An Evaluation of Acoustic Doppler Velocimeters as Sensors to Obtain the Concentration of Suspended Mass in Water

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ABSTRACT

During the last two decades, acoustic Doppler velocimeters (ADVs) and other acoustic sensors have been used by researchers in the ocean science community to acquire information on current velocity and turbulence. More recently, acoustic backscatter systems (ABS) and acoustic Doppler current profilers (ADCPs) have been investigated for their use in determining sediment concentrations and particle sizes. Acoustic systems tend to be less prone to biofouling than optical turbidity sensors, and the high-frequency velocity measurements allow for a direct estimation of turbulence by the flux of particulate materials.

This work investigates the responses of two commercially available ADVs to changes in mass concentrations of particles. A careful laboratory characterization of each sensor's response to concentrations of three different size classes of polymer beads is evaluated and compared with the predicted response from acoustic scattering theory. Within uncertainties, experimental results are shown to agree with theory and these results demonstrate that, if the basic acoustic properties of the scatterers are known or if a local, vicarious calibration is performed, then ADV-type sensors can provide a robust estimate of particle concentrations from the measured acoustic return.

1. Introduction

Acoustic Doppler velocimeters (ADVs) are marine acoustic sensors manufactured to measure current flow. These single-frequency, logarithmic instruments utilize the three-directional, Doppler-shifted acoustic backscatters to determine the velocity of particles passing through the sampling volume, which is a proxy for the velocity of the water. To determine when velocity measurements are likely to be robust, the ADV also measures the acoustic backscattering strength (Sontek Application Notes 1997). In acoustic backscattering theory, as developed for the linear responses of acoustic backscatter systems (ABS), the received intensity of the scattered wave is directly proportional to the concentration of ensonified particles (Hay and Schaafsma 1988; Thorne et al. 1991; Hay and Sheng 1992). A recent investigation of a multifrequency ABS has shown that both concentrations and sizes of sediment particles can be inferred from the backscattering signal (Betteridge et al. 2008). The ABS study suggested, and the acoustic sensor manufacturer Sontek has also suggested, that a laboratory calibration of the logarithmic ADV should be performed, using particles of known size distributions and acoustic properties in order to obtain mass concentration from the acoustic signal. Prior investigations of ADVs and acoustic Doppler current profilers (ADCPs; another logarithmic Doppler sensor) to measure suspended mass concentration have reported that these sensors respond monotonically to the increase in the concentration of acoustic particles, and thus should be able to be used to measure particle mass concentration (e.g., Fugate and Friedrichs 2002; Ha et al. 2009; Gostiaux and van Haren 2010); however, a laboratory assessment of the linearity of the acoustic backscattering as a function of particle mass concentration has not been performed.

Two velocimeters were tested in this work: the Nortek Vector and the SonTek MicroADV (see Table 1 for each sensor's characteristics). The objectives of these tests were twofold; by applying the theory governing sound scattering from a suspension of spheres to a series of laboratory calibrations on two different, commercially available acoustic Doppler velocimeters, this work explores first the linearity of the acoustic response to relevant concentrations of particles of a given size, and then explores the sensitivity of the mass-normalized acoustic response to particles of different sizes. Because each sensor transmits

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TABLE 1. Characteristics of the acoustic sensors used in this work.

Instrument	Transmit frequency	Range to sampling volume	Backscattering angle (off acoustic axis of transmission)
Vector	6 MHz	15.7 cm	30°
MicroADV	16 MHz	5 cm	25°

a wave at a different frequency, it is expected that each one will also exhibit peak sensitivity to certain sizes of particles (Hay and Schaafsma 1988; Kostaschuk et al. 2005). Experiments were performed with each instrument for the same classes of particle sizes in order to demonstrate the size-dependent sensitivity of each sensor.

2. Theory

The theory for this work (for a list of symbols see Table 2) builds from the expression for the mean backscattered pressure $\langle P_b \rangle$ from a suspension of spherical scatterers (e.g., Downing et al. 1995),

$$\langle P_b \rangle = k_s k_t \sqrt{M} e^{-2\alpha r}. \quad (1)$$

In this expression, k_s [N (kg m)$^{1/2}$] is a size-dependent parameter describing the material properties of the scatterers, k_t is the unitless instrument constant to be determined through experiment, and M (kg m^{-3}) is the mass concentration of scatterers in suspension. The acoustic attenuation α is dependent upon both water and suspended mass concentration, $\alpha = \alpha_w + \alpha_s$ (m^{-1}). For freshwater at a given distance r away from the transducer, α_w is temperature and frequency dependent (e.g., Thorne et al. 1991). The acoustic sensors used in this work are single-point sensors, and because water temperature is controlled in the experiment, attenuation resulting from water amounts to a constant factor that can be accounted for as a part of the background measurement (see section 3a). Acoustic attenuation resulting from the concentration of sediments α_s can be further decomposed into the product of the mass-specific attenuation $\alpha^\star$ (m^2 kg^{-1}) and the mass concentration, $\alpha_s = \alpha^\star M$, where $\alpha^\star$ is typically determined theoretically by computing the total scattering cross section of the scatterer. The sediment scattering parameter k_s is defined as

$$k_s = \frac{\langle f \rangle}{\sqrt{\langle a_s \rangle \rho_s}}, \quad (2)$$

where $\langle f \rangle$ is the mean normalized form function

$$\langle f \rangle = \left[\frac{\langle a_s \rangle \langle a_s^2 | f(a,\theta)|^2 \rangle}{\langle a_s^3 \rangle} \right]^{1/2},$$

and ρ_s is the density of the scatterer (Thorne et al. 1991). The mean radius of the particles in suspension $\langle a_s \rangle$ is given by

$$\langle a_s \rangle = \int_0^\infty a_s p(a_s)\, da_s, \quad (3)$$

where the operator $p(a_s)$ is the normalized probability size distribution for the particles.

The form function $f(a_s, \theta)$ is akin to the reflectivity factor, the angular acoustical scattering normalized by the total acoustical scattering. The form function can be decomposed into a series expansion (Thorne and C. Manley 1993),

$$|f(a_s,\theta)| = \left| \frac{2}{ika_s} \sum_{n=0}^{\infty} (2n+1) b_n P_n(\cos\theta) \right|, \quad (4)$$

which can be solved numerically. The quantities $P_n(\cos\theta)$ are the Legendre polynomials and the b_n are expansion coefficients. For an average size particle, the acoustic

TABLE 2. List of symbols.

a_s	Radius of spherical scatterers (m^{-1})
b_n	Expansion coefficients in the series solution to the form function
c	Speed of sound in water (m s^{-1})
$f(a_s, \theta)$	Form function (unitless)
I_s	Acoustic intensity from the sample (W m^{-2})
I_0	Reference intensity (W m^{-2})
$I_{\text{background}}$	Background intensity (W m^{-2})
k	Acoustic wavenumber (m^{-1})
k_s	Constant describing thephysical properties of the scatterers (N kg$^{-1/2}$ m$^{-1/2}$)
k_t	Instrument specific constant
K	$(1/\rho c)k_t^2$
M	Suspended mass concentration (kg m^{-3})
$\langle P_b \rangle$	Mean backscattered pressure (N m^2)
P_n	Legendre polynomial
$p(a_s)$	Probability density function
r	Acoustic range to the sampling volume (m)
T	Water temperature (°C)
α	Acoustic attenuation (m^{-1})
$\alpha^\star$	Mass-specific attenuation (m^2 kg^{-1})
ρ	Density of pure water (kg m^{-3})
ρ_s	Density of the scatterers (kg m^{-3})
σ_t	Total scattering cross section (m^2)
ν	Acoustic frequency (Hz)

TABLE 3. Theoretical values for α^* (m^2 kg^{-1}) calculated using Eq. (6) for the polymer particles used in this work.

$\langle D \rangle$ (μm)	48.05	67.13	218.6
6 MHz	0.0079	0.0078	0.0004
16 MHz	0.2012	0.1344	0.0096

TABLE 4. Physical properties of the polymer particles used in this work.

$\langle D \rangle$ (μm)	48.05	67.13	218.6
ρ (g cm^{-3})	1.19	1.19	1.06
c_{bead} (cm s^{-1})	2780	2780	2350
Poisson's ratio σ	0.39	0.39	0.4

scattering cross section (m^2) is calculated by integrating the form function over the scattering angle (Medwin and Clay 1998)

$$\sigma_t = \pi \frac{\langle a_s \rangle^2}{2} \int_0^{\theta} |f(a_s,\theta')|^2 \sin\theta' \, d\theta'. \quad (5)$$

The concentration-specific acoustic attenuation coefficient $\alpha^{\star}$ is calculated from the total scattering cross section of each of the particles used in this work (Table 3),

$$\alpha^{\star} = \frac{3\sigma_t}{4\pi\rho_s \langle a_s \rangle^3}. \quad (6)$$

Because the instrument response signal is proportional to the acoustic intensity (W m^{-2}), it is useful to recast (1) in those terms (Medwin and Clay 1998),

$$I = \frac{1}{\rho c} \langle P_b \rangle^2, \quad (7)$$

where the quantity $1/\rho c$ is the acoustic impedance of pure water.

In this work, the form function was calculated numerically using a MATLAB script (Anderson 1997). The program solves the equations that describe a plane-parallel sound wave incident on a homogeneous, elastic sphere (Faran 1951). The form functions were calculated for particles that scatter the transmitted wave at each instrument's receiver angle (see Table 1) using the experimental particles' size distributions that we obtained in our laboratory with an optical particle sizer. With respect to concentration, it was our intention to investigate the response of these sensors only within the linear regime of the acoustic intensity. To determine the concentration range with which to experiment that would best elucidate the linear regime for the backscattering of each sensor, we computed the scattering cross sections for the particles used in the experiments. It was determined that a concentration series up to 0.08 g L^{-1} was sufficient to pull samples of measurable concentrations out of the sampling volume, as well as to observe the acoustic backscattering without significant effects from attenuation (within $\leq 2\%$). Because the contribution is small, the sediment attenuation term embedded in Eq. (1) is excluded from the remainder of our analysis. The model inputs simulated the physical properties of the polymer microspheres used in the experiments (Table 4).

3. Methods

a. Acoustic velocimeters

Acoustic Doppler velocimeters measure the backscattered response amplitude from an ensonified sampling volume and output the signal in units proportional to the log of the intensity received at the transducer face, referred to as ''counts.'' Each manufacturer publishes a conversion factor (A) for the proportion of counts that equals 1 dB. For the SonTek MicroADV, $A = 0.43$ counts per decibel and for the Nortek Vector, $A = 0.45$ counts per decibel. The conclusions based on our observations are unchanged if these factors are increased or decreased by 20%, and thus for this work, these factors are assumed known.

For our measurements, we relate counts to the backscatter intensity

$$A \times \text{counts} = 10 \log_{10}\left(\frac{I_s + I_{\text{background}}}{I_0}\right). \quad (8)$$

The quantities I_s and $I_{\text{background}}$ are the backscattered intensities resulting from the sample scattering material and the ambient background, respectively; I_0 is the reference intensity of instrument, unknown a priori. When no scattering material is present in the water ($M = 0$), ambient noise is perceptible, resulting from the instrument itself and concentrations of bubbles, and other contaminants present in the water. The ambient noise is nearly constant throughout, for the time it takes to execute a single experiment, though it may be different between experiments. We first record a blank sample to correct for background noise,

$$A \times \text{counts}_{\text{background}} = 10 \log_{10}\left(\frac{I_{\text{background}}}{I_0}\right). \quad (9)$$

Exponentiating Eqs. (8) and (9) in powers of 10 and subtracting out the background, we have a linearized expression for the received backscatter intensity at the transducer face,

$$10^{A\times\text{counts}/10} - 10^{A\times\text{counts}_{\text{background}}/10} = I_s/I_0. \quad (10)$$

Using relation (7) and substituting Eq. (1), neglecting attenuation resulting from particles, we obtain the model equation to which the experiments are compared,

$$\frac{I_s}{I_0} = 10^{A\times\text{counts}/10} - 10^{A\times\text{counts}_{\text{background}}/10} = Kk_s^2M, \tag{11}$$

where K is $(1/\rho c)k_t^2$. To assess the instrument response to changes in mass concentration, we conducted a series of experiments using well-characterized beads of known size and composition. For particles of a given size, we varied the concentration and, using a type-II linear regression (lsqfitgm.m written by E. T. Peltzer; for details, see http://www.mbari.org/staff/etp3/regress.htm), fit the experimental data to an equation of the form

$$\frac{I_s}{I_0} = aM, \tag{12}$$

which is predicted to be the instrument response based on Eqs. (10) and (11). To determine k_t^2, we set Kk_s^2 in Eq. (11) equal to a in Eq. (12) and solved. The slope calculated from each concentration experiment effectively provides a concentration-normalized backscattered intensity (because it is an effective measure of the change in intensity divided by the change in concentration) that can be used to compare with the normalized backscattered acoustic intensity predicted by theory.

b. Experiment

For all experiments performed, both velocimeters were suspended downward facing into a plastic container that was large enough to accommodate them both so that when the container was filled with deionized water, the transmitting transducers of each sensor were completely submerged. Prior to the experiments and by simultaneously operating both sensors a distance of 20 cm away from one another, we assessed the possibility of one sensor interacting or interfering with the signal of the other; it was observed that each sensor acted autonomously with no interference from the other. In this work, both sensors were arranged such that their sampling volumes corresponded to the same depth.

The container was filled with 22.5 L of deionized water circulated by an electric pump fitted with Tygon tubing. For each experiment an initial measurement was taken, a ''background'' sample to measure the response to the ambient water environment. The beads used were three size classes of latex microspheres with diameters and densities as provided by the manufacturer (Bangs Laboratories): 70–90 μm (1.19 g cm^{-3}), polymethylmethacrylate; 150–180 μm (1.19 g cm^{-3}), polymethylmethacrylate; and 149–350 μm (1.06 g cm^{-3}), polystyrene. The size spreads on these beads were large, and their size distribution was obtained in our laboratory using an optical Laser In situ Scattering and Transmissometer (LISST) sensor. The particles were found to have a lognormal size distribution from which the areal mean was computed (Table 4).

Each experiment proceeded as follows: dry beads were weighed in 0.6 ($\pm$0.01)-g parcels and placed in 50 mL of deionized water; then the mixture was vigorously shaken to make a suspension. One parcel suspension was added to the container at a time. After each addition, the beads were allowed to circulate through the pump and the container until a steady acoustic intensity signal was established, indicating an even distribution throughout the pump–container system. For each suspension, the backscattered signal output from a sensor was recorded for 5 min using the manufacturer's software. To assess the concentration distribution of particles within each sensor's sampling volume, between 75 and 100 mL were piped out and deposited onto a glass fiber filter for subsequent drying and weighing of the residual mass, according to the standard protocol for total suspended sediment analysis, described in section 3c (Environmental Sciences Section Inorganic Chemistry Unit 1993). Experiments were performed with both sensors simultaneously sampling the same water and particles. Data were recorded from each of three receiving sensor arms and for each added concentration. The received amplitude responses from all three were subsequently averaged to maximize the signal-to-noise ratio. The concentration series for beads of a given size class was fit to Eq. (12).

c. Total suspended sediment analysis

Standard glass microfiber filters (GF/F) were prepared for use by being washed under a vacuum first, 3 times successively with 25 mL of deionized water, and then briefly being air dried. The washed filters were then placed individually in open foil packets, dried overnight in an oven heated between 60° and 85°C, and then brought to room temperature for weighing. Once prepared, the filter packets were kept in a dessicator until needed. Concentration samples were deposited under vacuum on prepared filters and dried under the same conditions.

4. Results and discussion

Within the uncertainties of the experiment, the acoustic intensity varied linearly with concentration for a given mean particle size (Fig. 1). For comparable concentrations, each sensor demonstrated a greater response to suspended particles of a characteristic size (Fig. 1). During the course of a single experiment, concentrations pulled from the sampling volumes of both sensors were similar, suggesting

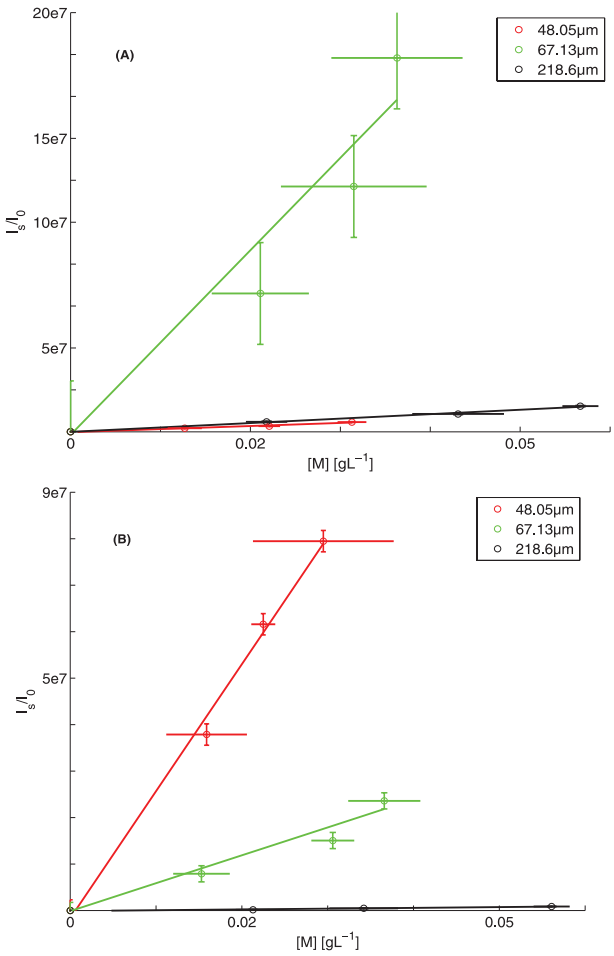

FIG. 1. Concentration profiles for the (a) 6- and (b) 16-MHz sensor with all sizes of polymer particles. The regression line is calculated using Eq. (12), and error bars are represented as the standard error in the backscattered intensity and as the standard error in concentrations that were taken in triplicates at the depth of the sampling volume.

that the horizontal concentration gradients at the sampling depth were small (Table 5).

For each particle size, k_t^2 is calculated based on the concentration experiments and Eqs. (11) and (12) (Fig. 2). Large variations between each estimate give rise to large standard deviations. The median k_t^2 value calculated for each sensor provides an amplitude constant that matches the theoretical predictions to the experimental outcomes, $k_t^2 = 14.9$ dB $\pm$ 0.875 dB for the 6-MHz sensor, and 14.20 dB $\pm$ 1.82 dB for the 16-MHz sensor (in which the uncertainty is based on two standard deviations, shown in logarithmic space in Fig. 2).

The slope calculated from each concentration experiment provides an effective, mass-normalized acoustic backscatter that, as a function of particle size, can be used to compare with the theory-predicted, mass-normalized

TABLE 5. Concentrations of particles (M_n) pulled from each sensor's sampling volume (g L^{-1}) during each experiment.

Sensor	(M_1)	(M_2)	(M_3)	$\langle D \rangle$ (μm)
6 MHz	0.0127	0.0221	0.0313	48.05
16 MHz	0.0159	0.0225	0.0295	
6 MHz	0.0211	0.0315	0.0363	67.13
16 MHz	0.0153	0.0306	0.0366	
6 MHz	0.0218	0.0431	0.0567	218.6
16 MHz	0.0213	0.0342	0.0561	

acoustic backscatter intensity. Form functions were calculated from the model equations based on the physical properties of the scatterers. Two of the three sizes of particles used are composed of the same material, the third and largest particle size is made of a different material with different acoustic properties. The median k_t^2 value of each sensor, bounded by two standard deviations, is used to match the model response calculated from

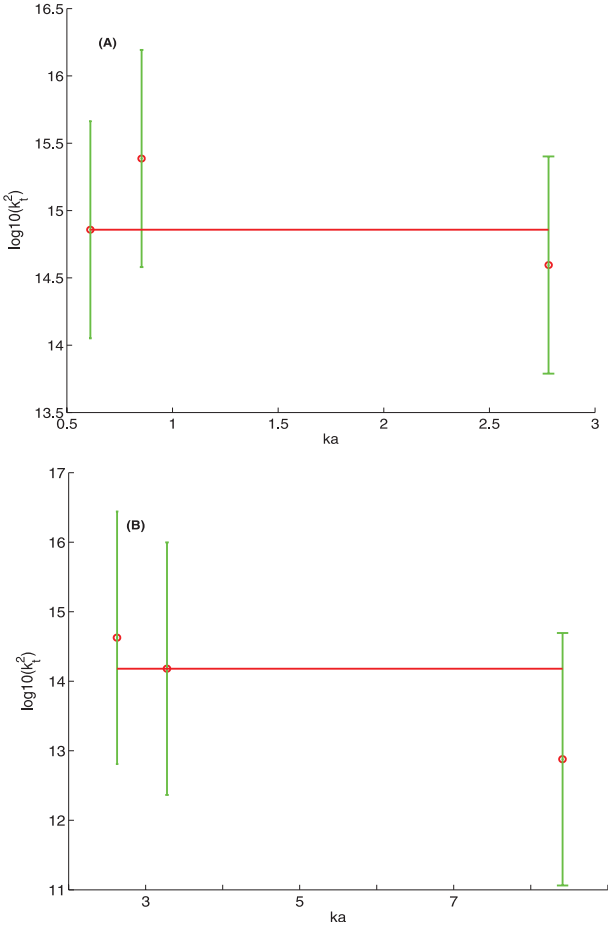

FIG. 2. Independent calculations for the instrument constant k_t^2 as a function of particle size for the (a) 6- and (b) 16-MHz sensors. The median value of the three (red line) is shown, and error bars represent two standard deviations in the estimates.

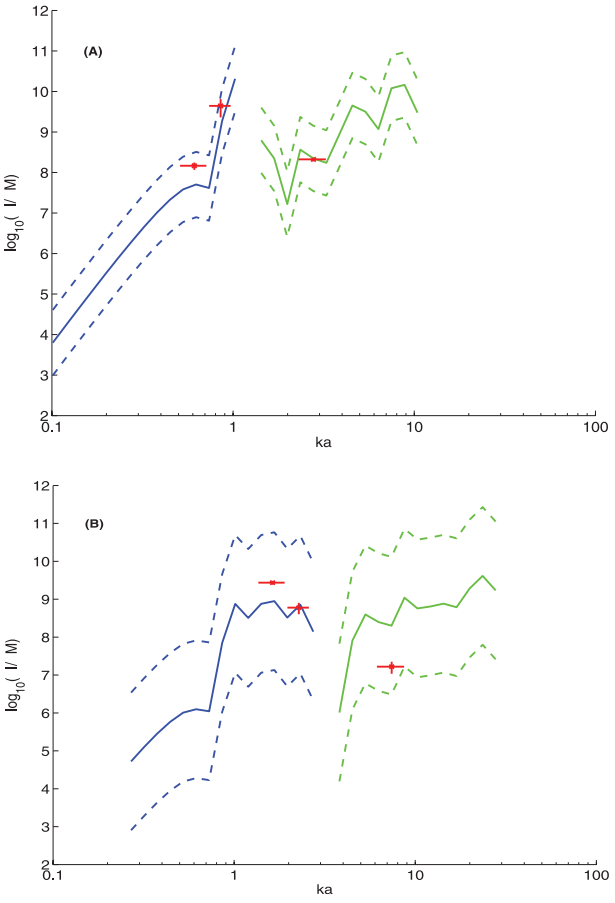

FIG. 3. The concentration-normalized acoustic intensity for each experimental polymer particle size used with the (a) 6- and (b) 16-MHz sensors, plotted logarithmically against theory from the model equations $[1/\rho c(\langle f\rangle/\sqrt{\rho_s\langle a_s\rangle})^2$, where $\langle f\rangle$ is averaged over size], adjusted for the instrument constant k_t^2. The bounds for the model predictions (dashed lines) are shown, provided by two standard deviations in k_t^2. Error bars depict (vertical) the standard deviation in the slope calculated from each concentration experiment, and (horizontal) two standard deviations in size.

acoustic scattering theory [where $\langle f\rangle$ is the size-averaged form function, as in Eq. (2)] to the concentration-normalized experimental response as a function of particle size (Fig. 3). Given the linear nature of the received amplitude intensity to the mass concentration of particles of a given size, it is expected that the amplitude response to particle size is predictable as dictated by theory. However, the predictability of the backscattered intensity as a function of particle size relies on the knowledge of the instrument constant based on the concentration experiments. We found that the experimental results from both sensors could be matched to their theoretical predictions to within two standard deviations of k_t^2.

For field applications, it is important to note that the concentrations, composition, and size distributions of marine particles vary in space and in time. Knowledge regarding the particles' physical properties is necessary in order to apply theory to field samples, but most often, however, vicarious calibrations are performed using field samples. Short time changes in particle size distributions and composition of the field samples can result in size/concentration ambiguity that may lead to large uncertainties when using acoustic theory to convert the scattering intensity to concentration (Hay and Sheng 1992).

5. Conclusions

In this work, the backscattering responses of two ADVs to changes in mass concentrations of particles were investigated. The instruments' intensities increased linearly with concentration, at least up to 0.08 g L^{-1}. Both sensors show promise in estimating concentrations from the acoustic intensity signal if the basic acoustic properties of the scatterers are known, or if a vicarious calibration is performed. The strength of the return signal is biased toward particles of a characteristic size, which is dependent upon the frequency of the specific sensor. These observations demonstrate the utility of deploying an ADV to provide information on suspended loads and thereby increase the information available regarding suspended particles.

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