Design and Performance of a New Multi-Frequency Coherent Doppler Profiler

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ABSTRACT

Acoustic systems provide great potential for non-invasive sampling of near bottom sediment transport processes: acoustic backscatter can be inverted to infer the concentration of suspended particles, and the Doppler shift can be used to determine flow speeds. We present a coherent Doppler system employing multiple frequencies between 1.2 and 2.4 MHz. The use of multiple frequencies allows ambiguity resolution in the coherent Doppler velocity and can also be used for the estimation of suspended particle size distribution. The combination of measurements allows direct estimation of the sediment transport flux. As with any acoustic system design there are many performance characteristics that must be taken into consideration and the use of multiple frequencies further complicates this problem. The design process was facilitated through use of a model of coherent acoustic backscatter developed for this purpose. We present the principles of coherent sonar systems in general. The prototype system can generate three component velocity profiles with 0.3 cm range resolution over a 40 cm range at a rate of up to 100 per second. Horizontal velocities as high as $4\ \mathrm{m\,s^{-1}}$ can be resolved. System performance is demonstrated with model simulations and examples from laboratory observations.

INTRODUCTION

Making observations of sediment transport presents a challenging instrumentation problem. The scales of interest close to the water-sediment interface are small and any instrument placed into the area being measured alters the flow and contaminates the measurements. Acoustic systems therefore have valuable capabilities for working in this environment because they provide a largely non-invasive measurement approach. Coherent Doppler operating at MHz frequencies is capable of providing velocity measurements over an interval of about 40 cm with sub-centimeter resolution [Zedel and Hay (2002)]. However, such observations are complicated by the occurrence of velocity ambiguities that cannot always be resolved. This paper describes a new instrument that addresses these ambiguities through the simultaneous use of multiple frequencies [Hay et al. (2008)]. The multi-frequency capability also allows for coincident particle concentration and size distribution measurements: such co-

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incident measurements are required in order to estimate turbulent fluxes of suspended sediment.

MULTI-FREQUENCY, PULSE-TO-PULSE COHERENT DOPPLER

Pulse-to-pulse coherent sonar measures profiles of phase in acoustic backscatter. If successive profiles are collected quickly enough so that the phases are correlated then the change in phase can be related to the velocity according to

$$v = \frac{\delta\phi}{4f\pi\tau}C \tag{1}$$

where $\delta\phi$ is the change in phase, f is the system frequency, τ is the time between transmit pulses and C is the speed of sound. This approach is used in "pulse coherent" radar [Zrnic (1977)] and is the basis for point acoustic Doppler velocimeters (ADV's) in use today [see Lohrmann et al. (1994)].

Ultimately, the accuracy of these systems is limited by the degree of correlation between successive pulses (quantified by the correlation coefficient). Generally, for systems operating over 1 m in range so that transmit pulses can be sampled at intervals of order 1 ms, high levels of coherence at MHz frequencies are possible. What limits the application of these systems for profiling applications is the occurrence of velocity ambiguities that arise in Equation (1) because $\delta\phi$ can only be determined to within $\pm\pi$. There are two standard approaches that have been applied to deal with this problem: one is to use different values of τ, [see for example Joe and May (2003)], and the other is to consider flow geometry as is done in Smyth et al. (2002). In practice, the choice of pulse interval (τ) is not strictly a free parameter as it is constrained by the deployment geometry and the occurrence of multiple acoustic reflections. It is not always possible to select a suitable combination of pulse intervals to work with. In addition, it takes time to make the additional measurements so that they can never be made simultaneously. For the case of tracking flow geometry, it is not always possible to know or track the flow structure as it evolves.

The approach that we take to resolve the velocity ambiguities is to use backscatter from two (or more) frequencies simultaneously [Hay et al. (2008)]. Considering Equation (1), if two frequencies are sampled for the same flow velocity, then by requiring the two velocities to agree, the ambiguity velocity can be eliminated. When calculated directly using now two measured phase differences, the velocity can be estimated as

$$v = \frac{\delta\phi_2 - \delta\phi_1}{4(f_2 - f_1)\pi\tau}C \tag{2}$$

where $\delta\phi_1$ and $\delta\phi_2$ are the phase changes corresponding to frequencies f_1 and f_2.

Equation (2) still has an ambiguity velocity corresponding to the limitation on measuring the difference between the two phase differences, that is $\delta\phi_2 - \delta\phi_1$, however the associated velocity ambiguity is scaled by $1/(f_2 - f_1)$. Mathematically, the value of $f_2 - f_1$ could be made arbitrarily small so that the maximum velocity that can be measured would become very large. In a practical system this is not the case because at some point, the uncertainty in measuring the $\delta\phi$'s becomes comparable to the value of $\delta\phi_2 - \delta\phi_1$ itself and the velocity estimates become meaningless.

PRACTICAL SYSTEM

Equation (2) or (1) allow velocity estimates for a simple backscatter system which can only allow measurement of one velocity component. In order to resolve three component velocities, it is necessary to have at least three separate beams. We employ a bistatic arrangement with one vertically directed transmitting and receiving beam that, by itself, allows direct measurement of vertical velocity [for example, see Hurther and Lemmin (2000)]. A pair of receivers is arranged around the central transducer as shown in Figure 1 to make x-component measurements with a second pair arranged in the y-z plane to define the y-component measurements. The redundancy in this geometry is used to further reduce errors and the symmetry provides some correction for geometric alignment errors.

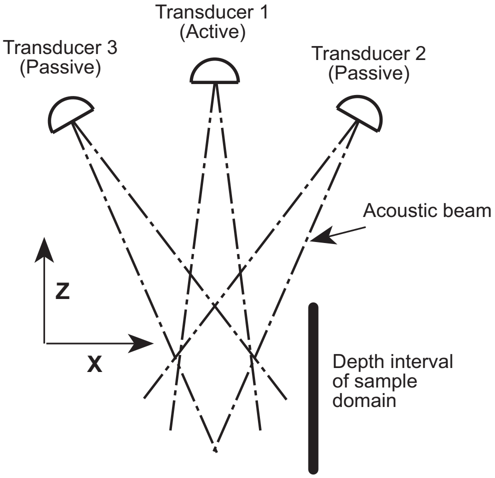

Figure 1: Geometry of bistatic transducer arrangement. For clarity, only the two receivers used for extracting x-component velocities are shown. An additional pair situated in the y-z plane are required to determined the y-component velocities.

In order to work over a reasonable range of conditions, the multi-frequency approach needs to use a relatively wide bandwidth. We employ transducers with a center frequency of 1.6 MHz and a bandwidth of 1.0 MHz. The central transducer is used to transmit a single pulse consisting of 4 separate tones at 1.2, 1.5, 1.8, and 2.1 MHz. The transmit pulse at each frequency is typically 5 μs duration giving a bandwidth of about 200 kHz for each frequency. Backscatter from this single pulse is recorded by all five receivers. For each receiver, the signal is separated into four independent channels using digital tuning techniques. The data is sorted into 5 μs range gates giving a range resolution of $dr = C\tau/2 = 3.25$ mm. Spatial resolution across the beam is determined by the beam geometry and depends on range, varying between 1 and 2 cm.

There are many operational constraints that have been considered in choosing the final combination of operating parameters. In order to tune the final design of all aspects of the system, a model of acoustic backscatter was used as described in Zedel (2008). This model simulates the entire acoustic scattering process and then simulates the analog and digital signal processing in use. An example of model output is shown in Figure 2. This data simulates a system operating at four frequencies (1.5, 1.8, 2.1, and 2.4 MHz), and generating profiles at a rate of 1000 s^{-1}: after averaging over 10 pulse pairs generating profiles at a rate of 100 s^{-1}. The flow field that has been modeled is a purely horizontal sinusoidal velocity with amplitude 3 $m\,s^{-1}$ that is uniform in depth. The flow is sampled at a range of 70 cm from the central transducer (see geometry in Figure 1). Data are simulated over the entire sample interval of the profiler but for clarity, only data from one of the range bins at 70 cm is presented. The dashed line in Figure 2a shows the directly measured horizontal velocity component at 2.1 MHz demonstrating the characteristic velocity wrapping associated with the ambiguity velocity for that acoustic frequency. When the velocity is recalculated using Equation (2), the resultant velocities are shown by the solid line in Figure 2a. Figure 2b shows the difference between the input velocity and the extracted velocities. Notice that velocity uncertainty scales with the magnitude but there is no evidence of any bias. The transitions through ambiguity wraps of individual frequencies does not increase the estimate errors.

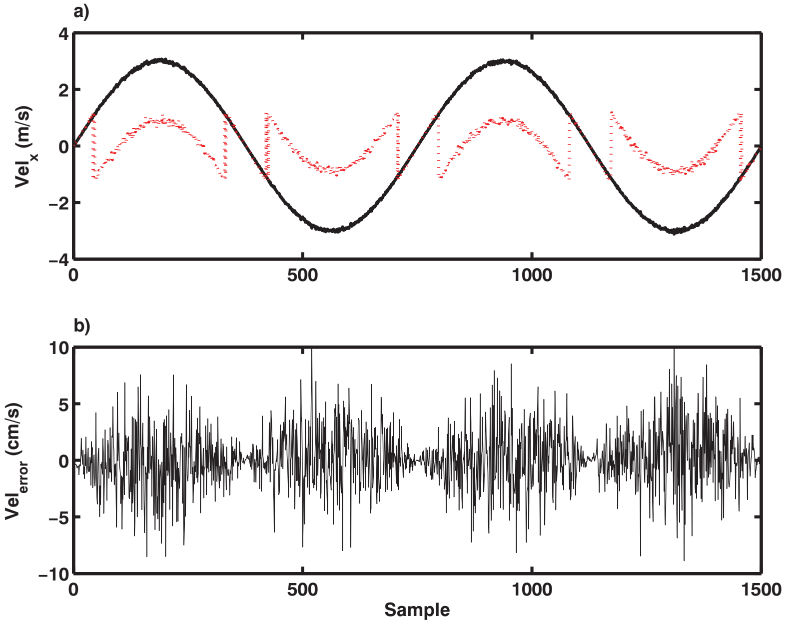

Figure 2: Simulation of multi-frequency sampling scheme. a) 2.1 MHz extracted (dashed line) and multi-frequency corrected (solid line) horizontal velocity. Input data is a 3 $m\,s^{-1}$ sinusoidal signal. b) Error in the measurement plotted as measured x-velocity - true x-velocity.

LABORATORY DEMONSTRATION

We demonstrate the performance of the prototype system operating in the turbulent jet described by [Hay, (1991)]: in this system, a particle laden turbulent jet is directed vertically into a tank measuring approximately 1 m^3. The Doppler profiler is rotated so that the active beam is directed across the turbulent jet as shown in Figure 3. This system allows evaluation of the acoustic measurements in a well characterised, turbulent environment [see for example, Zedel and Hay (1998)].

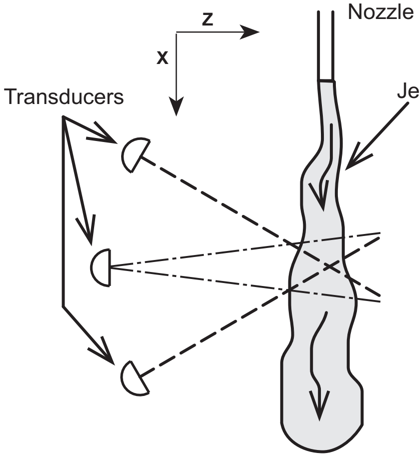

Figure 3: Geometry of the multi-frequency Doppler system sampling a turbulent, sediment laden jet. Notice that the coordinate system is rotated by 90°.

An example of coherent Doppler observations from the turbulent jet is shown in Figures 4a, b and c, representing axial velocity, transverse velocity, and concentration respectively. In this system, data is only extracted from regions of the jet where there is adequate backscatter from the particles suspended in the jet. Poor data quality in velocity (Figures 4a, and b) at cross jet positions approaching ±10 cm is associated with low backscatter levels (consider Figure 4c). The velocities show the turbulent nature of this flow and yet close inspection of the Figure 4a, and b shows correlation between bursts in axial speed and transverse flow. Concentration (Figure 4c) is represented by backscatter intensity at 1.2 MHz: these values are un-calibrated and the multiple frequency information is not being used.

The velocity and concentration data of Figure 4 can be combined to estimate transport both along the jet and across the jet (Figure 5). Transport in this case is in arbitrary units because the concentration data is uncalibrated, however these units are the same between both axial and transverse transports. The basic form of the transport is as expected for such a system [Zedel and Hay (1998)]: Figure 5a shows a roughly Gaussian axial transport with a low transport away from the jet axis.

CONCLUSIONS

We have reported on a prototype instrument that collects (phase coherent) backscatter data simultaneously at four frequencies. When processed as pulse-coherent Doppler, this approach allows the resolution of velocity ambiguities by considering apparent velocity measurements at the different frequencies. In addition, the multiple independent measurements allow for reduced velocity

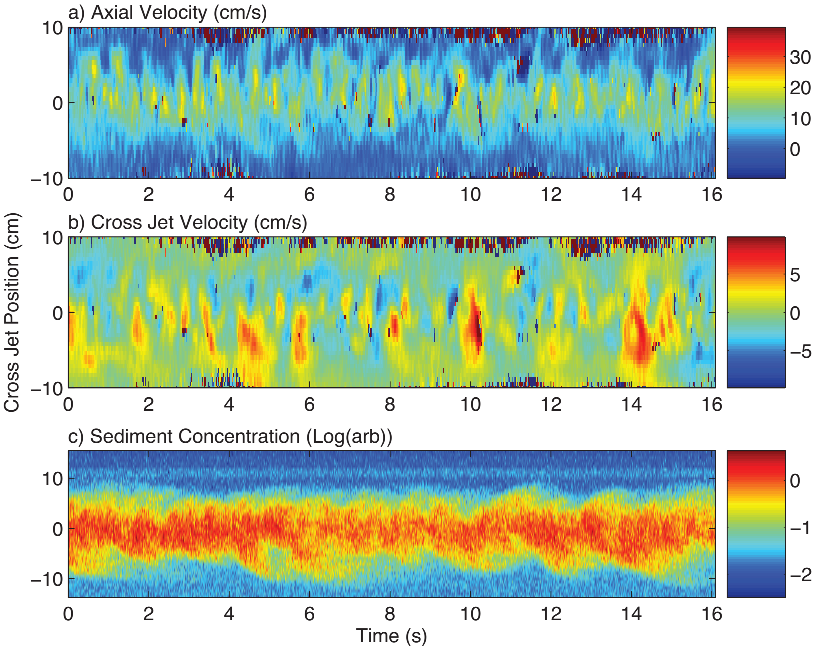

Figure 4: Example of observations across a turbulent jet: a) axial velocity, b) cross jet velocity, c) sediment concentration.

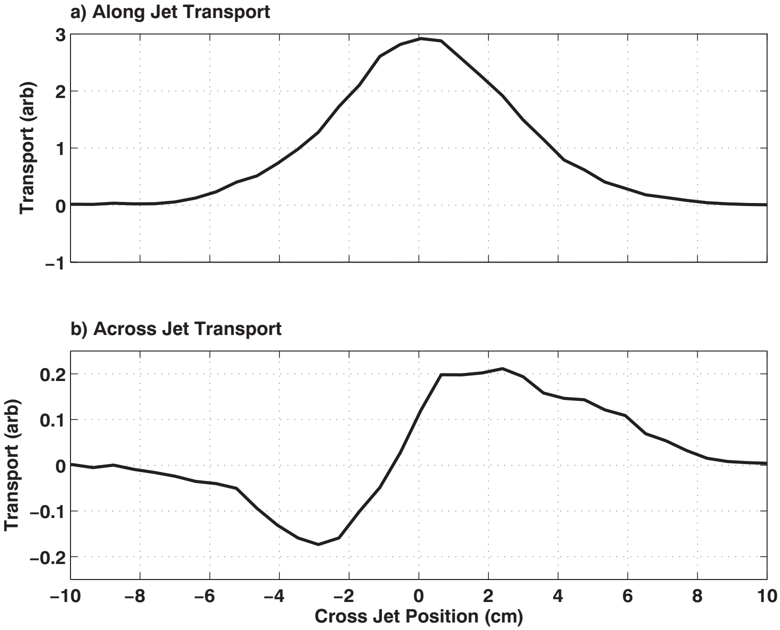

Figure 5: Transport extracted from velocity and concentration measurements: a) axial transport, and b) cross jet transport.

variance. Our model tests of this approach suggest that we should be able to operate in environments with velocities as high as 4 $\mathrm{m\,s^{-1}}$. Future development of this system will involve direct comparison of the Doppler resolved velocities with Particle Image Velocimetry (PIV) observations in the turbulent jet and possibly other flow geometries. An overall velocity accuracy test will be completed by assessing system performance in a towtank [similar to that described in Zedel and Hay (2002)].

A parallel capability and equal motivation for the present development is the ability to infer particle size distributions from the backscatter intensity data [Hay and Sheng (1992)]. The contribution here is the use of broad-band transducer technology to make those measurements simultaneously with a single system. We will be implementing this technique once we have undertaken backscatter calibrations of the final system.

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