

Fig. 5. Measured acoustic backscatter versus Rayleigh scattering target strength.

equation. Mechanistically, the LISST-100 utilizes the principle that small particles scatter light energy in an angular range unique to that size [35]. The contribution to scattering from an ensemble of particles of a particular angle (i.e. particle radius) may be expressed as the sum intensity by all particles at the specified radius. Therefore, the particle size distributions and the ADCP echo intensities are generated using analogous principles and further suggest that suspended solid estimations based on echo intensity are suited to estimate particle volume concentrations.

The analysis presented above demonstrates that a correlation between ABS and volume concentration is conserved over a variable PSD assuming that the particle density and compressibility remain constant. Using a modified Rayleigh equation allows TS_R to be calculated for particles not adhering to the assumptions of the general equation (i.e. dense rigid spheres). To evaluate the effect of clay properties on the observed response, TS_R was calculated with Equation 1 where the term $\left(1 + {}^3\!/_2\mu\right)^2$ was replaced with Equation 7, $p' = 2.5$, and assumed clay particle compressibility was similar to sand with a $k' \approx 0.1$ as evaluated in Urick [34]. Using these values for p' and k', the modified TS_R values were found to be approximately 3.5 dB less than predicted by the standard TS_R equation. Considering the average slope of 0.2, generated from the regression of the measured ABS vs. TS_R (Figure 5), a TS_R difference of 3.5 dB would translate to about 0.7 dB difference in the measured ABS with the StreamPro, or about 10% of the ABS range.

V. Conclusion

Log linear acoustic backscatter responses to volume concentrations were observed with a 2400 kHz ADCP over PSD's that varied within the Raleigh region. This observed correlation between ABS and volume concentration is due to a shared dependence on the particle size distribution as defined by Rayleigh and Mie scattering assumptions, respectively. These findings suggest that volume concentration is appropriate for developing ABS suspended solids response factors.

Despite the strong correlation between ABS and volume concentration, care must be taken when inferring volume concentrations from ABS measurements. Many environmental factors can adversely affect the observed ABS. During preliminary testing, much effort was focused on obtaining reproducible echo intensity profiles for given particle mass concentrations and it was observed that environments with elevated background noise could easily swamp out the signal due to the presence of scattering particles. The source of the background noise was found to be associated with elevated bubble concentrations and also observed on very windy days, which can induce bubble formation in the water column. Other interferences that were experienced during preliminary experiments with a 1200 kHz ADCP included elevated noise floor that was found to be coincident with pump operations. Thus, indicating the need to ensure that interferences originating from engines, prop wash, propeller signature, etc. do not affect echo intensity measurements made from boat based ADCP operations. Additionally, care must be taken to characterize the weather conditions at the time measurements are being taken. In the event of high winds, precautions must be taken to ensure that echo intensity is not due to the formation of bubbles.

References

[1] J. R. Gray and J. W. Gartner, "Technological advances in suspended-sediment surrogate monitoring," *Water Resour. Res.*, vol. 45, no. 4, p. W00D29, Apr. 2009.

[2] U.S. Environmental Protection Agency. (1998). *The Quality of Our Nation's Waters*, Washington, DC, USA [Online]. Available: http://www.epa.gov/305b/98report/98brochure.pdf

[3] C. A. Page, J. S. Bonner, P. L. Sumner, and R. L. Autenrieth, "Solubility of petroleum hydrocarbons in oil/water systems," *Marine Chem.*, vol. 70, nos. 1–3, pp. 79–87, May 2000.

[4] M. C. Sterling, J. S. Bonner, A. N. S. Ernest, C. A. Page, and R. L. Autenrieth, "Chemical dispersant effectiveness testing: Influence of droplet coalescence," *Marine Pollution Bull.*, vol. 48, nos. 9–10, pp. 969–977, May 2004.

[5] M. C. Sterling, J. S. Bonner, C. A. Page, C. B. Fuller, A. N. Ernest, and R. L. Autenrieth, "Modeling crude oil droplet-sediment aggregation in nearshore waters," *Environ. Sci. Technol.*, vol. 38, no. 17, pp. 4627–4634, Sep. 2004.

[6] M. C. Sterling, J. S. Bonner, A. N. S. Ernest, C. A. Page, and R. L. Autenrieth, "Application of fractal flocculation and vertical transport model to aquatic sol–sediment systems," *Water Res.*, vol. 39, no. 9, pp. 1818–1830, May 2005.

[7] L. S. Garton, J. S. Bonner, A. N. Ernest, and R. L. Autenrieth, "Fate and transport of PCBs at the new bedford harbor superfund site," *Environ. Toxicol. Chem.*, vol. 15, no. 5, pp. 736–745, May 1996.

[8] J. S. Kuwabara, C. C. Y. Chang, J. E. Cloern, T. L. Fries, J. A. Davis, and S. N. Luoma, "Trace metal associations in the water column of South San Francisco Bay, California," *Estuarine, Coastal Shelf Sci.*, vol. 28, no. 3, pp. 307–325, Mar. 1989.

[9] M. S. Islam, J. S. Bonner, C. Fuller, B. Kirkey, and T. Ojo, "Understanding particle-mediated contaminant transport through real-time monitoring," in *Proc. OCEANS*, Sep. 2011, pp. 1–10.

[10] C. Bent, J. Gray, K. Smith, and G. Glysson. (2003). *A Synopsis of Technical Issues for Monitoring Sediment in Highway and Urban Runoff: National Highway Runoff Data and Methodology Synthesis*, U.S. Geological Survey, Reston, VA, USA [Online]. Available: http://ma.water.usgs.gov/fhwa/products/ofr00497.pdf

[11] J. R. Gray. (2002). *The Need of Sediment Surrogate Technologies to Monitor Fluvial-Sediment Transport*, U.S. Geological Survey. Reston, VA, USA [Online]. Available: http://water.usgs.gov/osw/techniques/TSS/gray/pdf

[12] M. S. Islam, J. S. Bonner, C. Fuller, W. Kirkey, and T. Ojo, "Impact of an extreme flooding event in the Hudson River watershed captured by the River and Estuary Observatory Network," in *Proc. OCEAN Sci. Meeting*, Feb. 2012, pp. 1–10.

[13] I. D. Avramov, M. Rapp, S. Kurosawa, P. Krawczak, and E. I. Radeva, "Gas sensitivity comparison of polymer coated SAW and STW resonators operating at the same acoustic wave length," *IEEE Sensors J.*, vol. 2, no. 3, pp. 150–159, Jun. 2002.

[14] J. D. Sternahagen, C. E. Wold, W. A. Kempf, M. Karlgaard, K. D. Mitzner, R. D. Mileham, and D. W. Galipeau, "A novel integrated acoustic gas and temperature sensor," *IEEE Sensors J.*, vol. 2, no. 4, pp. 301–306, Aug. 2002.

[15] D. D. Stubbs, S. Lee, and W. D. Hunt, "Molecular recognition for electronic noses using surface acoustic wave immunoassay sensors," *IEEE Sensors J.*, vol. 2, no. 4, pp. 294–300, Apr. 2002.

[16] U. Wolff, F. L. Dickert, G. K. Fischerauer, W. Greibl, and C. C. W. Ruppel, "SAW sensors for harsh environments," *IEEE Sensors J.*, vol. 1, no. 1, pp. 4–13, Jun. 2001.

[17] G. R. Wall, E. A. Nystrom, and S. Litten. (2006). *Use of an ADCP to Compute Suspended Sediment Discharge in the Tidal Hudson River, New York*, U.S. Geological Survey, Reston, VA, USA [Online]. Available: http://pubs.usgs.gov/sir/2006/5055/pdf/SIR2006-5055.pdf

[18] G. Reichel and H. P. Nachtnebel, "Suspended sediment monitoring in a fluvial environment: Advantages and limitations applying an acoustic Doppler current profiler," *Water Res.*, vol. 28, no. 4, pp. 751–761, Apr. 1994.

[19] J. W. Gartner, "Estimating suspended solids concentrations from backscatter intensity measured by acoustic Doppler current profiler in San Francisco Bay, California," *Marine Geol.*, vol. 211, nos. 3–4, pp. 169–187, Oct. 2004.

[20] R. Meral, "Laboratory evaluation of acoustic backscatter and LISST methods for measurements of suspended sediments," *Sensors*, vol. 8, no. 2, pp. 979–993, Feb. 2008.

[21] S. A. Moore, J. L. Coz, D. Hurrther, and A. Paquier, "On the application of horizontal ADCPs to suspended sediment transport surveys in rivers," *Continental Shelf Res.*, vol. 46, pp. 50–63, Sep. 2012.

[22] C. R. Russo and E. S. Boss, "An evaluation of acoustic Doppler velocimeters as sensors to obtain the concentration of suspended mass in water," *J. Atmospheric Ocean. Technol.*, vol. 29, no. 5, pp. 755–761, May 2012.

[23] J. Baugh, N. Feates, M. Littlewood, and J. Spearman, "The fine sediment regime of the Thames Estuary—A clearer understanding," *Ocean Coastal Manag.*, vol. 79, pp. 10–19, Jul. 2013.

[24] M. Simpson, "Discharge measurements using a broad-band acoustic Doppler current profiler," U.S. Geological Society, Sacramento, CA, USA, Open-File Rep. 01-1, 2001.

[25] R. Hirsch and J. Costa, "U.S. Stream flow measurement and data dissemination improve," *EOS Trans., Amer. Geophys. Union*, vol. 85, no. 20, pp. 197–203, May 2004.

[26] M.S. Islam, J. Bonner, T. Ojo, and C. Page, "A mobile monitoring system to understand the processes controlling episodic events in Corpus Christi Bay," *J. Environ. Monitor. Assessment*, vol. 175, nos. 1–4, pp. 349–366, Apr. 2011.

[27] M.S. Islam, J. Bonner, C. Page, and T. Ojo, "An integrated real time monitoring system to investigate the hypoxia in a shallow wind-driven bay," *J. Environ. Monitor. Assessment*, vol. 172, no. 1, pp. 33–50, Jan. 2011.

[28] M. S. Islam, J. Bonner, and C. Page, "A fixed robotic profiler system to sense real-time episodic pulses in Corpus Christi (CC) Bay," *Environ. Eng. Sci.*, vol. 27, no. 5, pp. 431–440, May 2010.

[29] C. Sahin, I. Safak, I. T. Hsu, and A. Shermet, "Observations of suspended sediment stratification from acoustic backscatter in muddy environments," *Marine Geol.*, vol. 336, pp. 24–32, Feb. 2013.

[30] J. F. Lynch, J. D. Irish, C. R. Sherwood, and Y. C. Agrawal, "Determining suspended sediment particle size information from acoustical and optical backscatter measurements," *Continental Shelf Res.*, vol. 14, nos. 10–11, pp. 1139–1165, Aug./Sep. 1994.

[31] P. D. Thorne, Y. C. Agrawal, and D. A. Cacchione, "A comparison of near-bed acoustic backscatter and laser diffraction measurements of suspended sediments," *IEEE J. Ocean. Eng.*, vol. 32, no. 1, pp. 225–235, Jan. 2007.

[32] T. Hunter, L. Darlinson, J. Peakall, and S. Biggs, "Using a multi-frequency acoustic backscatter system as an *in-situ* high concentration monitor," *Chem. Eng. Sci.*, vol. 80, pp. 409–418, Oct. 2012.

[33] *Acoustic Doppler Current Profiler, Principles of Operation, a Practical Primer*, RD Instrum. Inc., San Diego, CA, USA, 1996.

[34] R. J. Urick, *Principles of Underwater Sound*. New York, NY, USA: McGraw-Hill, 1983.

[35] Y. C. Agrawal and H. C. Pottsmith, "Laser diffraction particle sizing in STRESS," *Continental Shelf Res.*, vol. 14, nos. 10–11, pp. 1101–1121, Aug./Sep. 1994.

[36] C. Fuller, "Ecological effects and in-situ detection of particulate contaminants in aqueous environments," Ph.D dissertation, Dept. Civil Eng., Texas A&M Univ., College Station, TX, USA, 2011.

[37] I. A. Droppo, "Rethinking what constitutes suspended sediment," *Hydrol. Processes*, vol. 15, no. 9, pp. 1551–1564, Jun. 2001.

[38] G. S. Bilotta and R. E. Brazier, "Understanding the influence of suspended solids on water quality and aquatic biota," *Water Res.*, vol. 42, no. 12, pp. 2849–2861, Jun. 2008.

[39] M. Davis and D. Cornwell, *Introduction to Environmental Engineering*, 4th ed. Boston, MA, USA: McGraw-Hill, 2008.

[40] K. L. Deines. (1999). *Backscatter Estimation Using Broadband Acoustic Doppler Current Profilers* [Online]. Available: http://www.commtec.com/Library/Technical_Papers/RDI/echopaper.pdf

[41] A. Downing, P. D. Thorne, and C. E. Vincent, "Backscattering from a suspension in the near field of a piston transducer," *J. Acoust. Soc. Amer.*, vol. 97, no. 3, pp. 1614–1620, 1995.

[42] M. Schulkin and H. W. Marsh, "Sound absorption in sea water," *J. Acoust. Soc. Amer.*, vol. 62, no. 3, pp. 558–564, 1962.

[43] G. H. Flammer, "Ultrasonic measurement of suspended sediment," U.S. Geological Survey Bulletin, 1141-A, United Status Government Printing Office, Washington, DC, USA, 1962.

[44] D. Lee, J. Bonner, L. Garton, N. Ernest, and R. Autenrieth, "Modeling coagulation kinetics incorporating fractal theories: A fractal rectilinear approach," *Water Res.*, vol. 34, no. 7, pp. 1987–2000, 2000.

[45] Y. C. Agrawal, A. Whitmire, O. A. Mikkelsen, and H. C. Pottsmith, "Light scattering by random shaped particles and consequences on measuring suspended sediments by laser diffraction," *J. Geophys. Res., Ocean.*, vol. 113, no. 4, pp. 1–9, Apr. 2008.

[46] F. O. Lorenz, "Teaching about influence in simple regression," *Teaching Sociol.*, vol. 15, no. 2, pp. 173–177, Apr. 1987.

[47] J. R. Gray, G. D. Glysson, and D. S. Mueller, "Comparability and accuracy of fluvial-sediment data-a view from the U.S. Geological Survey," presented at the Specialty Conf., Hydraulic Measurements Experimental Methods, Washington, DC, USA, 2002.

[48] R. Johnson, *Elementary Statistics*. Boston, MA, USA: PWS, 1984.

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