Measurements of Settling Velocity with an Acoustic Backscatter Instrument

Andrew Smerdon[1]

[1]Aquatec Group

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Abstract

Multi-frequency acoustic backscatter measurement can be used to observe spatial profiles of suspended sediment. The use of multiple frequencies helps to resolve mean particle size by exploiting the frequency-dependent relationship between scattering intensity and particle size. The AQUAscat acoustic backscatter profiler uses this principle to estimate mean particle size and concentration profiles with spatial resolution between 2.5 mm and 40 mm. The instrument is usually configured to acquire profiles of backscatter amplitude. However, an infrequently used setting on the standard instrument provides direct access to the quadrature sampled backscatter data stream, from which amplitude is normally calculated. By using the in-phase and quadrature sample data, the backscatter phase can also be calculated. The rate of phase change between profiles can then be related to the along-beam velocity of the scatterers. For a vertical beam, in the absence of vertical water motion, this is the settling velocity. This paper evaluates datasets and data processing approaches for estimating particle settling velocity. The experimental data is acquired with various types of laboratory generated suspensions, including glass spheres, sands, and flocculating mud. Besides extracting settling velocity data, the processing aim is to enhance the quality of acoustic backscatter data analysis.

Measurements of Settling Velocity with an Acoustic Backscatter Instrument

Andy Smerdon ≈ *Aquatec Group* and *University of Aberdeen, Department of Engineering, UK* ≈ asmerdon@aquatecgroup.com

Why?

Understanding settling velocity provides insight into flocculation processes and turbulent resuspension of sediment. In industry it aids understanding of processes involving precipitation of suspended solids, including mining and effluent treatment. However, it is difficult to measure directly *in situ*, especially without disturbing the measurement environment.

We are seeking improvements to measurement capabilities of a commercial multi-frequency acoustic backscatter profiler, the AQUAscat®. Knowledge of terminal velocity of suspended scatterers assists in:

- Classifying particle size and composition
- Identification of bubbles (easily confused with suspended solids)

Techniques such as PIV, holographic imagery, and acoustic Doppler velocimeters are invasive, while other *in situ* measurement techniques require sediment to pass through an instrumented settling tube, decoupling turbulent forces. Observation of hindered settling near the bed boundary layer is also difficult without disturbing the sediment.

What? The Acoustic Backscatter Instrument

The AQUA*scat*® 1000 multi-frequency acoustic backscatter profiler, manufactured by Aquatec Group, UK (Smerdon & Caine, 2007) transmits short pulses of ultrasound into the water column at different frequencies along a narrow beam. Particles in the beam scatter a proportion of sound back towards the instrument, according to the particle size and the frequency of the transmission. The arrival time of the received scattered sound is used to infer the distance from the transducer given the known speed of sound, with spatial resolution between approximately 2.5 mm and 40 mm.

Use of multiple frequencies allows particle size to be calculated from the different responses. The overall scattered sound level then determines the suspended load (Thorne & Hanes, 2002). The instrument is used in laboratory and field applications to record profile time series of suspended sediment load and mean particle size.

How? The Velocity Measurement Technique

Typically, the instrument measures averaged acoustic backscatter signal intensity at each frequency within spatial range bins. However, a rarely used feature provides a time series of real and imaginary components of the signal, from which both intensity and phase of backscatter in a given range bin can be calculated. The rate of change of phase between successive samples is used to derive mean velocity of the bin contents.

Short pulses of sound are transmitted at frequency f_r, wavelength λ_r and duration t_p. The cycle repeats after period t_r. Each transmission begins at the same phase, assumed to be zero at the transducer face. As the sound pulse travels away from the transducer through the suspension, particles in its path scatter sound, some of which is directed back towards the transducer, now acting as a receiver. The received signal voltage V_p generated at the transducer by the backscattered sound, initially at distance x_p from the transducer face, and travelling axially away from it at velocity c_p in a medium where the speed of sound is v_s, is given by

$$V_p(t) = a\sin\left(2\pi f_r + \varphi_p(t)\right) \quad where\ \varphi_p(t) = \frac{2\pi(x_p + c_p t)}{\lambda_r} \quad and\ \lambda_r = \frac{v_s}{f_r}$$

When V_p is quadrature sampled, it is represented by a complex sample stream $s(t)$:

$$s(t) = V_{Re}(t) + iV_{Im}(t) \quad where\ V_{Re}(t) = V_p(t)\sin\varphi_p(t) \quad and\ V_{Im}(t) = V_p(t)\cos\varphi_p(t)$$

From this we can compute the backscatter voltage V_b and phase φ_p

$$V_b(t) = \sqrt{V_{Re}(t)^2 + V_{Im}(t)^2} \quad and\ \varphi_p(t) = \tan^{-1}\frac{V_{Re}(t)}{V_{Im}(t)}$$

Now calculate the rate of change of phase - the phase velocity $d\varphi/dt$ - from consecutive samples taken at the same time after transmissions that are separated by t_r.

$$\frac{d\varphi}{dt} = f_r\left(\varphi_p(t) - \varphi_p(t-1)\right)$$

For a two-way transmission, the particle velocity u_p is given by

$$u_p = \frac{\lambda}{4\pi}\frac{d\varphi}{dt}$$

Does it Work?

Settling velocity u of particles of diameter d and density ρ_s in a fluid of density ρ_f and viscosity η, in the absence of turbulence, and in a low concentration suspension is given by (Stokes, 1901).

$$u = \frac{d^2 g(\rho_s - \rho_f)}{18\eta}$$

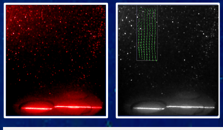
A series of experimental observations of settling sediment in a sediment tower (see right) showed that non-turbulent conditions were difficult to achieve. Consequently, the measurement of velocity was instead demonstrated by lowering a solid target along the transducer axis at a steady velocity, which was confirmed by video footage analysis.

Experiments in a Sediment Tower

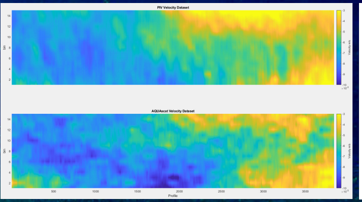
We used Aquatec's cylindrical, clear Perspex sediment tower (height 2.5 m, diameter 0.4 m) (right). Normal use is with a recirculating pump that draws sediment from the bottom and reintroduces it at the top with sufficient turbulence to create a homogeneous suspension. Unfortunately, this is not ideal for creating stable settling velocities. We opted to set up a DIY PIV system.

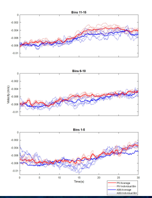
Our DIY PIV used a Bosch DIY Laser Level (Model PCL 20) introducing a vertical light sheet through the side of the tank and a GoPro Hero 3+ video camera deployed inside the tank with 40-70 µm diameter glass beads. The camera was set to 15 fps, 4k video for optimum resolution and exposure in the low powered laser light sheet. The video data was split into frames and processed in the PIVlab package (Thielicke & Stamhuis, 2014).

Video Frame Still *PIV Flow*



The images to the left show the red laser light sheet across the face of two upward-facing AQUA*scat* transducers. The 1 MHz transducer is the left hand one. PIV processing was constrained to the region directly above the transducer corresponding approximately to the acoustic beam cross-section. As can be seen from the flow lines, although there is a general downward settling flow, there is a clear turbulent eddy to the top left of the analysed region.

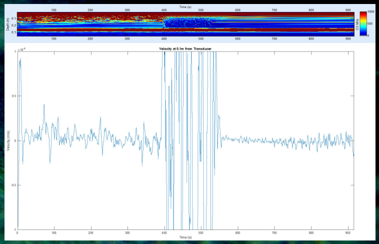




The data from the 1 MHz transducer and the PIV data are compared in the two plots to the left. A data set of 30 seconds of samples of fifteen 2.5 mm bins at 128 Hz (3840 profiles) is plotted on an intensity plot (left) with profile number on the x-axis, bin number on the y-axis, and velocity as intensity for both PIV and acoustic data. On the right, velocity time series for each individual bin are plotted in groups of 5 bins for clarity. The traces are in good general agreement in these initial experimental results, although there appears to be a small bias for the acoustic data to be slightly higher velocity than the PIV data.

Gloopy Mud in a Bucket

We took measurements of 'fluid mud' suspensions of fine sediment from the River Parrett near Bridgwater, UK. The mud was placed with fresh water in a container 200 mm x 300 mm, 300 mm deep, and agitated with a speed stirrer at the highest speed that prevented air being drawn down into the mix. The concentration was measured with physical samples to be near 6 g/l near the surface, and 108 g/l near the bed. The figure below shows on the upper plot backscatter intensity profiles from the 0.5 MHz transducer during a 25-minute experiment beginning 5 minutes after stirring had stopped. After 400 s, the stirring restarted for a period, after which the sediment began to resettle. On the lower trace is the calculated velocity time series from the bin corresponding to a range of 0.1 m from the transducer, calculated using the phase velocity algorithm.



The sediment appears to be oscillating up and down with a peak velocity of ±0.04 mm/s until agitation restarts. Then, because of limitations in the velocity calculation (further details below), the velocities were undersampled and have been clipped. Once agitation stops, the sediment resettles. Although initially stable, oscillations gradually resume.

Given the high concentrations, we know that we are observing hindered settling. We can speculate that as the previously agitated fine particles begin to flocculate, larger flocs tend to settle preferentially, putting pressure on the suspension below it. Local disruptions allow the lower suspension to escape and move upwards until the next layer of flocs descends.

What Next?

This method has a maximum velocity limit of around 10 mm/s for two reasons. It relies on the phase difference between successive complete profiles, whose timing is dependent on the maximum range of the profile. It is also constrained by the internal instrument signal processing, which imposes additional filtering on the data. Options are being explored to extend the velocity limit significantly.

Also of significant interest is the assessment of turbulence in the measurement volume. The measured particle velocity is the difference between gravitational settling, and upward turbulent diffusion. The AQUA*scat* has the capability to record simultaneous profile time series of mass concentration and along-beam velocity. This theoretically allows the estimation of diffusive flux.

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