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# Using ADV backscatter strength for measuring suspended cohesive sediment concentration

H.K. Ha [a,*], W.-Y. Hsu [b], J.P.-Y. Maa [a], Y.Y. Shao [c], C.W. Holland [d]

[a] Department of Physical Sciences, Virginia Institute of Marine Science, School of Marine Science, College of William and Mary, Gloucester Point, VA 23062, USA
[b] Hydraulic and Ocean Engineering Department, National Cheng Kung University, Tainan, Taiwan
[c] State Key Laboratory of Hydrology, Water Resources and Hydraulic Engineering, Hohai University, Nanjing, China
[d] Applied Research Laboratory, Pennsylvania State University, State College, PA 16804, USA

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ABSTRACT

Laboratory experiments were conducted at two institutes to reveal the relationship between acoustic backscatter strength and suspended sediment concentration (SSC). In total, three acoustic Doppler velocimeters (ADVs) with different frequencies (5, 10 and 16 MHz) were tested. Two different commercial clays and one natural sediment from Clay Bank site in the York River were checked for acoustic responses. The SSCs of selected sediments were artificially changed between a selected low and a high value in tap or de-ion water. Each ADV showed quite different backscatter responses depending on the sediment type and SSC. Not all devices had a good linear relationship between backscatter strength and SSC. Within a limited range of SSC, however, the backscatter strength can be well correlated with the SSC. Compared with optical backscattering sensor (OBS), the fluctuation of ADV backscatter signals was too noisy to be directly converted to the instantaneous changes of SSC due to high amplification ratio and small sampling volume. For the more accurate signal conversion for finding the fluctuation of SSC, the ensemble average should be applied to increase the signal-to-noise ratio. There are unexpected responses for the averaged backscatter wave strength: (1) high signals from small particles but low signals from large particles; and (2) two linear segments in calibration slope. These phenomena would be most likely caused by the different gain setting built in ADVs. The different acoustic responses to flocculation might also contribute somewhat if flocs are tightly packed. This study suggests that an ADV could be a useful instrument to estimate suspended cohesive sediment concentration and its fluctuation if the above concerns are clarified.



## 1. Introduction

When acoustic waves travel in a medium and hit a spherical solid with diameter, $d$, that is comparable or smaller than the acoustic wavelength, $\lambda$ (i.e., $\pi d/\lambda < 5$), the scatter waves generated can be described by the Mie theory which is an analytical solution of Maxwell's equations (Bohren and Huffman, 1998). For a non-spherical solid, there are several techniques to compute the scattering as extensions of the Mie theory (for review, see Mishchenko et al., 2000). In general, suspended granular sediments are not spherical solids, however, they are practically treated as spherical solids with a single parameter, i.e., equivalent diameter, $d_e$, for simplicity. When the circumference of sediment particle is much smaller than the acoustic wavelength (i.e., $\pi d_e/\lambda \ll 1$), the simplified Rayleigh scatter waves can be used to describe the scattering characteristics for a single particle (Hay, 1983; Haus and Melcher, 1989).

Backscatter strength is predominantly determined by the abundance of suspended sediments, their reflection properties and the ratio of $d_e/\lambda$. With a variety of acoustic instruments available, the aforementioned acoustic scattering theories have been employed to reveal the relationship between backscatter wave strength and suspended sediment concentration (SSC) (e.g., Vincent et al., 1991; Kawanisi and Yokosi, 1997; Land et al., 1997; Fugate and Friedrichs, 2002; Kim and Voulgaris, 2003; Hosseini et al., 2006; Merckelbach and Ridderinkhof, 2006). To date, the successful use of sound to measure the SSC has been mostly confined to the suspension of granular sediment within a limited range of SSC before multiple scattering and attenuation by suspended sediments become significant (Thorne and Hanes, 2002). For cohesive sediments, however, the applicability of above theories has not been clearly proven because cohesive sediments are less sensitive to long acoustic wavelength (i.e., 100–300 μm) than granular sediments, and they rarely exist as primary particles in natural waters. In these aspects, the acoustic scattering responses to cohesive sediments remain to be verified.

* Corresponding author. Present address: Department of Marine Sciences, University of South Alabama, Dauphin Island Sea Lab., Dauphin Island, AL 36528, USA. Tel.: +1 251 861 7503; fax: +1 251 861 7540.
*E-mail address:* hokyung.ha@gmail.com (H.K. Ha).

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With the above motivation, this paper reports the findings of a preliminary investigation on the possible relationship between backscatter strength and suspended cohesive sediment concentration using three SonTek® acoustic Doppler velocimeters (ADVs) with different frequencies (5, 10 and 16 MHz, respectively). The limitation of using ADVs for estimating SSC and the possible improvement will be discussed.

## 2. Materials and methods

Because of the availability of instruments and the intention for future cooperative studies, four institutes were involved to conduct this study for sharing the resources and experimental results. However, there is a limitation of data set that three ADVs were not used for all sediments. The Virginia Institute of Marine Science (VIMS) posed the questions and carried out the first set of experiments. The Tainan Hydraulic Laboratory of the National Cheng Kung University (NCKU) in Taiwan conducted the second set of experiments. The Hohai University (HHU) in China and the Pennsylvania State University (PSU) helped analyze and interpret the data. HHU is also preparing to conduct field experiments in the Changjiang Estuary.

### 2.1. ADV

An ADV operates by emitting a burst of sound waves with known duration and frequency from a source transducer and using three receiving transducers to measure the backscatter waves. Since the backscatter wave frequency is shifted by moving particles available in the target area, the magnitude of this frequency shift (also known as "Doppler shift") is proportional to the flow velocities. For this reason, ADV can measure flow velocities without a calibration. Owing to a high temporal resolution by the fast response, it is suitable to measure instantaneous velocities of turbulent flow.

The signal (in count) obtained by ADV is proportional to the logarithm of acoustic strength (1 count = 0.43 dB; SonTek, 2001). Because this signal is a function of the amount and type of suspended sediments present in the sampling volume, ADV could be used to measure SSC if the acoustic response to sediment is known. The sampling volume is roughly a cylinder located at a selected fixed distance (i.e., 5, 10 or 18 cm, respectively) away from the source probe (Table 1). In the signal processing, the backscatter strengths from the ADV's three receiving transducers were averaged to obtain the representative mean value, $S$.

If the sediment particle densities are the same, the backscatter signal strength is controlled by the parameter, "$ka$" where $k$ ($=2\pi/\lambda$, $\lambda$ is the acoustic wavelength) is the acoustic wave number and $a$ is the particle radius. This strength is the maximum when the circumference of particle is close to the acoustic wavelength (i.e., $ka \approx 1$), and it is more or less constant when $ka > 1$ (SonTek, 1997; Thorne and Hanes, 2002; Betteridge et al., 2008). For the three types of ADVs used in this study, the particle sizes for peak backscatter strength were given in Table 1.

### 2.2. VIMS experiments

VIMS experiments were conducted with a 5 MHz ADVOcean in a water tank (diameter = 0.75 m and height = 1.5 m). Two types of sediments were used: (1) commercial kaolinite; and (2) natural sediment collected from Clay Bank site in the York River, Virginia. The commercial kaolinite shows a unimodal distribution that major (>50%) component is distributed in the neighborhood of 1 μm. In contrast, Clay Bank sediment shows a bimodal distribution. The first mode (ca. 45%) and the second mode (ca. 30%) are found in the clay ($d = 1$ μm) and very fine sand ($d = 88$ μm) range, respectively. Organic content is about 6%. The clay minerals are composed of mainly Illite (75%) and the rest are Kaolinite, Chlorite and Smectite (ca. 8% each) (Maa and Kim, 2002).

Sediment slurries were prepared first, and in particular, the kaolinite slurry was prepared 30 days before the experiment to let it reach a fully water-saturated condition. Before ADV was plunged for measurements, a selected amount of kaolinite (or Clay Bank sediment) slurry was placed in the tank, and diluted with tap water for a pre-determined SSC. In the calibration for ADV backscatter strength, three submersible pumps were operated to fully mix the sediment–water mixture in the tank. The downward-looking ADV was installed to record the velocities and backscatter strengths at a location of 0.5 m below the water surface and the sampling rate was approximately 10 Hz. Different SSCs were artificially made by adding up the sediment slurry. For the settling measurement, all pumps were stopped after mixing for 24 h. Due to a quiescent flow condition, the lowest velocity range ($\pm 5$ cm s$^{-1}$) was selected in system setup. In order to acquire the time series of SSC as another reference, an optical backscattering sensor (OBS; Downing, 2006) was also installed at the same sampling level of the ADV. The sensing volume of the OBS was horizontally off the sound propagation path of ADV to avoid any possible interference between these two instruments. In order to calculate the SSC, water samples were taken through the drainage port of tank sidewall which corresponds to ADV's sampling level. If the estimated SSC is low (roughly less than 1 g l$^{-1}$, judged by naked eyes), the withdrawn samples were filtered through 0.7 μm glass fiber filters. The residues on filters were oven dried at 103–105 °C for 24 h, and then weighed for determining the SSC. When the SSC is expected to be high (>1 g l$^{-1}$), a pre-weighed aluminum pan was used to hold the withdrawn sample. The pans with entire samples were oven dried

**Table 1**
Specification (as given by SonTek®) of three ADV systems and experimental conditions.

| | 5 MHz ADVOcean | 10 MHz ADV | 16 MHz MicroADV |
|---|---|---|---|
| Sampling rate (Hz) | 0.1–25 [10] | 0.1–25 [5] | 0.1–50 [5] |
| Sampling volume (cm$^3$) | 2.0 | 0.25 | 0.09 |
| Distance to sampling volume (cm) | 18 | 5 or [10] | 5 |
| Velocity range setting ($\pm$cm s$^{-1}$) | [5], 20, 50, 200, 500 | [3], 10, 30, 100, 250 | [3], 10, 30, 100, 250 |
| Particle radius for peak strength (μm) | 50 | 25 | 15 |
| Min. detectable particle radius (μm) | 2 | 1 | 0.5 |
| Sediments ($d_{50}$ in μm) | Kaolinite (1) Clay Bank (88[a]) | 6180 mud (11) | 6180 mud (11) |
| Used water | Tap water | De-ion water | De-ion water |

The numbers in brackets indicate the system settings selected in this study.
[a] Due to the bimodal distribution, the second mode was used for evaluating backscatter strength.

at the same conditions mentioned above. Calculated mass concentrations were used to calibrate the backscatter strength of ADV.

### 2.3. NCKU experiments

The commercially available mud (6180 mud) purchased from Tachia, Taiwan was used. The sediment composition was about 80% of clay, 19% of silt and less than 1% of very fine sand. The mean grain size ($d_{50}$) was around 11 μm. X-ray diffraction test showed that the clay components are mainly Kaolinite (69%) and Illite (30%) with a small fraction of $SiO_2$.

For this experiment, a pre-selected amount of the prepared slurry was added into a tank (diameter = 0.6 m and height = 0.8 m) filled with de-ion water, and then fully mixed in the tank. Because of using de-ion water, the sediment–water mixture can keep the initial SSC for relatively long time. Water samples were siphoned out at six elevations (i.e., 3, 10, 18, 26, 34 and 42 cm above bottom). The two methods used in VIMS experiments were also employed to determine the SSC. The 10 MHz ADV and 16 MHz MicroADV were installed side-by-side to record backscatter strength and 3-D velocities at a location of 26 cm above the bed. Four OBSs were installed at 3, 10, 26 and 42 cm above the bed to measure the change of SSC. Thus, there was an alternative to estimate the mean value and fluctuation of SSC. For the optimal operation, the lowest velocity range ($\pm 3\,cm\,s^{-1}$) was chosen for all measurements. The sampling rates and durations for all instruments were 5 Hz and 1 min, respectively.

## 3. Results and discussion

### 3.1. VIMS experiments

In calibration, 2 min average of backscatter strength, *S*, was compared with the sample-derived SSC. Both experiments with different types of sediments showed that *S* increased with SSC, reached a maximum strength when the SSC surpassed an upper limit, and then decreased even though SSC was still increasing (Fig. 1). The similarity, however, stops here. For kaolinite, *S* gently increased in the lower SSC ranges ($<4\,g\,l^{-1}$), and then also gently decreased when the SSC was higher than $4\,g\,l^{-1}$. On the other hand, Clay Bank sediment had a more rapid increase of *S* when the SSC was less than $1\,g\,l^{-1}$. The instrument was obviously saturated while SSC was changing in the range from 1 to $10\,g\,l^{-1}$, so that the output was almost constant around 72 dB. *S* rapidly decreased after $10\,g\,l^{-1}$. For the increasing parts of responses, good correlations can be found (see $r^2$ in Fig. 1).

The above differences in ADV responses might be associated with the fact that the acoustic signal response mainly depends on the sediment grain size and the reflectivity of particles (or flocs) for the given frequency (Thorne and Hanes, 2002). Since the 5 MHz acoustic wavelength is approximately 300 μm in water, the values of "*ka*" for kaolinite ($a = 0.5$ μm) and very fine sand portion ($a = 44$ μm) of Clay Bank sediment are about 0.01 and 0.9, respectively. Based on the scattering theory, the acoustic backscatter signal amplitude is proportional to $(ka)^2$ for small particles (i.e., $ka<1$) (SonTek, 1997; Thorne and Hanes, 2002). Moreover, the acoustic strength (or intensity) is proportional to the square of signal amplitude, i.e., acoustic strength detected by the receiving transducer is proportion to $(ka)^4$. It is deduced, therefore, that the majority of measured backscatter signals of Clay Bank sediment were originated from the very fine sand portion and the contribution from clay portion is negligibly small. In order to normalize the acoustic backscatter strengths produced by the suspended sediment with different sizes, the total volume of insonified particles must be the same. For this normalization, the following assumptions were also included: (1) the suspended particles are all spheres; (2) flocculation is prevented because of the continuous running of pumps for stirring up sediment. This assumption is supported by the linear OBS calibration lines (not shown) with good correlation ($r^2 = 0.85$ and 0.99 for Clay Bank sediment and kaolinite, respectively); and (3) the multiple scattering is negligible (i.e., the scattering is proportional to the amount of scatters). The volume of a single particle with $a = 44$ μm is equal to that of 681,472 particles with $a = 0.5$ μm. That is, *S* generated from very fine sand of Clay Bank sediment is proportional to SSC*$(0.9)^4$, while *S* generated from kaolinite is proportional to SSC*681,472*$(0.01)^4$. If SSC is less than approximately $1\,g\,l^{-1}$ and both sediments have the same SSC, *S* of Clay Bank sediment is expected to be approximately 2 orders of magnitude higher than *S* from kaolinite. The experimental results, however, show that the kaolinite has higher *S* than the Clay Bank sediment when SSC is lower than $0.5\,g\,l^{-1}$ (Fig. 1). This unexpected response indicates that the gain setting built in ADV might not be fixed. The ADV might apply a higher gain setting for kaolinite, otherwise the return signal would be too weak to be processed, whereas it used a lower gain for Clay Bank sediment of which particle size is relatively large. Also notice that the slopes of the best-fit lines are constant (Fig. 1). This implies that a fixed but different amplification ratio was applied for each sediment. Due to the above reasons, it is hard to directly compare the two signal strengths if only *S* information is available. If the gain setting information applied during the measurement can be archived in the output file, then the signal strengths can be compared for different sediments. At present, unfortunately, the gain setup is not provided with the output and the manufacturer insists that the amplification ratio should be fixed for all types of sediments (SonTek, personal communication). Because several acoustic current instruments have an internal logic to automatically adjust the receiver gain (see RDI, 2002), one needs to confirm the gain setup before converting the signal to SSC.

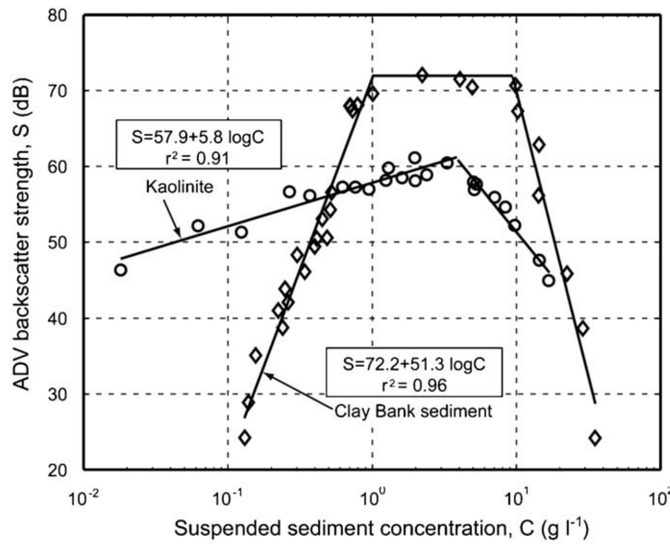


**Fig. 1.** Averaged backscatter strength of the 5 MHz ADV for kaolinite and Clay Bank sediment in tap water. The regression equations for the low SSC are marked with $r^2$ values.

If there are a few measurements of ADV backscatter strengths for the Clay Bank sediment sample with low SSCs (i.e., $<0.1\,g\,l^{-1}$), then these data can be used to judge "is there only one fixed amplification ratio?" This is based on the assumption that the amplified signal strength must be in a proper range for data processing. At this time, the guesstimated range is approximately between 25 and 75 dB. For these low SSCs, the corresponding signal strengths will be less than 25 dB if the same amplification ratio is applied (see the slope for Clay Bank sediment in Fig. 1). If there is another selectable amplification ratio, then we would expect a different slope for those data. Unfortunately, this scenario was not planned before the experiments, and thus, there is no data to confirm or against this hypothesis. Results from the NCKU experiments (Section 3.2), however, showed that two different slopes could be observed by the same sediment depending on the SSC, which may serve as evidence that there might be two automatically selected amplification ratios, at least for the 10 MHz ADV.

The inverse relationship between backscatter signal strength and SSC in high concentration range ($>4\,g\,l^{-1}$ for kaolinite; $>10\,g\,l^{-1}$ for Clay Bank sediment) is common for all instruments using the backscatter waves to measure the SSC. For example, Kineke and Sternberg (1992) found that OBS output had an exponentially decreasing trend with increasing SSC when SSC $>36\,g\,l^{-1}$. These decreasing trends of backscatter signals indicate the increase in sound (or light) absorption. As the amount of suspended materials increases, multiple scatterances become important because more backscatter waves off the suspended materials are redirected to ambient particles. As a result, more sound (or light) attenuation might occur along the propagation paths. Through the laboratory signal analysis, Gratiot et al. (2000) demonstrated that the high-frequency acoustic waves experiencing multiple paths are strongly dampened, and that ADV-measured backscatter signals are mainly contributed from a single traveling path between particles and the sensing probe.

Although $S$ showed a good linear correlation with SSC for low SSC, the instantaneous SSC derived from the ADV backscatter strength ($C_{ADV}$) fluctuated too much to believe. For instance, the fluctuation range measured by the ADV for Clay Bank sediment was approximately $160\,mg\,l^{-1}$ over the entire measurement period (see the gray line in Fig. 2a) with an average of about $400\,mg\,l^{-1}$. When compared with the simultaneously measured SSC from the OBS ($C_{OBS}$) at a nearby location, $C_{OBS}$ showed a much smoother response than $C_{ADV}$ (Fig. 2b). The high fluctuations in $C_{ADV}$ may be attributed to a high amplification ratio required for detecting the backscatter waves. In principle, an ensemble average of certain numbers (around 20–30) of pings should be included in

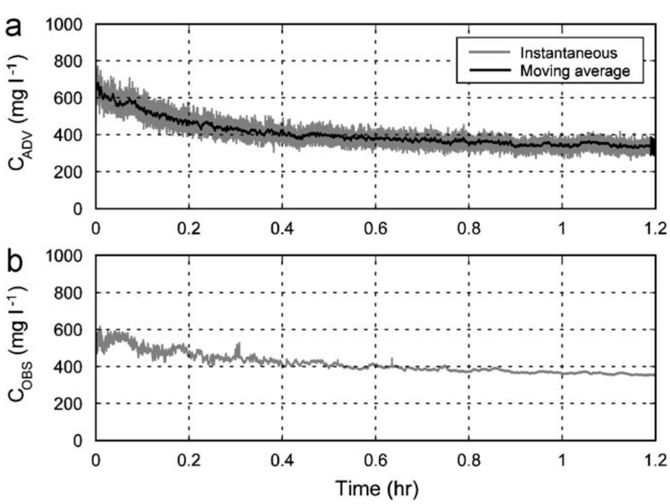


**Fig. 2.** Changes of SSC for Clay Bank sediment during the settling measurement: (a) ADV-derived SSC ($C_{ADV}$) and (b) OBS-derived SSC ($C_{OBS}$). The excessive fluctuation of $C_{ADV}$ may not be true because of the small sampling volume, high signal amplification and lack of ensemble average.

data processing (SonTek, personal communication). In the ADV's signal processing for velocities, a process that systematically averages a certain number of pings, depending on the sampling rate and velocity range, is included to enhance the signal-to-noise ratio (SNR). In order to more effectively remove the spike noises from ADV velocity data, several despiking algorithms (e.g., Goring and Nikora, 2002; Wahl, 2003) have been proposed, and the sources of acoustic noises were explained by Land et al. (1997) and Goring and Nikora (2002). A similar procedure to acquire ADV's signal strength data for SSC measurements should be also implemented to increase the SNR. Unfortunately, excessive fluctuations of $C_{ADV}$ were not recognized during the experiment, therefore a post-processing technique was suggested as a remedy to reduce the noise from the original ADV data acquired at 10 Hz. After taking a 40-point moving average with equal weight, the abnormal fluctuations induced by noises were significantly dampened (see the black line in Fig. 2a). Depending on the sampling rate and amount of noises, the adjustment of data points for averaging is needed to produce reasonable instantaneous variations of SSC. It is noted, however, that this moving-average approach will not increase the SNR because the signals will be smeared. Ensemble average, therefore, should be implemented while acquiring the data.

As might be expected, OBS showed relatively smooth responses because it senses the total light backscatter within a sampling domain around $20\,cm^3$ close to the sensor (D&A Instrument, 2001; Downing, 2006). Since this domain is about 10 times greater than that used in ADV (ca. $2\,cm^3$), the OBS responses represent the average of a spatial domain. This averaging process, although on spatial domain, can also smooth the data. Therefore, there is no need to average again the OBS signals. To summarize, the OBS responses may be too smooth to represent the true fluctuation of SSC at a point. On the other extreme, the ADV responses without ensemble average would be too rough due to low SNR.

### 3.2. NCKU experiments

The 10 and 16 MHz ADVs were tested together with 26 levels of SSCs from around $7.5\,mg\,l^{-1}$ to $2\,g\,l^{-1}$. When the SSC $<1\,g\,l^{-1}$, the vertical gradients of SSC profiles were negligibly small because of relatively weak flocculation in de-ion water. When SSC $>2\,g\,l^{-1}$, the ADV's outputs were practically saturated. Since the objective of this study is to find the upper limit of using ADV backscatter strength to estimate SSC, the experiment stopped at that concentration.

The calibration of OBS (using water samples withdrawn) indicates that floc size changed when the SSC was highter than $300\,mg\,l^{-1}$(Fig. 3). The two linear responses, however, indicate that flocculation did not continue with higher SSCs. It is not clear why the 6180 mud only changed floc size when the SSC is around $300\,mg\,l^{-1}$. Further understanding of this commercially available mud is necessary.

The relationships between acoustic backscatter strength and SSC (Fig. 4) are quite different for these two ADVs. The 16 MHz ADV showed a good linear response when SSC $<900\,mg\,l^{-1}$. Because the 16 MHz ADV has a shorter wavelength (ca. 94 μm), it is more sensitive to this sediment (with a relatively large $ka$ value of 0.37). For the 10 MHz ADV, the relationship showed two linear segments with a vertex point around $130\,mg\,l^{-1}$. This implies that the ADV has two amplification ratios in the signal conditioning. After receiving the backscatter signals, ADV selects one of the two available amplification ratios. If the amplified signal exceeds this pre-selected minimum (25 dB for 6180 mud), then the amplified signals will be recorded and processed for

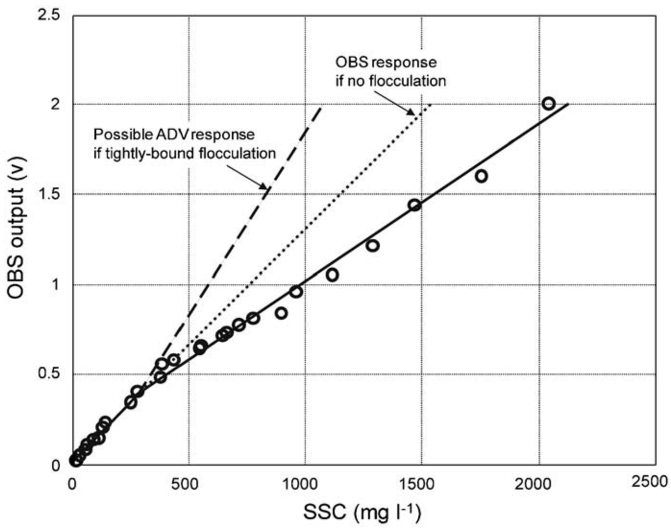


**Fig. 3.** Calibrations of OBS responses for the 6180 mud. OBS's sensitivity (solid line) would be decreased when the sediment particle (or floc) size increases. On the other hand, ADV's sensitivity (dashed line) would be increased with particle (or floc) size because of the relatively long wavelength.

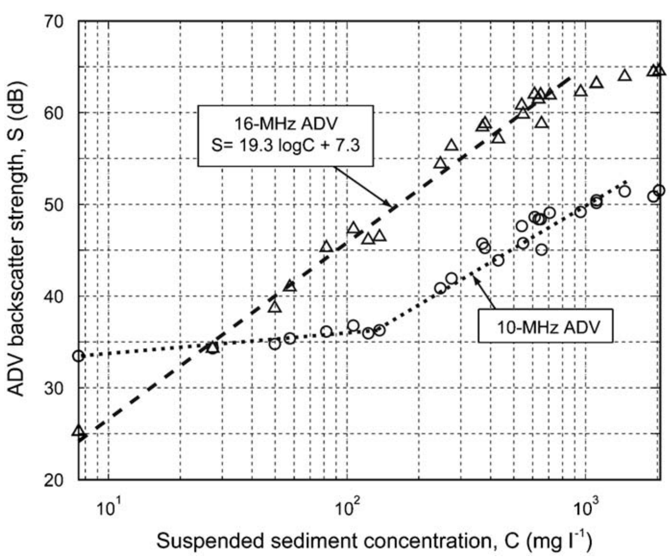


**Fig. 4.** Averaged backscatter strength of the 10 MHz ADV and 16 MHz MicroADV for 6180 mud in de-ion water. Notice that the ranges for linear response are different for the 10 MHz ADV (about 1.5 g $l^{-1}$) and 16 MHz MircoADV (about 0.9 g $l^{-1}$).

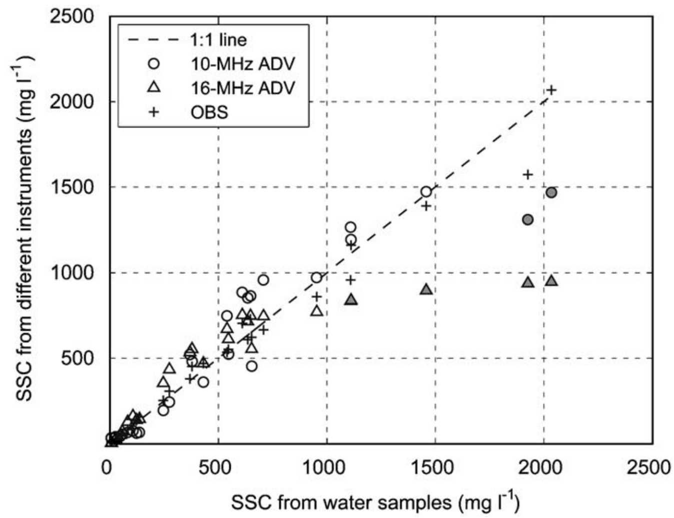


**Fig. 5.** SSC derived from three different instruments (10 MHz ADV, 16 MHz MircoADV and OBS) with 6180 mud in de-ion water versus SSC from water samples. Filled symbols represent the ADV's saturated signals.

calculating velocities. On the other hand, if the amplified signal is lower than the minimum requirement for signal processing, the ADV may change to a next higher amplification ratio for further boosting up the signal.

In as much as the linear response for the 16 MHz ADV, up to 0.9 g $l^{-1}$, and the fact that these two ADVs were used together, the effect of sediment flocculation is not measurable, at least for this experiment.

Signal saturation was unavoidable when the SSC was high (e.g., $>2$ g $l^{-1}$). It appears that the range of amplified signals varies with the sediment size, SSC and amplification ratio (see Figs. 1 and 4).

As another comparison of the linear range of ADV and OBS responses, both $C_{ADV}$ and $C_{OBS}$ were compared with the SSCs measured from withdrawn water samples ($C_{SAM}$) (Fig. 5). It appears that $C_{ADV}$ and $C_{OBS}$ were well correlated with $C_{SAM}$ until SSC reaches about 900 mg $l^{-1}$. Above this limit, $C_{ADV}$ responses become non-linear (see the filled symbols) as the sound attenuation becomes the dominant process. OBS clearly had a much better linear range, up to about 2 g $l^{-1}$.

### *3.3. Uncertainty of ADV backscatter strength in cohesive sediment*

Unlike non-cohesive sediments, flocculation or deflocculation of cohesive sediments can change the size of flocs. To date, the question on whether the acoustic response is mainly governed by the size and shape of floc as a whole or those of its primary particles has not been clearly answered. Based on ADV and OBS responses, Fugate and Friedrichs (2002) stated that the acoustic backscatter is relatively insensitive to floc size changes, when compared with optical device. It is the size and shape of constituent grains that are more important. In this context of acoustic backscatter, their findings are valid when the binding of flocs is loose enough for acoustic waves to only detect individual primary particles. If the flocs are composed of the firmly bound components, the acoustic waves may sense a floc as a single grain. In this case, the backscatter signal is strongly dependent on the properties of flocs. For example, it appears that the 10 and 16 MHz ADVs did not sense the change of floc size of 6180 mud, but the OBS clearly detected the change when the SSC was higher than 300 mg $l^{-1}$ (see Fig. 3).

Although the calibration of 10 MHz ADV showed clearly two linear slopes with a vertex at 130 mg $l^{-1}$ for 6180 mud, this response might not be caused by flocculation because the same linear outcomes were not found for the 16 MHz ADV. Nevertheless, it should be noted that the change of sediment particle (or floc) size has been reported in previous measurements using optical devices (e.g., Pak et al., 1988; Downing and Beach, 1989; Sanford et al., 2001). If the 16 MHz ADV also showed a slope change at the same time, then the change might be associated with the change of floc size. Because only the 10 MHz ADV showed a change of calibration slope, however, the change of floc size is not the reason of having the two different calibration slopes. As mentioned above, therefore, the automatic gain setup is still the most possible cause for the 10 MHz ADV's response shown in Fig. 4.

There is a salient difference between optical and acoustic responses to changes in particle (or floc) size. The slope for an OBS calibration line would be decreased at the relatively high SSC for flocculation (e.g., see the solid line in Fig. 3). This is because the flocculation decreases the total cross-sectional area of particles per unit area (Fugate and Friedrichs, 2002) and OBS's wavelength (780–865 nm) is much shorter than the diameter of aggregated particles. In contrast, the calibration line for an ADV would show a relatively steep slope at high SSC ranges when the floc is large and tightly bound enough to be sensed (e.g., see the dashed line in Fig. 3). In summary, the sensitivity of OBS is inversely proportional to the particle (or floc) diameter (Fugate and Friedrichs, 2002; Downing, 2006), whereas that of ADV increases with the growth of particle (or floc) when $ka<1$ due to the relatively long wavelength (100–300 μm).

In general, the effective density (i.e., the difference between floc density and water density) of floc would decrease with the increase of floc size (van Leussen, 1988; Manning and Dyer, 1999). Hence, a larger and loose floc might have less chance to be detected as a whole floc by acoustic waves. To verify the acoustic response to flocs, the simultaneous use of other instruments (e.g., LISST) that can provide floc size information is necessary, but unfortunately, that instrument was not available in our experiments. For high SSCs, however, LISST may not be the correct instrument to provide the floc density, as it would be also saturated. The upper limit of usable range for LISST depends on the sediment and the setup of optical path.

In the conversion of ADV backscatter strength to SSC, it is assumed that the size distribution of suspended sediments within the sampling volume remains constant with time. For practical applications, a single value (e.g., $d_{50}$) of particle size has been used to represent the entire group of particles that produced backscatter waves. This assumption, however, may produce a biased result when applying to a site where sediment grain size distribution is broad. Under that condition, it is necessary to know particle size distribution to correctly interpret acoustic responses. In addition, the single frequency of ADV cannot differentiate between the changes in SSC and those in particle size distribution such that a change in grain size might be misinterpreted as a change in SSC and limit the accuracy of ADV. This limitation could be partly removed by employing multiple frequencies for measurements (Hay and Sheng, 1992; Smerdon, 1996).

## 4. Conclusions and recommendations

An ADV could be a useful instrument to estimate SSC even though its primary function is to measure flow velocities at a fixed point. In order to accurately convert the received signal strength to SSC, the following concerns should be addressed: (1) the signal conditioner of an ADV appears to have at least two automatically selected amplification ratios to let the amplified signals fit into a pre-selected range. Thus, the amplification ratio should be also recorded with backscatter strengths; and (2) compared with OBS, ADV backscatter signals would be too noisy to address the instantaneous changes of SSC due to ADV's high amplification setting and small sampling volume. The use of ensemble average during data acquisition stage is needed to effectively enhance SNR.

The 5 MHz ADV has a linear operation range up to 1 and 4 $g\,l^{-1}$ for Clay Bank sediment and kaolinite, respectively. The 10 and 16 MHz ADVs have operation ranges up to 1.5 and 0.9 $g\,l^{-1}$ for 6180 mud, respectively. For higher SSCs, ADV backscatter strength is saturated or even decreases with increasing SSC due to the multiple scattering and associated severe sound absorption.

For having better responses when using ADV to measure the SSC for cohesive sediments, one should select an ADV with the wavelength that is close to the sediment particle size if possible. Precaution should be also taken when a measuring site has a significant change of particle (or floc) size with time.

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