SonTek/YSI Technical Note

9940 Summers Ridge Road • San Diego, CA 92121-3091 • Telephone (858) 546-8327 • Fax (858) 546-8150 • www.sontek.com

Experimental verification of acoustic Doppler velocimeter (ADV®) performance in fine-grained, high sediment concentration fluids

David W. Velasco and Craig A. Huhta

SonTek/YSI

+1-858-546-8327

dvelasco@sontek.com

www.sontek.com

April 2009 – Despite its widespread use, the performance of acoustic Doppler velocimeters (ADV®) in fine-grained, high concentration fluids (concentrations of 1-100+ g l^{-1}, i.e. fluid mud) has never been properly quantified due primarily to the physical and experimental complexities in determining their limitations in such conditions. This study evaluates the performance of three ADVs (5, 10, and 16 MHz carrier frequency) in a range of fluid mud concentrations created with natural and synthetic fine-grained sediments. An experimental approach is used that does not seek to compare the ADV response to known velocities or other technologies, but rather through proxy data quality parameters. We show how ADV performance varies with concentration, pulse lag (velocity range) and sediment type. Data show that, for long pulse lags (low velocity ranges), valid velocity data can be collected up to ~50 g l^{-1}, ~28 g l^{-1}, and ~18 g l^{-1} for the 5, 10 and 16 MHz ADVs, respectively.

1. Introduction

Since its commercial introduction in 1992, the acoustic Doppler velocimeter (ADV®) has become a standard tool for accurate single-point velocity measurements in support of a variety of coastal oceanography applications, from hydraulics research to benthic boundary layer studies (Voulgaris and Trowbridge 1998; Lane et al. 1998; Seabergh et al. 2001; Elgar et al. 2001; Haas and Svendsen 2002; White and Nepf 2003; Maddux et al. 2003; Trevethan et al. 2006). One area it has seen use is fine-grained (silts and clays) sedimentation and transport studies in the laboratory, estuaries and the nearshore region (Fugate and Friedrichs 2002; McCool and Parsons 2004; Chang and Hanes 2004). However, its performance in fluid muds has never been appropriately quantified. This has been due primarily to the complexities in determining its limitations in these conditions, such as: the difficulty in keeping such concentrations in suspension in a controlled environment, the fundamental need to use an instrument employing a different technology as a reference for validation, the variable maximum measureable velocity as a function of the pulse lag used, and the difference in acoustic response generated by the sediment characteristics and flocculation status. This study evaluates ADV performance in a range of fluid mud concentrations through an experimental approach that relies on proxy data quality parameters for validation.

2. Instrumentation

2.1 Overview

ADVs operate using the pulse-to-pulse coherent processing technique (commonly called *pulse-coherent* or *PC*). They transmit one very short acoustic pulse, record its return signal (i.e. the reflection off particles in the fluid), and then transmit a second pulse, identical to the first, at a short time later. Each return is detected by acoustic receivers focused in a remote sampling volume (Fig. 1). The instrument measures the phase difference between the two returns and uses this to calculate the Doppler shift, which is directly proportional to the speed of the fluid. Velocity measurements made using pulse-coherent processing are highly precise, but have limited maximum measureable velocity.

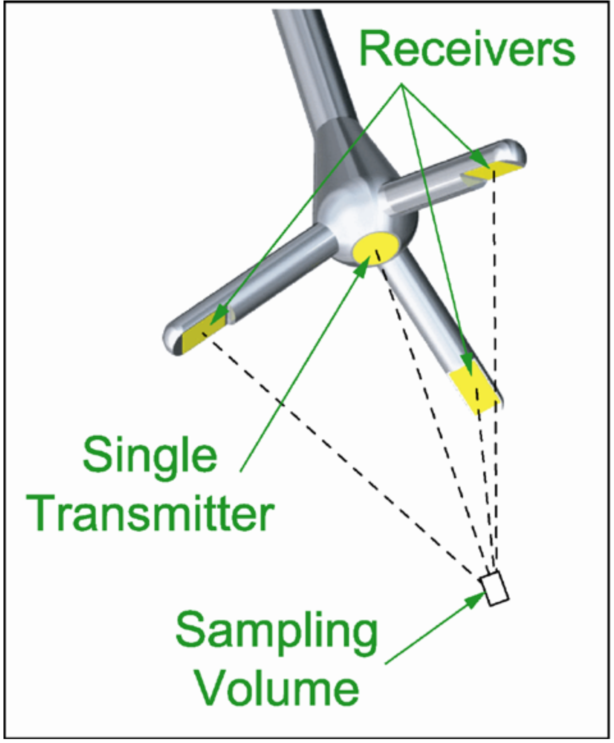

Fig. 1 Basic ADV probe configuration, showing transmitter, receivers and sampling volume location. Illustration is for a 3D probe type.

Each pulse pair transmitted by an ADV is separated by a user-defined time interval (called *pulse lag* or simply *lag*). The length of this lag (in time or physical distance, both often interchangeable in acoustics) is inversely proportional to the maximum velocity that the ADV can measure. Accordingly, SonTek ADVs offer five preset lag settings (as well as automatic pulse lag adjustment on some models), each corresponding to a nominal velocity range as shown on Table 1. Preset lags are never equal the distance between transmitter and sampling volume or otherwise the pulses in each pulse pair may interfere with each other. However, large changes in speed of sound within a data burst, proximity to a boundary or attenuation due to high concentration may cause pulse interference. This is critical in understanding ADV performance once concentrations become high enough to significantly impact signal attenuation for a given pulse.

The pulse lags used by SonTek ADVs have lengths either greater than or shorter than the distance between transmitter and sampling volume. Lags which are shorter than this distance offer the highest measurable velocity (i.e. the largest velocity range, but corresponding higher levels of noise). Conversely, lags whose lengths are longer than the distance between transmitter and sampling volume offer the lowest measureable velocity (i.e. the smallest velocity range, but lower levels of noise). For the five preset lags used by SonTek ADVs, the lowest two velocity ranges always use pulse lags longer than the distance between transmitter and sampling volume, while the highest velocity range always uses a lag shorter than this distance. For the lags covering the two middle velocity ranges (200/50 cm s^{-1} for the 5 MHz and 100/30 cm s^{-1} for the 10 and 16 MHz; see Table 1), these may be either shorter than, or longer than this distance. The choice on whether the short or the long lag is used for these velocity ranges is determined automatically by the ADV, which, prior to sampling, checks for the presence of a nearby boundary. If a boundary is detected and found to be at a distance similar to the preset lag, the ADV will automatically adjust the lag to prevent pulse interference.

	5 MHz ADV	**10 MHz ADV**	**16 MHz ADV**
Sampling volume [cm^3]	2.0	0.25	0.09
Sampling volume distance [cm]	16 – 18	10 – 12	5 – 7
Velocity ranges [cm s^{-1}]	500, 200, 50, 20, 5	250, 100, 30, 10, 3	250, 100, 30, 10, 3

Table 1 SonTek ADV basic system specifications. All values are nominal and can vary from probe to probe (especially the sampling volume distance from the transmitter).

Because velocity ranges are effectively changes in pulse lag lengths, the terms can generally be used interchangeably (albeit inversely proportional). Historically, the term "velocity range" has been preferred (and is the language used in SonTek's software and documentation) because of its application-oriented meaning. However, in this paper we favor the term "pulse lag" due to its greater physical meaning that is more fitting to the acoustic discussion.

2.2 Data types

ADVs collect three basic data types: velocity, signal strength and correlation coefficient scores. Velocity is reported in either two or three dimensions, depending on ADV configuration, and is almost exclusively the parameter of most interest; however, the other two parameters hold valuable data quality information.

Signal strength data is typically discussed in terms of signal amplitude or signal-to-noise ratio (SNR). For SonTek ADVs, signal amplitude is measured in internal logarithmic units called counts. SNR is derived from signal amplitude by subtracting the ambient, background electronics noise level and converting to units of dB, where 1 count = 0.43 dB (SonTek 2001), thus making SNR a more descriptive value than signal amplitude. An SNR value of 0 dB means that there is no difference between the acoustic energy being detected by the ADV and the background noise level. Short-term uncertainty in the velocity measurement increases as SNR decreases. For low sample rate data collection (e.g. 1-2 Hz), SNRs as low as 4 dB allow for accurate velocity measurements. For higher sample rates (e.g. 25 Hz), SNRs higher than about 15 dB are recommended (SonTek 2001).

Correlation coefficient score is a direct measurement of ADV data quality. In simple terms, it is a measure of how well the particles inside the sampling volume maintain their relative position with respect to each other such that the strength and relative phases of the individual pulse echoes are unchanged from one pulse to the next (SonTek 1997). It is reported as a percentage, with 100% meaning that perfect phase coherence is maintained between the pulses and noise is inexistent. When the signal is dominated by noise and no phase coherence exists, the correlations coefficient is 0%. Sources of noise in correlation coefficient include electronics noise, residence time of the particles within the sampling volume, sampling volume turbulence, beam divergence, and pulse interference. A typical threshold for data acceptance is correlation coefficient of 70% or higher (SonTek 2001), although this can vary depending upon the environment and application.

In addition to signal strength and correlation coefficient, another important tool for determining ADV data quality is the profile of signal strength, commonly called BeamCheck. Unlike the signal strength discussed above, which is collected only inside the sampling volume (i.e. a single point), BeamCheck data represents a profile of the signal strength from the transmitter, pass the sampling volume, and well into the maximum range of the acoustic pulse transmitted. As such, BeamCheck allows the user to observe how the fluid's characteristics affect the acoustic pulse, particularly in the region immediately before and after the sampling volume. The shape and limits of a BeamCheck (starting amplitude, peak position, and noise levels) hold critical details in describing the acoustic characteristics of the fluid. Additionally, BeamCheck data can be used to determine the electronics' noise floor level and the operational condition and alignment of each acoustic transducer.

3. Experiment Setup

Three SonTek ADVs of different carrier frequencies (5, 10 and 16 MHz) were setup separately in a circular tank as illustrated in Figure 2. Sediment was added to form the following nominal concentrations: 0.1, 0.5, 1, 3, 5, 7, 10, 13, 18, 23, 28, 35, 42, 50, 59, 68, 79, 90, and 100 g l^{-1}. Particles were kept in suspension with a circulating pump and vigorously stirred with a mixing propeller prior to each data run. The general condition of the flow was turbulent, with a small circular component along the edge of the tank generated by the pump. For each data run, signal strength profiles (BeamCheck) were recorded, in addition to velocity, correlation coefficient and signal strength inside the sampling volume. Each data run was repeated with long lags (low velocity ranges) and short lags (high velocity ranges). Data runs at each concentration for each ADV consisted of the following protocol:

1. Stirring with mixing propeller
2. Recording of BeamCheck for about 30 seconds

3. Re-stirring with mixing propeller
4. Recording of velocity, signal strength, and correlation at 25 Hz for 60 seconds with long pulse lags
5. Re-stirring with mixing propeller
6. Repeating step 4 with short pulse lags.

Two sediment types were used. The first type was naturally occurring muds from the shallow shelf off Louisiana, USA, west of the Atchafalaya Bay, consisting of approximately 70% clay and 30% silt and with a bulk density of 1.31 g cm^{-3}. The second type was synthetic hollow glass oxide spheres, on the order of 8 micron diameter, uniformly distributed, and with a bulk density of 1.1 g cm^{-3}.

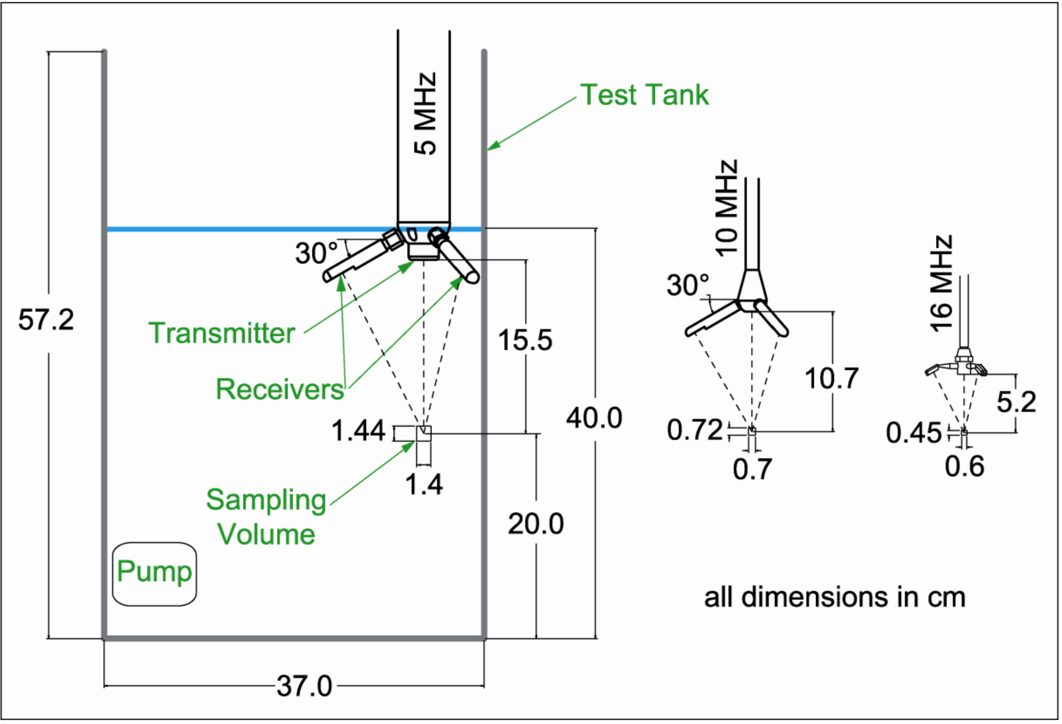

Fig. 2 Schematic of experiment physical setup. Volume of water used was approximately 40 l. Each ADV was mounted such that their sampling volume was at the same distance up from the bottom of the tank. However, only one ADV was used at a time. The smaller size of the 16 MHz's probe meant that its sampling volume was closer to the edge of the tank than the 10 MHz, and the 10 MHz closer than the 5 MHz ADV.

4. Observations

4.1 General data patterns with increasing concentration

ADVs are designed to operate in a wide range of conditions, from very low suspended sediment concentrations up to the fluid mud levels described in this paper. As acoustic scattering conditions change, there are predictable patterns in ADV data. This section describes these general patterns.

In fluids completely void of suspended particles (e.g. very clear water). SNR levels will be near 0 dB. This means the ADV cannot detect reflections from the water and it is simply measuring the ambient electronic noise. In these conditions, the correlation coefficient will be very low (e.g. 0-30%) and the ADV cannot make reliable velocity measurements. When small levels of suspended material are present, the pulses generated by the ADV start to reflect off these particles and SNR increases. As SNR reaches 4-5 dB (typically at concentrations of a few mg l^{-1}), the correlation coefficient will increase beyond the suggested threshold of 70% and velocity data becomes reliable. As suspended sediment concentrations increase further, SNR and correlation coefficient values will likewise increase. Once SNR reaches a level of about 15 dB, the correlation coefficient will typically be near 100% and the ADV will be operating at its peak performance level. It is important to consider that a number of factors can degrade the correlation coefficient and performance of velocity data even with good SNR levels, including high velocities, high turbulence, and aerated water; the description in this section assumes good operating conditions and looks at the affect of sediment concentration only.

As suspended sediment concentration continues to increase, the ADV continues to operate at peak performance over a wide dynamic range (with correlation values near 100%). Eventually sediment concentrations reach a point of maximum SNR, typically 60-80 dB at a concentration on the order of 1-10 g l^{-1}. When sediment concentrations increase past this point, SNR values start to decrease as attenuation from the sediment reduces the strength of reflections that reach the ADV. Even in this area the ADV continues to provide good performance with high correlation values. Eventually, suspended sediment levels reach a point where performance begins to degrade, most easily seen by decreasing correlation values. The experiments described in this paper focus on how to evaluate performance at these very high suspended sediment levels.

4.2 Velocity, signal strength and correlation coefficient

Velocity, SNR, and correlation coefficient data for selected runs are shown on Fig. 3a through Fig. 3e. Given that a total of 230 data runs were collected, only a small representative subset from the 5 MHz ADV runs are shown in this paper. Fig. 3a shows data at the highest SNR values and optimum ADV operating conditions, and is provided for comparison purposes. The remaining graphs show data collected at near maximum working concentration for both short and long lags as well as both sediment types used; these graphs illustrate how data quality changes when you reach the maximum working sediment concentration.

Figure 3a shows data from optimal particle scattering conditions (1 g l^{-1}) for a natural mud run at a short pulse lag setting. Due to the position and orientation of the ADV probe, cross-flow (x-axis) and vertical (z-axis) velocities have mean values around 0 cm s^{-1}, with a small positive along-flow component (y-axis) generated by the pump moving water around the circular tank. SNR values are nearly identical for all three receiving beams, indicating each beam was sampling the same volume of water and had similar acoustic properties. The value for SNR is also quite high (>60 dB) demonstrating the optimal scattering conditions of the fluid at this concentration. Correlation data show near perfect (100%) scores, indicating that little difference was observed between pulses in each pulse pair.

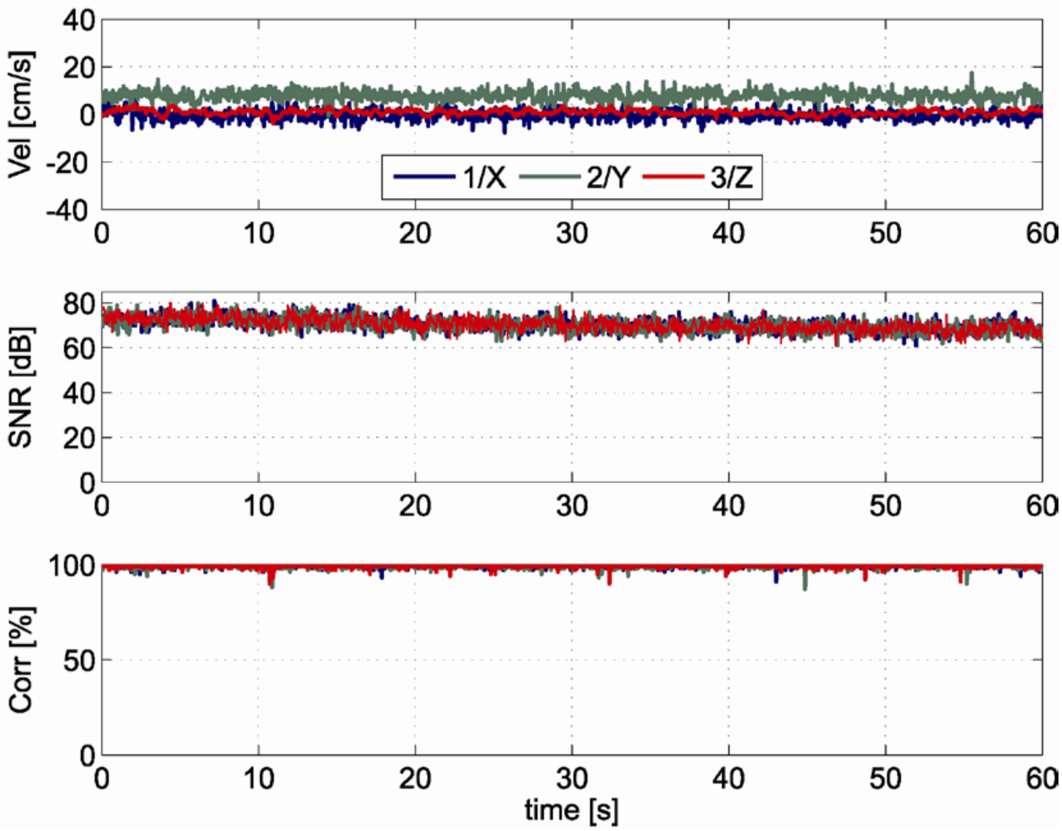

Fig. 3a 5 MHz ADV, at 1 g l^{-1} concentration, with short pulse lag and natural mud particles. This example is considered optimal scattering conditions for the 5 MHz ADV and is shown as a reference for near perfect ADV data. The top panel shows velocity data for each of the three coordinates (two horizontal and one vertical). The middle panel shows SNR data for each of the three beams. The bottom panel shows correlation coefficient scores for each of the three beams. Each data run consisted of 1500 samples (60 s of data acquisition at 25 Hz).

Fig. 3b shows data from high scattering conditions (50 g l^{-1}) for a natural mud run at a short pulse lag setting. X-axis and y-axis velocities both show much higher noise levels than the data shown in Fig. 3a, with lower noise levels seen in the z-axis velocity. A small positive mean value for the along-flow (y-axis) velocity can be noticed. After the first ~10 s of the run, noise in the velocity data decreases while SNR shows a small increase and correlation increases from ~50% to >80%. These changes are attributed to settling of some of the larger particles after the vigorous mixing was stopped, reducing the true sediment concentration. In the latter part of the measurement, even when correlation values have increased to >80%, the general noise level in velocity data is significantly higher than seen in Fig. 3a. SNR values are lower than in optimal scattering conditions (Fig. 3a) due to stronger attenuation of the acoustic signal at the higher concentration.

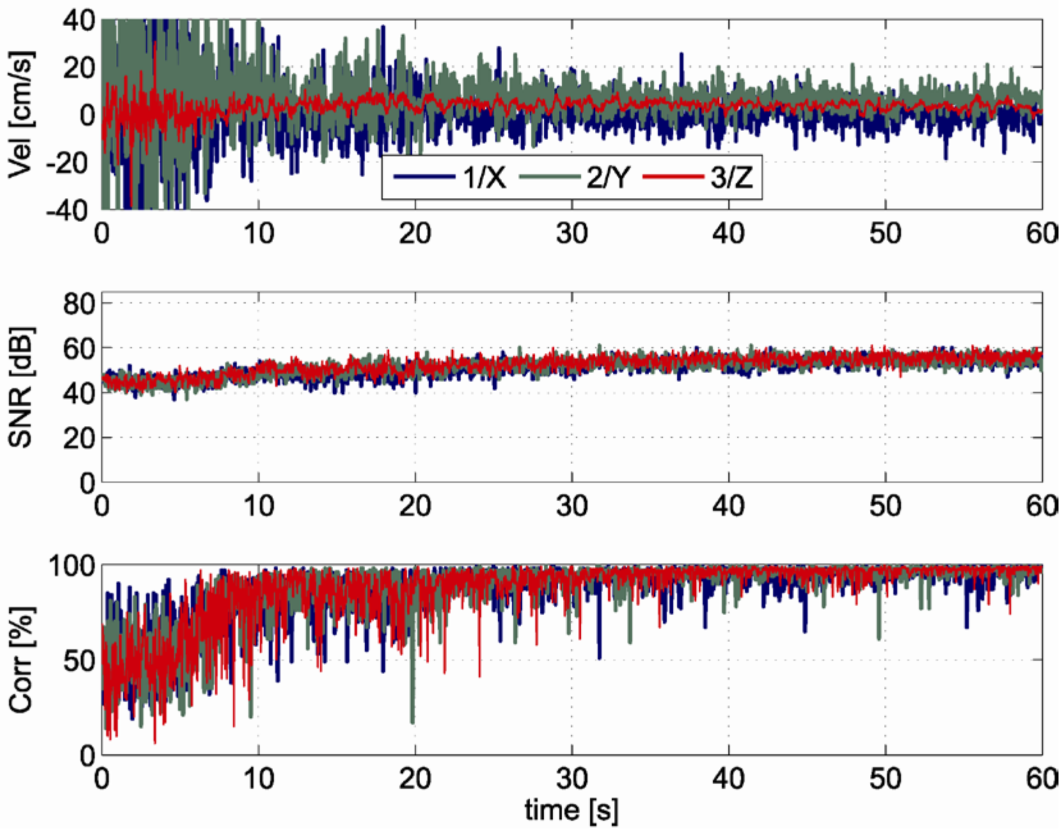

Fig. 3b 5 MHz ADV, at 50 g l^{-1} concentration, with short pulse lag and natural mud particles.

The only difference in system configuration and flow condition between the run shown in Fig. 3b and that shown in Fig. 3c is the length of the pulse lag used. Data shown in Fig. 3c used long pulse lags. Velocities for this run (Fig. 3c) show relatively low noise and little difference between the start and end of the run. As with other runs, SNR data for each beam are nearly identical, and like the data in Fig. 3b, increase throughout the run, with a faster increase during the first 10 s suggesting particle settling. Correlation coefficients display a small decrease in noise (more noticeable within the first ~20 s) and increase in value throughout the run, suggesting the flow is getting less turbulent with time. Comparing figures 3b and 3c illustrates that using a pulse lag (lower velocity range) longer than the sampling volume distance will generally allow the ADV to collect data in higher suspended sediment concentrations.

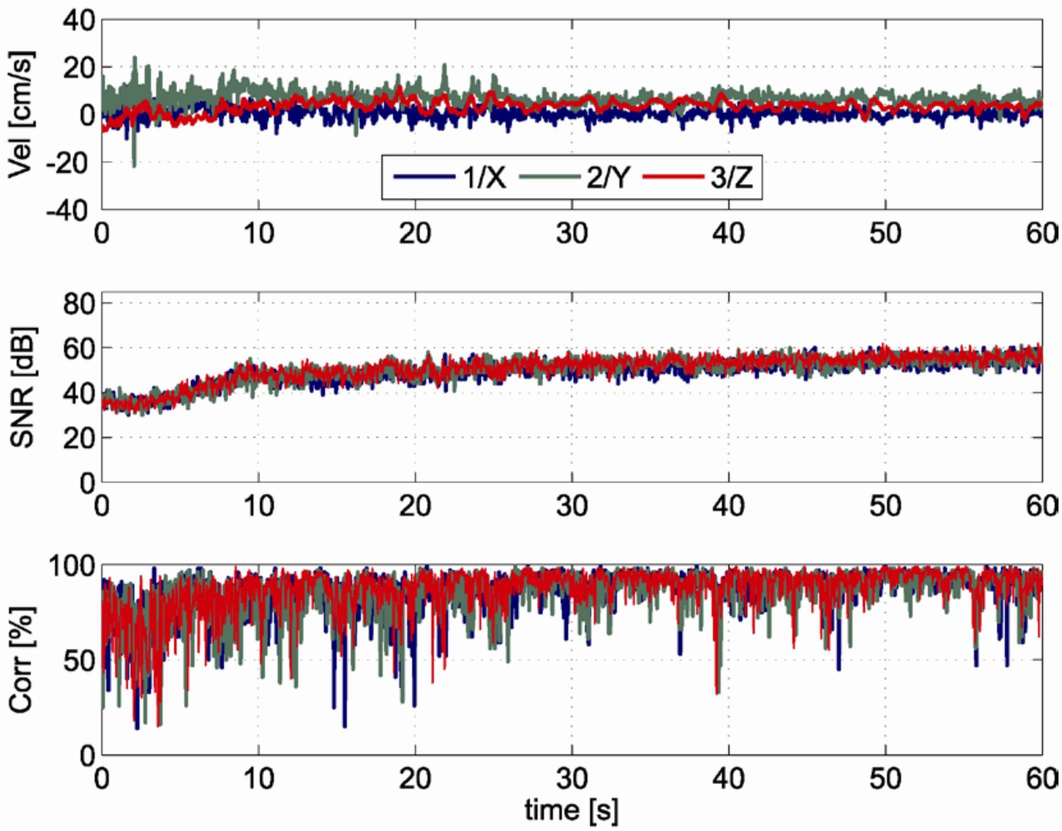

Fig. 3c 5 MHz ADV, at 50 g l^{-1} concentration, with long pulse lag and natural mud particles.

Data in Fig. 3d was collected at the same concentration and pulse lag as data shown in Fig. 3b, but the scattering material has been changed. Fig. 3d shows data collected with the uniformly distributed synthetic glass spheres. Velocity data from this run is dominated by noise, with practically no coherent signal identifiable. For easier comparison with the other runs, the velocity data is plotted only within the range of -40 to +40 cm s^{-1}, however the raw data shows fluctuations between -200 and +200 cm s^{-1} that could not have been produced by the pump or mixing propeller and illustrate the noise dominance of the data. Along the same lines, correlation coefficients are below 50% for nearly the entire run (save the first ~3 s) further indicating the lack of coherence in the pulses. SNR data does show what would otherwise be considered acceptable values (i.e. > ~15 dB at 25 Hz sampling). However, examination of additional data (namely BeamCheck, discussed in the next section) suggest the shape of the signal strength profile and characteristics of the signal's peak at the sampling volume are inadequate for proper velocity measurement with the pulse lags used in this run.

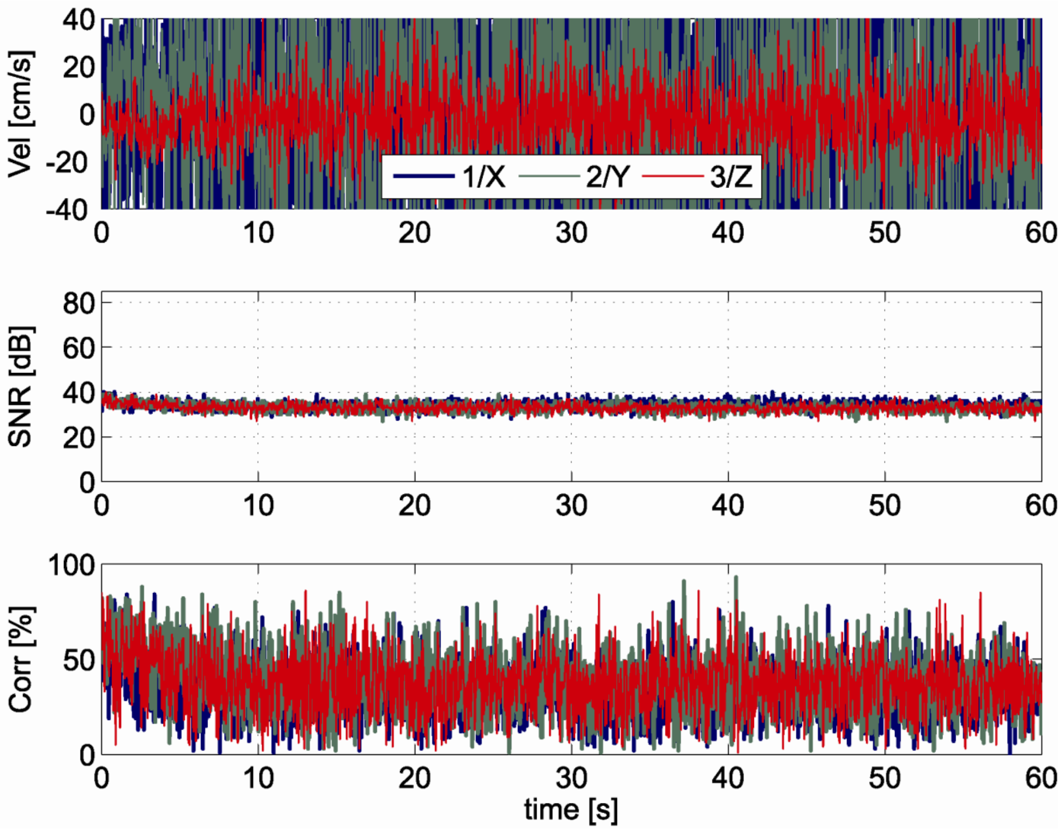

Fig. 3d 5 MHz ADV, at 50 g l^{-1} concentration, with short pulse lag and synthetic glass spheres.

Fig. 3e shows data at 50 g l^{-1} with glass sphere particles as scatterers, similar to Fig. 3d, but this time using a long pulse lag setting. The effect of different pulse lag lengths is clearly seen in comparing these two runs. For the data shown in Fig. 3e, velocities are very similar to those in the optimal scattering conditions case (Fig. 3a). Likewise, correlation scores are above 70% for almost the entire run indicating good coherence between the two pulses in each pulse pair. Unlike the SNR data shown in Fig. 3d, however, SNR data in Fig. 3e are less than half that value, in effect at the ~15 dB recommend threshold for 25 Hz sampling. Nevertheless, this run shows acceptable velocity data for the pulse lags used.

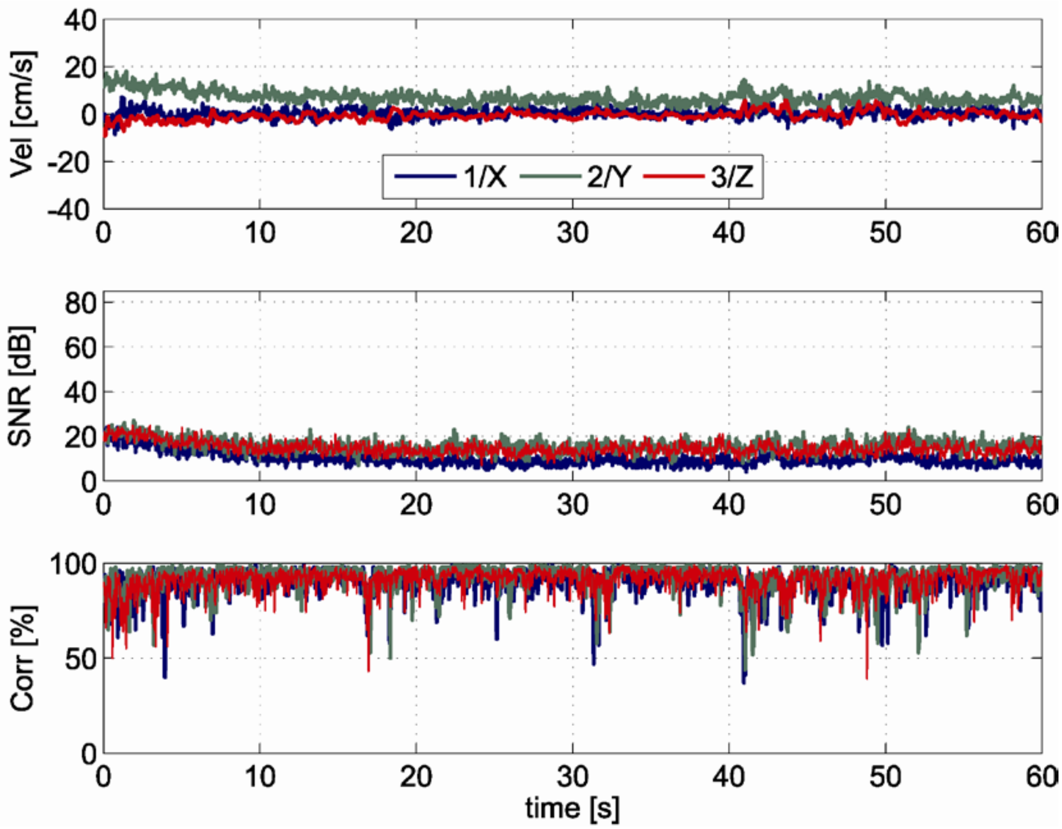

Fig. 3e 5 MHz ADV, at 50 g l^{-1} concentration, with long pulse lag and synthetic glass spheres.

In summary, for the 5 MHz ADV, data collected with long lags presented higher correlation coefficients and less noise in velocity for both sediment types than runs with short lags. This is especially the case for the glass spheres where correlations were well below the 50% level and velocity was dominated by noise (Fig. 3d) for data collected with short lag settings. Signal strength remained well above the electronics noise floor level for three of the four selected runs, with the long lags and glass sphere runs (Fig. 3e) approaching this level. Settling effect is also observed, especially in the natural mud and short lag runs (Fig. 3b), where the correlations can be seen increasing from about 50% up to >90% suggesting settling.

The general patterns observed in the 5 MHz ADV data with increasing concentrations (i.e. decrease in correlation, increase in noise in velocity data, variations with lag lengths and fluctuations in signal strength) are also observed in the other two frequencies. However, they are generally detected at lower concentrations.

4.3 BeamCheck

Signal strength profiles, commonly called BeamCheck, provide valuable diagnostic data and are critical in any thorough examination of ADV data and system performance. BeamCheck data can indicate things such as: misalignment of receiver arms, electronics noise floor level, distance to nearby boundaries, relative amount of scatterers (particles) in the fluid, proper transmitter operation, and relative amount of noise in the sampling environment. BeamCheck operates by sending a pulse from the ADV's transmitter and sampling the reflection (echoes) of this pulse as it propagates through the water column along the central axis of the transmitter.

The reflections are picked up by each receiver and sampled with roughly 1 mm resolution, allowing the detection of all major acoustic features (Fig. 4).

In addition to showing the main features typically encountered when analyzing BeamCheck data, Fig. 4 also shows the impact of varying amounts of scatterers (sediment particles) on the acoustic signal (normally plotted as amplitude for BeamCheck data). Four different conditions are shown: no scattering (fluid totally void of any particles; i.e. clean water), optimal scattering conditions, high attenuation caused by high particle concentration, and full attenuation caused by excessive particle concentration. A 5 MHz ADV was used to generate the data in Fig. 4 and its setup up was identical to the one shown on Fig. 2, with exception of the no scattering conditions case, where no nearby boundary was present. About 50 individual transmit/receive cycles (pings) were averaged to generate each of the four curves shown. Each line is also the average from all three beams. Each distance sample (x-axis) is a function of system frequency, speed of sound and probe geometry, and for the data in Fig. 4 equals 0.110 cm/sample.

In a typical BeamCheck plot (such as the optimal scattering curve in fig. 4), several characteristic features can be observed. Signal strength starts low and then increases as the pulse moves toward the sampling volume. Signal strength reaches a peak in the center of the sampling volume, and then decreases again as the pulse moves past the sampling volume. If a solid boundary is within range, the plot may show a spike in signal strength corresponding to the reflection of the pulse from that boundary.

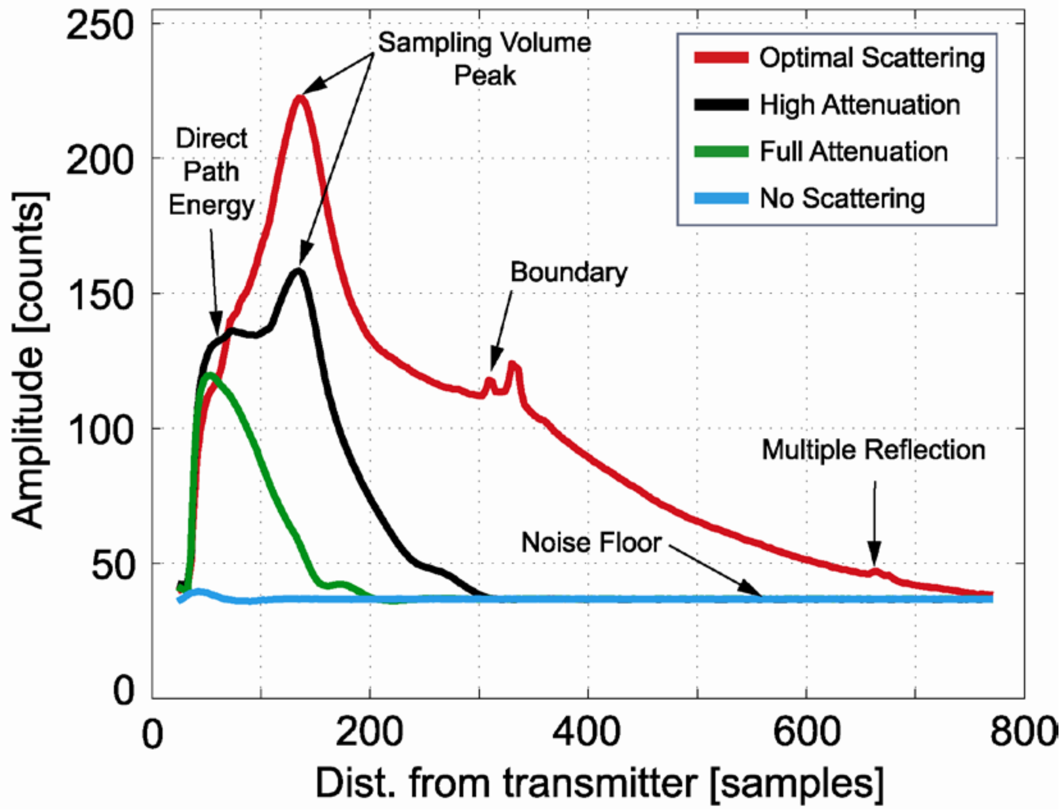

Fig. 4 Major features of a BeamCheck at four different scattering conditions.

The sampling volume peak shown in Fig. 4 is the foci of the three receivers, which for this probe were located around sample 140 (~15.5 cm) from the transmitter. The peak can be clearly seen in both optimal scattering and high attenuation conditions, but is barely discernible in the full attenuation condition because almost all of the acoustic energy has already been absorbed by the time the pulse travels from the transmitter to the sampling volume and then back to the receivers.

In only the optimal scattering case can the boundary (i.e. bottom of test tank) be detected. The boundary is identified in Fig. 4 as a small spike in the curve after the sampling volume. Furthermore, a smaller, multiple reflection, is observed around sample 660, where the transmitted pulse has reflected off the bottom of the tank, then back off the surface of the water, then off the bottom a second time.

The instrument's noise floor is clearly seen under conditions where no scatterers are present; this same level could also be detected if the unit was in air. The data for this condition only was collected with no nearby boundaries and hence no other significant features can be discerned; had the probe been placed in the same location as for the other three cases, a boundary spike would have been clearly visible around sample 310.

Clearly seen under high attenuation conditions is the energy reflected off particles prior to the pulse reaching the sampling volume. Because the direct distance from the transmitter to the receivers is shorter than the distance from the transmitter to the sampling volume (see Fig. 2), this appears as increase in signal amplitude prior to the sampling volume.

BeamCheck data for selected experiment runs are shown on Figure 5. Data for each of the three acoustic receivers has been averaged and plotted as a single line for each concentration step, similar to Fig. 4. Only 6 out of the 20 concentration steps are plotted in order to keep the graphs uncluttered. For all conditions, optimal scattering concentrations (typically up to 10 g l^{-1}) show a distinct signal strength peak at the sampling volume location due to it being the focus of the three receiving transducers. The black vertical line indicates the center of the sampling volume and its distance from the transmitter for each probe is indicated in cm. Signal strength trails to noise floor (where all lines converge) with distance due to attenuation, with past-volume peaks indicating the bottom of the tank and multiples. With increasing concentration, the sampling volume peak amplitude decreases as the acoustic energy is absorbed and scattered by the particles in all cases. At the same time, an increase in energy is observed closer to the transmitter. Eventually, at high enough concentrations, the sampling volume peak can no longer be detected above the electronics noise floor. Although the hollow glass spheres are excellent acoustic reflectors, the higher amplitude values shown in the natural mud case may be due to the wider size distribution present in these scatterers, covering a wider range of acoustic wavelengths than the uniformly distributed glass spheres.

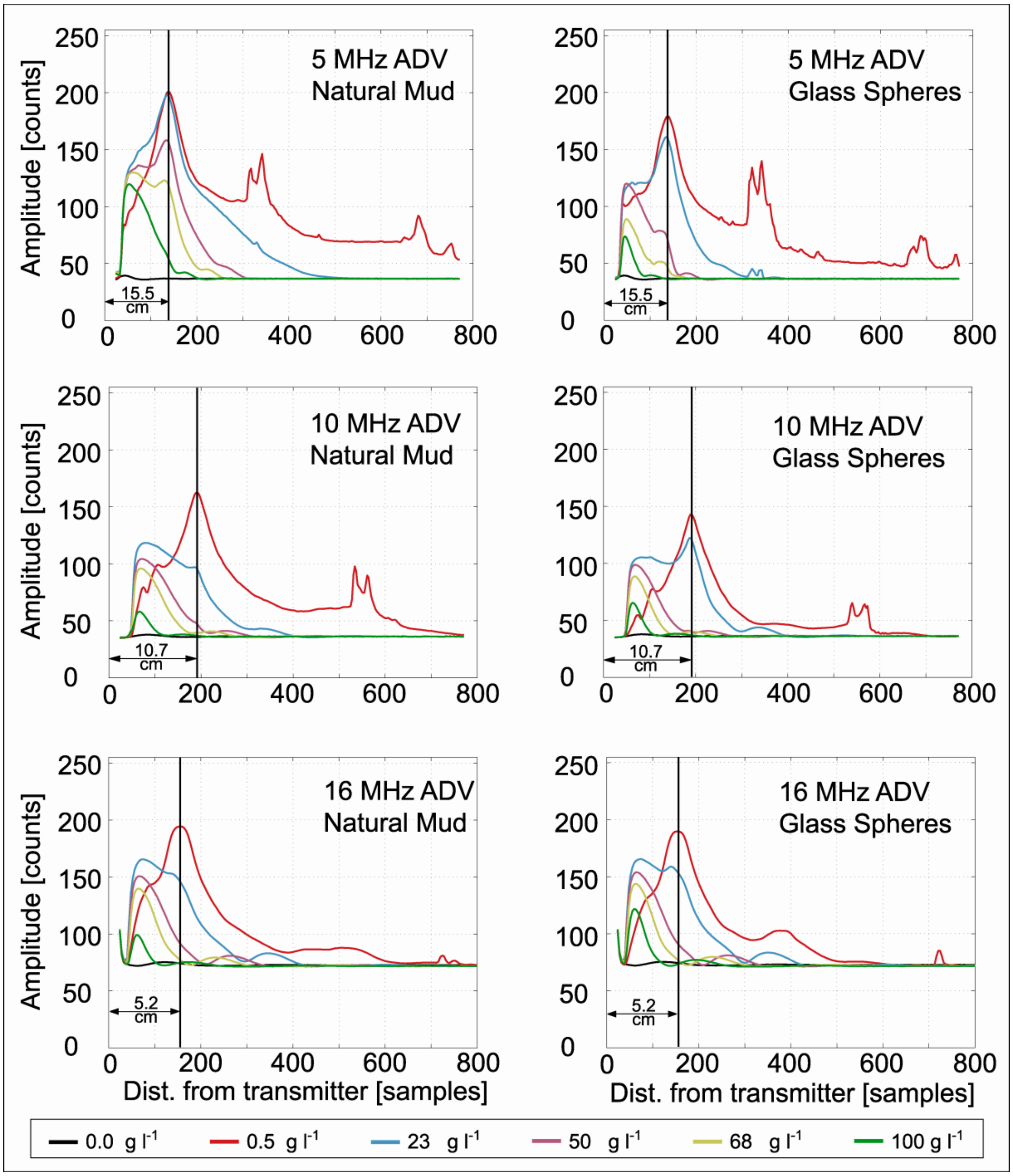

Fig. 5 BeamCheck data for selected runs for the two sediment types and all three ADV types. The black vertical line indicates the distance from the transmitter to the center of the sampling volume, in cm. The x-axis scale in cm varies with ADV frequency, speed of sound and probe geometry. For this work these values are: 0.110, 0.055, and 0.034 cm/sample for the 5, 10 and 16 MHz ADV, respectively.

Because an ADV's primary function is to measure velocity, under normal sampling conditions ADVs "listen" to reflections only off the sampling volume. More specifically, the window within which each receiver detects the reflections from the transmitted pulse is around 2-3 times the size of the pulse itself, with each receiver focused on the same location (SonTek 2001). As such, much of the information collected by a BeamCheck never makes it into traditional ADV data files. Therefore analyzing BeamCheck data offers a critical insight into data quality.

5. Discussion

Like all acoustic Doppler velocity sensors, ADVs do not actually measure fluid movement, but rather measure the movement of the particles contained within the fluid (it is assumed that this movement is the same as the fluid's). As such, sensors like the ADV can only operate when acoustically-detectable particles are present in their sampling volume and when those signals can be detected without interference. And, like all acoustic sensors, ADV pulses are susceptible to attenuation generated through absorption by the same particles they are measuring. At excessively high particle concentrations, this attenuation can be so severe that not enough signal is returned back towards its receivers and therefore accurate and precise velocity estimates cannot be obtained. Data quality parameters are then used to screen this data.

Review of correlation coefficient data as a function of sediment concentration for all three ADV frequencies, pulse lag lengths and sediment type yields curves useful in quantifying ADV performance (Figs. 6a and 6b). However, as the acoustic signature of the return pulses is not just a function of concentration, this data alone is insufficient to properly quantify ADV performance for a given sediment type. Additional data such as SNR (Figs. 6c and 6d), standard deviation of velocity (Figs. 6e and 6f) and BeamCheck (Fig. 5) are essential in this analysis. The data in Fig. 6 (a through f) represent the average of the first 10 s of each run, where settling effects were minimal.

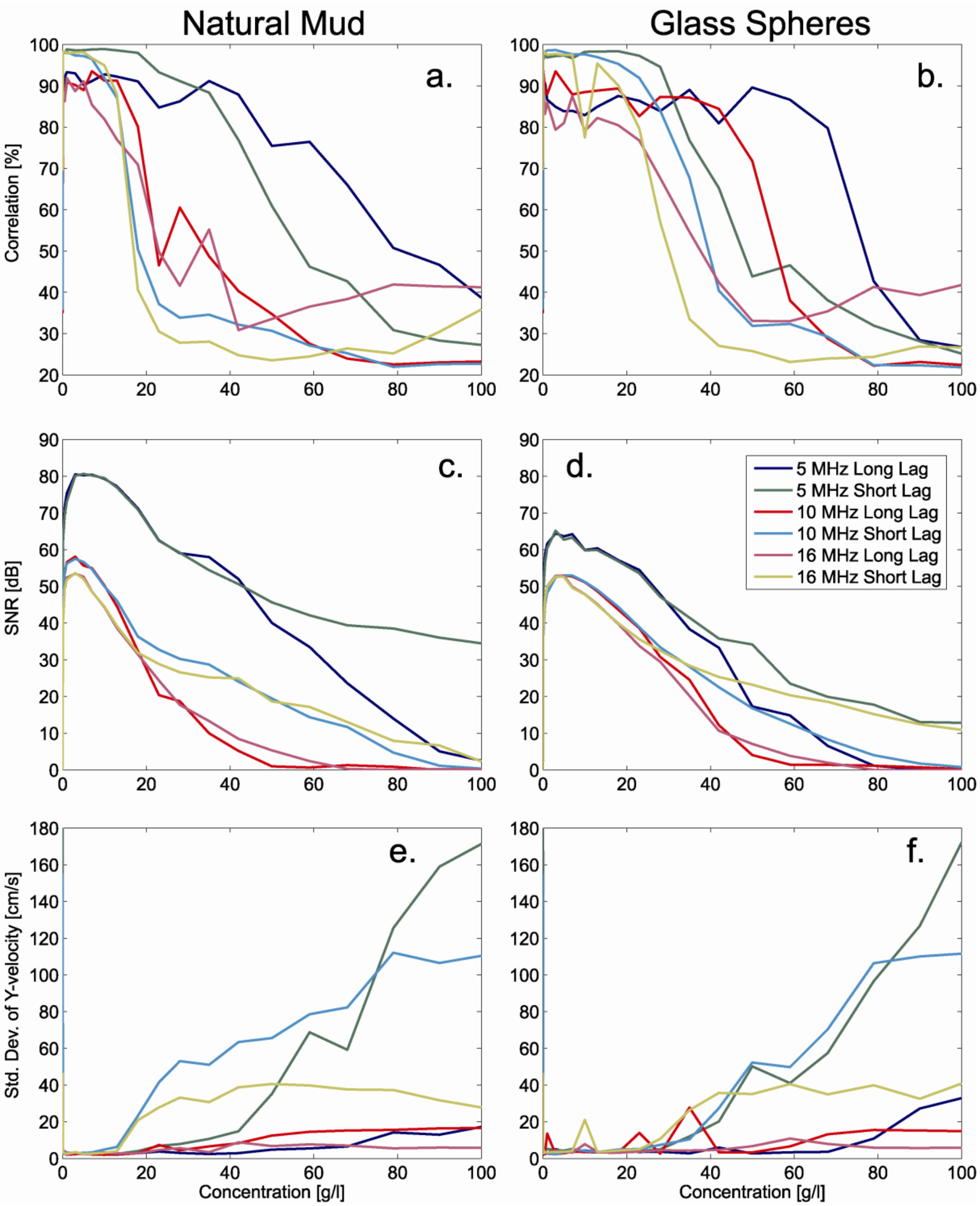

Fig. 6 ADV data as a function of concentration, sediment type and pulse lag length. Graphs a. and b. show correlation coefficient data. Graphs c. and d. show signal-to-noise (SNR) data. Graphs e. and f. show standard deviation of y-axis velocity. Data represents an average of the first 10 s of each run. Graphs on the left (a, c, e) are natural mud fluids, and the right (b, d, f) are glass spheres.

As expected, correlation curves (Figs. 6a and 6b) show high values for lower concentrations and then decrease at higher concentrations. The transition zone between acceptable (>70%) and poor (<40%) correlation scores varies with ADV frequency, pulse lag length and sediment type. Data collected from glass sphere suspensions show a more uniform pattern (primarily similar slopes) between correlation curves than those collected with natural mud, as the glass spheres are more equally distributed in size and are also smaller. Based on a

70% correlation score threshold, correlation curves suggest concentration limits of ~45-65 g l^{-1} for the 5 MHz ADV and ~15-25 g l^{-1} for both the 10 and 16 MHz ADVs for natural mud sediments. Higher values are observed for the more uniformly distributed glass spheres.

Signal-to-noise data (Figs. 6c and 6d) present rapidly increasing values at lower concentrations, peaking at the optimal scattering conditions and then decaying with increasing concentrations. Illustrating the 5 MHz ADV's improved performance under higher concentrations, SNR data for both natural mud and glass sphere cases present higher values than from the 10 and 16 MHz ADVs, both of which are very similar at low concentrations. This gap is more evident in the natural mud suspension given its wider particle size distribution and generally larger sizes.

At low concentrations effectively no distinction in SNR data exists between the two different pulse lags for the same frequency, the reason being that signal strength data is only recorded for the first pulse in a pulse pair, not both. As such, lags of different lengths will start to return different signal strength from the same concentrations once these concentrations become excessively high. If the separation point between the two curves of same frequency is taken as the threshold of acceptable data, Fig. 6c suggests limits of ~45 g l^{-1} for the 5 MHz ADV and ~18 g l^{-1} for both the 10 and 16 MHz ADVs for natural mud sediments. SNR data for glass spheres (fig. 6d) show more unified thresholds for each frequency, although following the same general pattern as for the natural mud. Alternatively, if the specified ~15 dB SNR threshold cutoff is used (SonTek 2001), working limits will vary considerably between frequencies and pulse lags used, varying from 30-85 g l^{-1}, highlighting the fact that often no one single parameter can be used to screen for valid data at very high concentrations.

Figures 6d and 6f show standard deviation of velocity for velocity along the y-axis. As expected, standard deviations are low for lower concentrations, and increase with increasing concentrations. As with correlation data, noticeable differences exist between data collected with short versus long pulse lags. Given the turbulent nature of the flow in this experiment, standard deviation data shows significantly reduced upper concentration thresholds when compared to both correlation score and SNR data. It is also notable that natural mud sediments have a lower threshold for acceptable standard deviation data than for glass spheres.

Complementary to correlation, SNR and standard deviation data, BeamCheck data (Fig. 5) more clearly demonstrates how the acoustic signal behaves under different concentrations, both before and after the sampling volume. In order for valid velocity measurements to be made, ADVs require that a discernable sampling volume peak to be present *and* that the signal strength in the sampling volume be higher than the noise floor level for the system. The height of the sampling volume should typically be greater than any signal closer to the transmitter. It is possible to make measurements at higher concentrations where signal strength near the transmitter is actually higher than at the sampling volume, however this is typically achieved with longer lags, which give enough time for the signal to dissipate and hence reduce the possibility of pulse interference. When a longer lag (lower velocity range) can be used, it may provide better performance at higher suspended sediment concentrations. However, if high velocity values are seen in a given environment it may not be possible to use the lower velocity range setting.

Reviewing all the data available in this experiment, we show that, for long pulse lags (low velocity ranges), valid velocity data can be collected up to ~50 g l^{-1}, ~28 g l^{-1}, and ~18 g l^{-1} for the 5, 10 and 16 MHz ADVs, respectively. And although the specific impact of particle size as a function of acoustic signal wavelength has not been addressed in this paper, the data presented here shows that, in general, the more uniformly distributed that the particles in the fluid are, the higher the working limit for an ADV will be (up to the point where concentration fully attenuates the signal).

6. Conclusions

This work represents the latest attempts known to date to evaluate ADV performance in fine-grained, high concentration fluids (i.e. fluid muds). We have not attempted to compare ADV data to known velocities, but rather present guidelines for the evaluation and validation of ADV data in fluid muds based on proxy data quality parameters. Some of these parameters, such as signal-to-noise ratio and correlation coefficient scores, are collected inside the ADV's sampling volume, while another parameter (BeamCheck) is collected as a full profile. We have also presented pulse lag settings as a core technique all ADVs use for specifying maximum measurable velocities, and how these can have a significant impact on the quality of ADV data in high concentration conditions. After analysis of the sample data collected, we have concluded that, for long pulse lags (low velocity ranges), valid velocity data from naturally occurring mud suspensions can be collected up to ~50 g l^{-1}, ~28 g l^{-1}, and ~18 g l^{-1} for the 5, 10 and 16 MHz ADVs, respectively.

7. Acknowledgements

We would like to acknowledge and thank Brett Patterson for his assistance during data collection and initial preparation for this work. We are also grateful for Michelle Lermon of Boston College for providing the mud and particle size data for this experiment. Without their help, this work would not have been possible.

8. References

Chang YS, Hanes DM (2004) Suspended sediment and hydrodynamics above mildly sloped long wave ripples. Journal of Geophysical Research 109:C07022

Elgar S, Raubenheimer B, Guza RT (2001) Current meter performance in the surf zone. Journal of Atmospheric and Oceanic Technology 18:1735-1746

Fugate DC, Friedrichs CT (2002) Determining concentration and fall velocity of estuarine particle populations using ADV, OBS and LISST. Continental Shelf Research 22:1867-1886

Haas KA, Svendsen IA (2002) Laboratory measurements of the vertical structure of rip currents. Journal of Geophysical Research 107:C5

Lane SN, Biron PM, Bradbrook, KF et al (1998) Three-dimensional measurements of river channel topography and flow processes using acoustic Doppler velocimetry. Earth Surface Processes & Landforms 23:1247-1267

Maddux TB, Nelson JM, McLean SR (2003) Turbulent flow over three-dimensional dunes: 1. Free surface and flow response. Journal of Geophysical Research 108:F1

McCool WW, Parsons JD (2004) Sedimentation from buoyant fine-grained suspensions, Continental Shelf Research 24:1129-1142

Seabergh WC, King DB Jr, Stephens BE (2001) Tidal inlet equilibrium area experiments, inlet laboratory investigations. US Army Corps of Engineers Report No. ERDC/CHL TR-01-20

SonTek (1997) Pulse coherent Doppler processing and the ADV correlation coefficient. SonTek Technical Note, November 1997

SonTek (2001) ADVField Technical Manual. SonTek Technical Documentation, September 2001

Trevethan M, Chanson H, Brown R (2006) Two series of detailed turbulence measurements in small subtropical estuarine system. Report No. CH 58/06, Division of Civil Engineering, The University of Queensland, ISBN 1864998520

Voulgaris G, Trowbridge JH (1998) Evaluation of the Acoustic Doppler Velocimeter (ADV) for Turbulence Measurements. Journal of Atmospheric and Oceanic Technology15:272-289

White BL, Nepf HM (2003) Scalar transport in random cylinder arrays at moderate Reynolds number. Journal of Fluid Mechanics 487:43-79

Contact Information

We welcome any comments, questions, or suggestions you may have.

SonTek/YSI, Inc.
9940 Summers Ridge Road
San Diego CA 92121-3091

Tel: +1 (858) 546-8327
Fax: +1 (858) 546-8150

E-mail: **inquiry@sontek.com**
Web: **www.sontek.com**