MEASUREMENT OF NEAR-BED SEDIMENT LOAD, PARTICLE SIZE, SETTLING VELOCITY AND TURBULENCE FROM A MULTI-FREQUENCY ACOUSTIC BACKSCATTER INSTRUMENT

ANDY SMERDON[1,2], DOMINIC VAN DER A[2], TOM O'DONOGHUE[2]

1. *Aquatec Group Ltd, Aquatec House, Stroudley Road, Basingstoke, RG24 8FW, UK. asmerdon@aquatecgroup.com.*
2. *School of Engineering, University of Aberdeen, Aberdeen, AB24 3UE, UK.*

Abstract: Observations of near-bed sediment suspension processes typically rely on a combination of acoustic and other ancillary sensors to monitor the dynamic suspended sediment environment. In addition to the suspended load, it is also of interest to quantify the settling and resuspension processes. Multi-frequency acoustic backscatter is an established technique for estimating vertical profile time series of mean particle size and concentration. Acoustic Doppler instruments are also used to measure water velocity intrusively at a single point, or in profiles of 3-dimensional velocity with spatial incoherence increasing as the measurement beams diverge from the transducers. Siting multiple acoustic instruments alongside one another can cause interference, leading to measurements having to be taken with either spatial or temporal separation. In this paper, we describe an approach for monitoring not only suspended load, but also parameters relating to settling velocity and turbulence in a single acoustic instrument with coincident beams.

Introduction

Measurement and analysis of the intensity of acoustic backscatter from suspensions of particles in liquids is an established technique for evaluating the characteristics of the suspended material. In the right circumstances, the use of multiple incident frequencies can provide sufficient information to estimate profiles of mean particle size and suspended load over depth (Thorne and Hanes, 2002; Thorne and Hurther, 2014). This has applications in science and industry, including observation of fundamental oceanographic processes, monitoring of coastal and civil engineering operations, and analysis of industrial processes.

Commercial instruments exist for the measurement and interpretation of multi-frequency acoustic backscatter from suspended sediments, including the AQUA*scat*® 1000 instrument from Aquatec Group, UK (Smerdon and Caine, 2007). With typical operating frequencies in the range 0.5 MHz to 5 MHz, this instrument exploits the frequency- and size-dependent response of sediments with radii between approximately 20 µm and 500 µm to derive profiles of mean particle radius from which mass concentration profiles can be calculated.

We use an enhanced configuration of a standard AQUA*scat* instrument with newly developed processing software functions. The instrument can use up to three acoustic transducers transmitting at different frequencies to measure suspended sediment load while also using one acoustic transducer to measure vertical suspension velocity and estimated turbulent kinetic energy dissipation rate, all in the same measurement volume.

While such commercial instruments have been available for over two decades, the data they acquire and the processing thereof are subject to several limitations. These include the adverse effect of bubbles within the suspension, which can appear acoustically similar to sediment particles, and difficulty in interpreting backscatter from very fine particles that may also have aggregated into larger flocs. To allow such instruments to be used widely outside the research domain, for example in coastal survey or industrial process instrumentation, these limitations must be addressed.

The motivation behind the work described in this paper is to identify some of these confounding components in an observed suspension by extracting additional information from the acoustic backscatter signal characteristics. A technique for observing settling velocity is described and illustrated with examples of hindered settling and rising bubbles. Observations of the latter provide one means of identifying bubbles in a suspension through their positively buoyant behavior. In addition, a method for assessing turbulent kinetic energy is explored as a means of establishing the likelihood of floc formation.

This paper begins with an introduction to the current state of the art in multi-frequency acoustic backscatter measurement, followed by further detail on settling velocity and turbulence measurement.

Multi-Frequency Acoustic Backscatter

The basic principle of the acoustic backscatter technique involves the transmission of a pulse of acoustic energy by a narrow-beam sonar transducer into the suspension. As the acoustic pulse moves away from the transducer, it insonifies any suspended material in the liquid. This material scatters sound energy, some of which travels back towards the sonar transducer, which also acts as a sound receptor. With knowledge of the speed of sound in water, the scattering strength of the suspended material, and the sound propagation characteristics, a relationship may be developed between the intensity of the received signals and the characteristics of the suspended material. Eq. (1) is a generalized backscatter equation for mass concentration, M at range r from the transducer (Thorne and Meral, 2008).

$$M = \left\{\frac{V_{rms}\psi r}{k_s k_t}\right\}^2 e^{4r(\alpha_w+\alpha_s)} \qquad (1)$$

where V_{rms} is the root-mean-square backscatter signal, ψ is a function that accounts for the acoustic transducer characteristics, k_s describes the scattering properties of the suspended sediment, and is a function of mean particle radius and incident frequency, k_t is an instrument system constant that takes account of all of the gain factors in the acoustic transmission and reception chain, and α_w and α_s are the attenuation due to absorption by water and sediment respectively.

The dependence of k_s on particle radius means that mass concentration cannot be calculated from backscatter at a single incident frequency. In Fig. 1, this is illustrated by plots of backscatter response at four typical AQUA*scat* frequencies on a fixed arbitrary y-scale for a fixed arbitrary mass concentration, versus mean particle size. However, the frequency dependence of k_s means that using multiple frequencies provides sufficient information to estimate particle size.

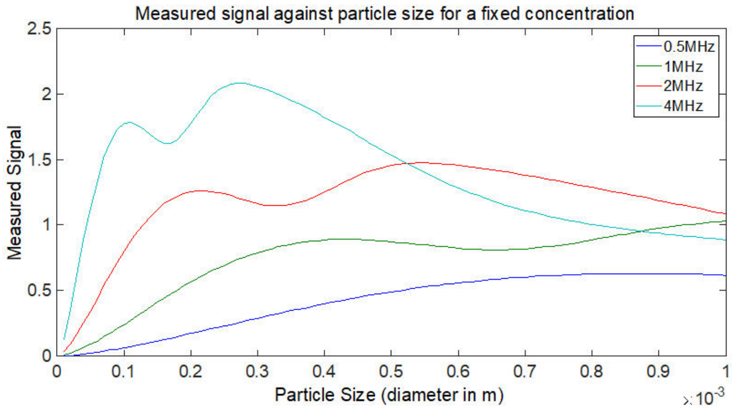

Fig. 1. Normalized multi-frequency response vs particle size for a fixed arbitrary concentration.

For an unknown mean particle size, Eq. (1) is applied to vertical profiles of acoustic backscatter at two or more frequencies. Different values of mean particle radii are tested to find the best fit and hence to estimate mean particle radius at each time and range. Once mean particle size has been derived, the mass concentration profile can be calculated.

Fig. 2 shows a typical time series of mass concentration and particle size that has been inverted using this method. The time series is of a coastal deployment of about 7 days leading up to, and then beyond a storm event. Time is on the x-axis with each profile representing an hourly sample; distance from the transducer is on the y-axis with the sea bed at the bottom of the plots; and color intensity is used to indicate mass concentration and particle size. Increased suspension activity occurs during the storm, first leading to bed accretion and then to erosion.

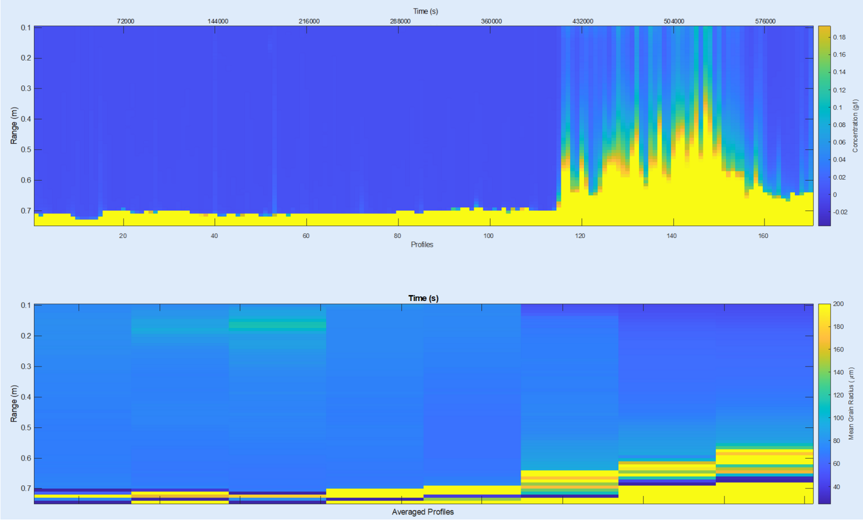

Fig. 2. Typical processed time series of vertical profiles of mass concentration and mean particle size.

Settling Velocity Measurement

In its standard configuration, the instrument gathers profiles of acoustic backscatter intensity at up to four frequencies, which are then inverted to size and mass concentration profiles. However, it is also possible to acquire the complex backscatter signal, comprising in-phase and quadrature components of the backscatter intensity. This allows not only the magnitude of the backscatter to be measured, but also its phase ϕ. Provided successive acoustic transmissions are synchronized in phase, the rate of change of backscatter phase from one transmission to the next can be measured. The rate of phase change is then converted to along-beam velocity c for the suspended scatterers (Eq. (2)).

$$c = \frac{\lambda}{2\pi} \frac{\mathrm{d}\phi}{\mathrm{d}t} \tag{2}$$

where λ is the acoustic wavelength. For a vertical beam, this velocity is the resultant of gravitational settling and turbulent lift. Initial experiments monitored the settling of fine sand in Aquatec's recirculating sediment calibration tower, which introduces sediment in a turbulent flow at the top that settles towards the bottom, and is then recirculated using a peristaltic pump (Fig. 3). The experiments have shown good correlation between acoustic measurements of velocity and Particle Image Velocimetry (PIV) measurements (Smerdon 2020). Fig. 4 compares velocity profile time series calculated from an AQUA*scat* instrument with PIV measurements from the same region. The x-axis is profile time sequence number; the y-axis is bin number, representing distance from the transducer in cm; and velocity is represented by the color intensity.

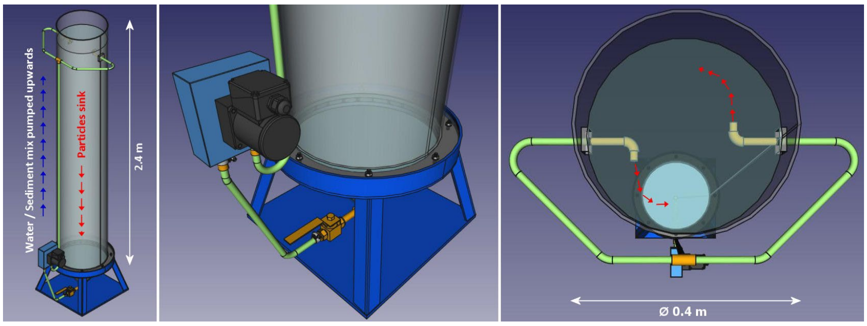

Fig. 3. Recirculating Sediment Tower.

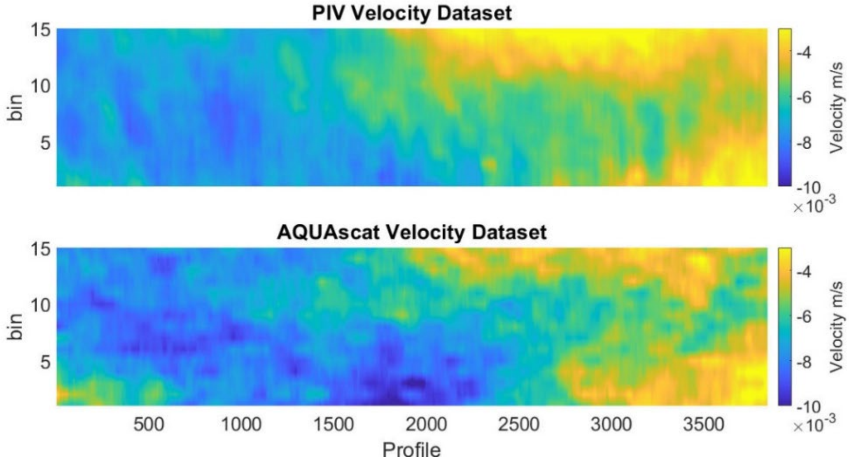

Fig. 4. Comparison of acoustic and PIV data.

The maximum unambiguous velocity measurement range of the instrument depends on the transmitted acoustic frequency and the time between successive transmissions, which should not result in phase change between measurements $d\phi$ exceeding π. In practical applications of the current instrument, this is limited to around 0.5 ms^{-1}.

The technique is also able to resolve very small settling velocities. Fig. 5 shows a time series of settling velocities in a sample of fluid mud. The mud was contained in a 0.25 m deep bucket with an intermittently operated stirrer. A 0.5 MHz acoustic transducer was deployed just below the surface, directed downwards. The y-axis shows the measured velocity at 0.1 m from the transducer, and is truncated to show the fine detail of the velocity variations. At time t = 0 s, the sampled concentration at the surface was 6 gl^{-1}, and 108 gl^{-1} at the bottom. Approximately 300 s prior to the start of the trace, the bucket was vigorously stirred, and this was repeated between time t = 400 s and t = 530 s, with velocity temporarily going off scale. The beginning of the trace shows velocity fluctuations of approximately ± 0.3 x 10^{-4} ms^{-1}. After the stirring event, the fluctuations initially cease, but gradually begin to increase again. We postulate that the observed velocity variance is due to the interactions between settling particles and the upwelling wake that they leave both in the fluid and from adjacent particles in this hindered settling environment.

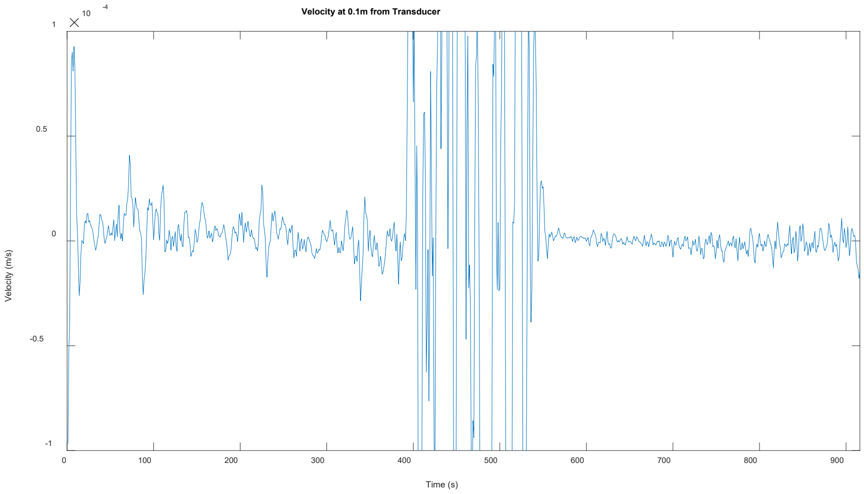

Fig. 5. Observations of velocity during hindered setting of fine mud.

The same acoustic technique for measuring along-beam velocity has also been used successfully to observe rising plumes of bubbles. An electrolytic bubble generator was deployed at the base of the same tower of Fig. 3. The bubble generator comprises two metal grids separated by 20 mm with insulating pillars. A direct current voltage of 15 V was applied across the two plates, causing the electrolytic generation of hydrogen and oxygen bubbles, which then rise towards a downward pointing acoustic transducer.

Fig. 6 shows a time series of velocity profiles following the brief actuation of the bubble generator. The x-axis is the velocity profile number, with profiles being measured 40 times per second. The y-axis is the range from the transducer, downwards towards the generator approximately 1.2 m below the transducer. The z-axis, also represented by color intensity, is the velocity. The generator creates a range of bubble sizes. The largest bubbles in the population rise most quickly, reaching the transducer after less than 2500 profiles (approximately 60 s, equivalent to about 0.02 ms^{-1}), while the smallest continue to linger for many minutes.

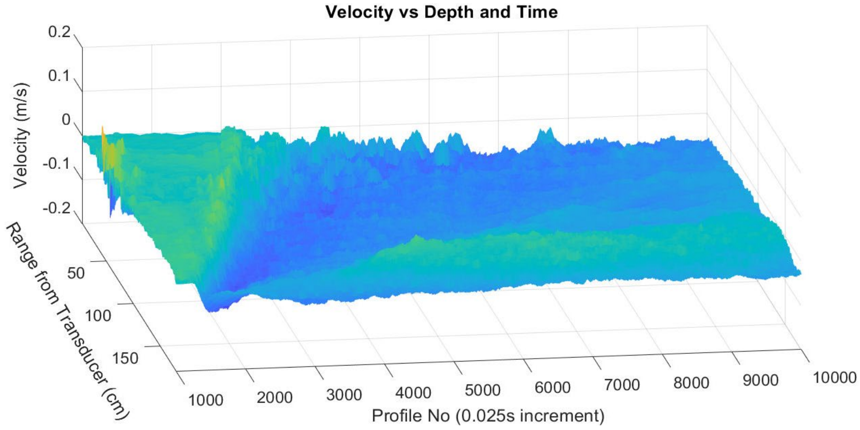

Fig. 6. Velocity measurements of a rising bubble population.

Turbulent Kinetic Energy Measurement

Turbulence measurement can provide insight into bed shear stress and cohesive sediment flocculation processes. If it can be assumed that the turbulent environment is locally homogeneous and isotropic, the turbulent kinetic energy dissipation rate ε can be derived by using a single vertical profiling beam such as the AQUA*scat*'s, uncontaminated by the wide bed echo from an angled conical beam such as from a Doppler profiler (Gargett, 1999). Turbulent kinetic energy dissipation rate is given by Eq (3).

$$\varepsilon = c_\varepsilon \frac{q'^3}{l} \tag{3}$$

where c_ε is a constant, and q' and l are respectively velocity and length scales of energy-containing eddies.

The technique requires analysis of the axial velocity deviations along the beam at an appropriate length scale. One challenge is how to select an appropriate length scale over which to measure the velocity variance. Gargett used a piecewise velocity zero-crossing analysis to assess the length scale and apply variance analysis. However, in studies of atmospheric turbulence (Akinlabi et al., 2019), velocity time series along a vertical beam have been processed using spectral analysis. This approach provides an energy spectrum that is partitioned according to length scale, with example spectra illustrated in Fig. 7. Experimental work is currently underway to validate these observations.

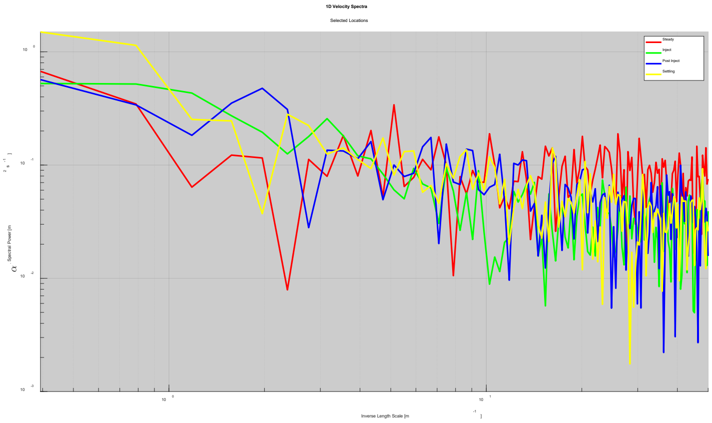

Fig. 7. An example of experimental one-dimensional velocity spectra.

Conclusions

We have described the current state of the art in the use of a commercial multi-frequency acoustic backscatter instrument for the measurement of suspended sediment mean particle size and mass concentration. By exploiting the instrument's capability to acquire a complex backscatter signal, profiles of the velocity of particles resolved along the acoustic beam can be calculated. When coupled with knowledge of particle size, this could be used to assess the density of the suspended particles and identify bubbles and flocs. Further statistical analysis of the velocity profiles has the potential to yield information about the turbulent kinetic energy dissipation rate over various length scales, which in turn can be used to assess the likelihood of floc formation.

Each measurement technique described in this paper has been demonstrated in stand-alone examples to emphasize the salient features. However, they are all mutually compatible in a single deployment by appropriate configuration of the instrument. It is therefore feasible to assess sediment load, mean particle size, vertical velocity and turbulent kinetic energy spectra on a single instrument and observation volume.

Acknowledgments

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