Multi-Frequency, Pulse-to-pulse Coherent Doppler Sonar Profiler

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Abstract **- Under ideal conditions, pulse-to-pulse coherent Doppler sonar can measure profiles of water velocity with unparalleled accuracy and resolution. However, this technique is limited in application by the occurrence of range and, more critically, speed ambiguities. A simple way to deal with speed ambiguities is to invert velocities using time history or prior knowledge of the flow structure, but these approaches are not always practical or reliable. Another technique is the use of a dual (or multiple) pulse repetition interval: this approach provides a reliable means of improvement but reduces the profile sample rate, and the pulse repetition interval is not always a free parameter (for example in the presence of a boundary). We present a new approach where multiple acoustic frequencies are used simultaneously, allowing a nearly five-fold increase in ambiguity velocity with no reduction in profile sample rate. Results are presented from a prototype multi-static system operating over the frequency range from 1.2 to 2.4 MHz, enabled in part through use of broad-band piezo-composite transducers. The prototype system generates two-component velocity profiles at a rate of 150 profiles/second over a 30 cm range interval with 3 mm range resolution. System performance is demonstrated under laboratory conditions with observations of flow in a turbulent jet.**

I. Introduction

Pulse coherent sonars have been used effectively to explore boundary layer characteristics in a variety of environments. [1], and [2] use the technique to explore turbulence generated by breaking waves. Studies of near-shore processes are reported by [3], [4], and [5]. Applications to studies of open channel flow have been reported by [6] and [7]. The occurrence of range and velocity ambiguities characteristic of the technique restrict more general application.

In this type of Doppler sonar, velocities are estimated by comparing backscatter from successive acoustic pulses. If the time between pulses is sufficiently short that the backscatter is correlated, then the change in phase of the backscatter is proportional to (a geometry dependent) velocity component [8],

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

where f is the reference (or system) frequency, $\Delta\phi$ is the change in phase, C is the speed of sound in water (about 1450 $\mathrm{m\,s^{-1}}$), and τ is the time between successive pulse transmissions or the pulse repetition interval. This interval must be less than the time it takes for backscatter from a given range to become decorrelated: the decorrelation time.

Backscatter range evolves with time according to the relation:

$$r(t) = \frac{Ct}{2} \tag{2}$$

where t is the time elapsed since the pulse was transmitted. In a typical sonar system, the maximum range is determined by that time (or range given (2)) at which acoustic absorption and spherical spreading decrease the signal level below the system noise level: the signal decay time. Range ambiguities arise because the decorrelation time is typically less than the signal decay time and thus backscatter from a sequence of pulses but different ranges can overlap in time.

The velocity ambiguity is an inevitable consequence of using phase change to determine velocity since phase can only be determined to within a $\pm\pi$ uncertainty. The corresponding velocity ambiguity is given as

$$\Delta v = \frac{C}{4f\tau}. \tag{3}$$

For sonar systems operating in typical oceanic conditions, the relations given by (1), (2), and (3) subject to the requirement for coherent backscatter constrain these systems to operate over distances on the order of 10 m (or less). And, for the boundary layer investigations that form the focus of our applications, (10's of cm in range and 10's of $\mathrm{cm\,s^{-1}}$ in velocity), both range and velocity ambiguities become important and greatly complicate the data interpretation.

Doppler sonar is not the only application of the pulse-coherent technique, medical Doppler ultrasound, and pulsed Doppler radar also use pulse-to-pulse coherent processing schemes that are subject to range and velocity ambiguities. In medical applications, the short ranges allow sufficiently short pulse delays thereby avoiding velocity aliasing in most applications. There are however circumstances where velocity aliasing can become a problem (see [9]). Pulsed radar does not generally encounter problems with range but must deal

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with speed ambiguities. Two general approaches are available for dealing with the velocity ambiguities; the time history and spatial structure of the velocity field can be used to reconstruct the data or, a variety of pulse delays can be used to solve for the actual speed.

The technique that we have used in the past for recovering ambiguity errors is that based on knowledge of the velocity field [5]. For us this has been a tedious approach requiring a great deal of manual intervention. More sophisticated approaches have been applied to radar data as described (for example) by [10]. Any approach based on velocity field history will potentially become application specific.

The other commonly used approach is based on interleaving two (or more) pulse delays giving rise to near coincident data with different characteristic ambiguity velocities as regulated by (3). Optimal ways of applying this approach are discussed by [11], and [12]. The drawback of the dual pulse delay approach is that it necessitates a decrease in the data rate by consuming time for the additional pulse pairs. There is also the problem that in the presence of a boundary, strong reflections (and multiples) may constrain the choice of possible pulse repetition rates.

In this paper, we introduce an approach based on the use of multiple carrier frequencies as described by [13]. This method is similar in concept to the dual pulse delay approach but there is no reduction in the data rate because multiple frequency pulses can be transmitted simultaneously. There is another benefit in that backscatter from multiple frequencies can be used to invert for scatterer size and concentration, with application to sediment transport, for example.

II. Multi-frequency Doppler: Theory

Consider the velocity estimate as generated using (1): for a given flow speed, the phase change $\Delta\phi$ is determined by the frequency and the inter-pulse interval τ. If $\Delta\phi$ is measured at two separate frequencies (say f_1 and f_2), the velocity can be found directly from each frequency, but it is also possible to form an estimate using the difference between the separate frequency results:

$$v = \frac{C}{4\pi\tau(f_2 - f_1)}\Big(\Delta\phi(f_2) - \Delta\phi(f_1)\Big). \qquad (4)$$

Equation (4) still contains a characteristic ambiguity now given by

$$\Delta v_{12} = \frac{C}{4(f_2 - f_1)\tau}. \qquad (5)$$

Equation (5) suggests that the ambiguity velocity can be made arbitrarily large by making the frequency difference $f_2 - f_1$ small. In practice, as $f_2 - f_1$ becomes smaller, so does the value of $\Delta\phi(f_2) - \Delta\phi(f_1)$. When this phase difference becomes comparable in size to the uncertainty in the phase measurements themselves, the velocity estimates made using (4) will decrease in accuracy (see [14]). A related consideration when using (4) is that it combines uncertainties from two phase estimates and so it is inherently noisier than a velocity estimate based on a single phase estimate. Both of these factors must be taken into consideration when applying the dual frequency method. The approach requires a minimum of two measurement frequencies but the use of additional frequencies provides independent measurements that can improve the estimate accuracy.

III. System Configuration

A. System Geometry

The realization of a practical Doppler system involves many trade-offs accounting for the velocity field that is being measured. In our particular application, we are interested in velocities above a rough boundary (the sea-bed) with a (usually) well-defined amplitude return. The horizontal velocities are of order 1 $\mathrm{m\,s^{-1}}$, and usually large compared to the vertical velocities. Both velocities go to zero at the bottom, and the vertical structure of the flow is of fundamental interest dynamically. Thus, we want to make observations as close as possible to the bottom but we also want simultaneous three component velocity measurements. The preferred geometry for this application is a bistatic system (as considered by [15] and [7]).

The geometry of the present system is shown in Fig. 1. By adjusting the angle between the tilted transducers, we reduce the component of horizontal velocity being sampled by the transducers while retaining accuracy in the vertical component. In addition, the downward looking geometry keeps the transducer assembly far from the region being sampled thereby minimizing flow disturbance. Our system has a total of five transducers: two additional transducers are positioned in the orthogonal plane but are not drawn in Fig. 1. In this configuration, the central transducer is used to transmit the acoustic pulse while all transducers receive backscatter. A single pair in a plane is adequate to resolve two components of velocity but the symmetrical pair affords an increase in measurement accuracy.

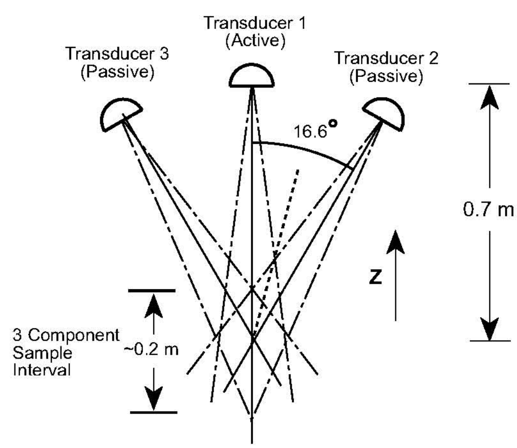

Figure 1: Bistatic beam geometry.

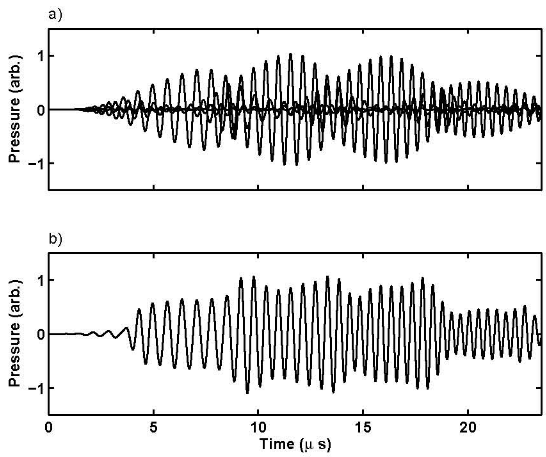

Figure 2: Transmit pulse template. a) Constituent pulses at 1.5, 1.8, 2.1, and 2.4 MHz and b) formed multi-frequency pulse. Each constituent is 4.7 μs in duration, the transducer has a center frequency of 1.8 MHz and bandwidth of 800 kHz.

B. Transducers

It is only possible to use the multi-frequency technique if a multiple frequency or a broadband acoustic pulse can be transmitted. We have used piezocomposite transducers that allow a bandwidth of about 60% of their center frequency [16]. We transmit four separate single frequency pulses in succession as shown in Fig. 2.

C. Data Acquisition

Pulse coherent Doppler requires that pulse transmission and backscatter sampling remain phase locked. This coordination is achieved using a controlling computer driving the transmission and data acquisition circuitry as shown in Fig. 3. Four separate frequencies are phase detected simultaneously and stored for later analysis: each of these signals is equivalent to a single frequency coherent sonar.

D. Data Inversion

The conversion of phase data into velocities is accomplished by using (4), allowing for the transducer geometry, and accounting for the various frequency combinations possible. Modeled data has been used to explore the velocity unwrapping algorithm [17]. In Fig. 4, a horizontal sinusoidal flow is sampled by the transducer geometry shown in Fig. 1. In Fig. 4a to d, extracted horizontal velocity estimates for frequencies 1.5, 1.8, 2.1, and 2.4 MHz respectively are shown: each of these frequencies shows ambiguity velocity wraps. The ambiguity wraps occur at lower velocities for the higher frequencies as regulated by (1) and (3). Fig. 4e shows the horizontal velocity recovered using phase differences among the four frequency combinations. It is important to note here that there is no consideration given to the time history or spatial structure of the velocity: each estimate is derived independently in time and range.

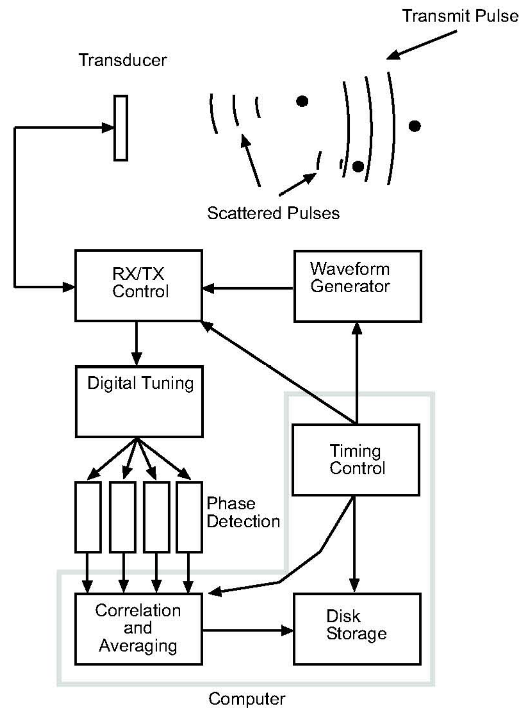

Figure 3: Block diagram identifying signal processing and control components used in the multi-frequency Doppler system.

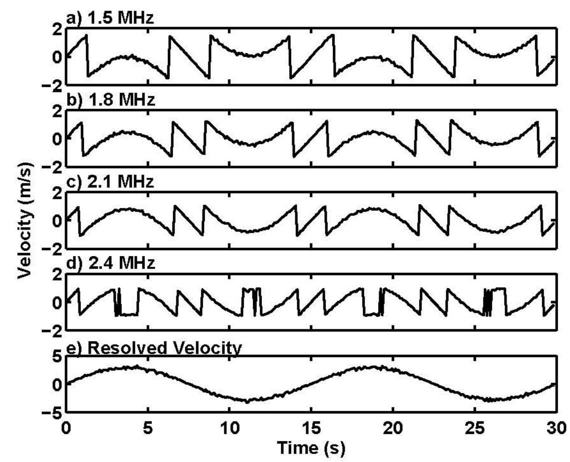

Figure 4: Example of velocities recovered from simulated backscatter plus noise at a) 1.5 MHz, b) 1.8 MHz, c) 2.1 MHz, d) 2.4 MHz. For these discrete frequency velocity estimates, output velocities are restricted by the ambiguity velocity. e) shows the reconstructed velocity using the multi-frequency information.

IV. Turbulent Jet Observations

A system operating at frequencies of 1.2, 1.5, 1.8 and 2.1 MHz has been tested in the laboratory using a turbulent wall jet as shown in Fig. 5. A sediment-laden flow is directed along a vertical back-plate to create a downward-flowing turbulent wall jet. The thickness of the jet is ca. 5-10 cm, approximating the vertical scale of the wave bottom boundary layer in coastal and continental shelf environments, including the nearshore

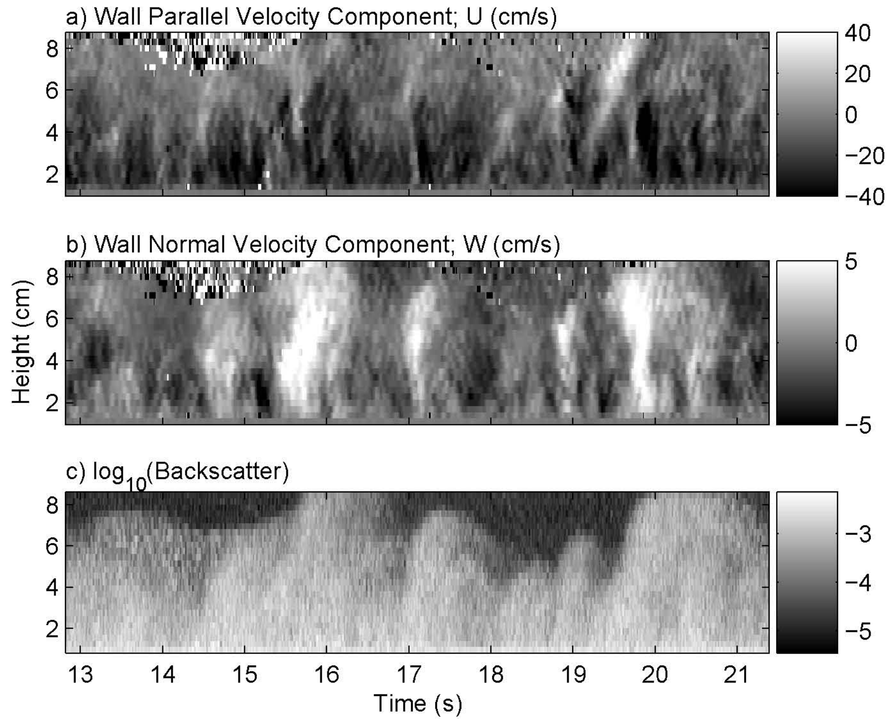

Figure 6: Time series of profiles spanning the turbulent wall jet. a) jet axial velocity, U; b) wall normal velocity, W; c) active (center) beam backscatter amplitudes at 1.5 MHz.

zone. For these data, averaged profiles are generated at a rate of 60 s^{-1} with a range resolution of 3 mm. The jet velocity is controlled by varying the rotation speed of the re-circulating pump. The system was oriented so that it profiled horizontally across the vertically-directed jet. An example of data collected with the system is shown in Fig. 6 with backscatter profiles from the active (horizontally directed) beam at 1.5 MHz, jet axial velocities, U; and transverse (normal to the wall) velocities, W, Fig.'s 6a, b, and c respectively. The observations reveal a richness of structure as turbulent bursts occur in the flow. Comparison between the velocity and backscatter data reveals correlations between sediment concentration and velocity fluctuations. Regions of the flow for which inadequate backscatter is available to reconstruct velocity profiles occurs at times: consider areas of low backscatter beyond 7 cm in height. Unlike a data processing method based on flow field structure, these data drop-outs do not propagate into areas of higher backscatter strength because each velocity estimate is determined individually.

A preliminary test of the system accuracy has been undertaken by comparing the mean profiler observations of the wall jet with a series of point observations made with a Nortek Vectrino Acoustic Doppler Velocimeter (ADV). Results of this comparison at four different flow speeds (determined by the operating speed of the recirculating pump) are shown in Fig. 7. Agreement between these independent measurements is

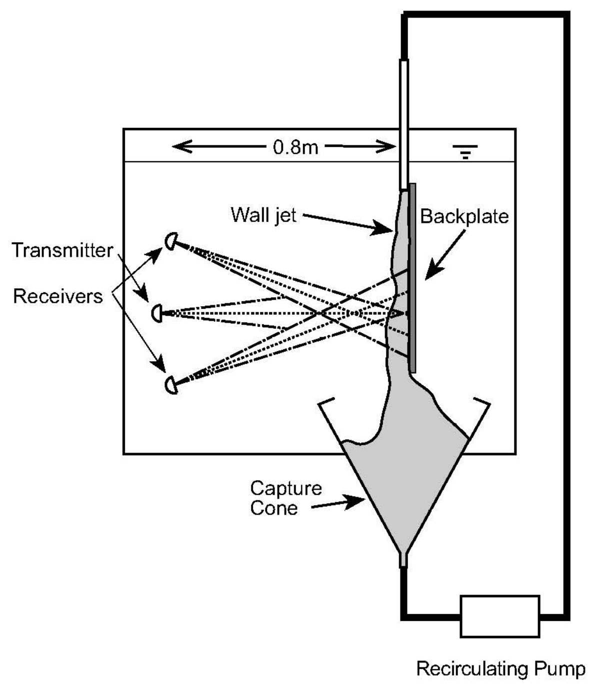

Figure 5: Wall jet experiment configuration. A sediment laden water jet is directed vertically into a 1 m^3 tank parallel to the edge of a backplate. The Doppler profiler is configured to sample a profile across the jet.

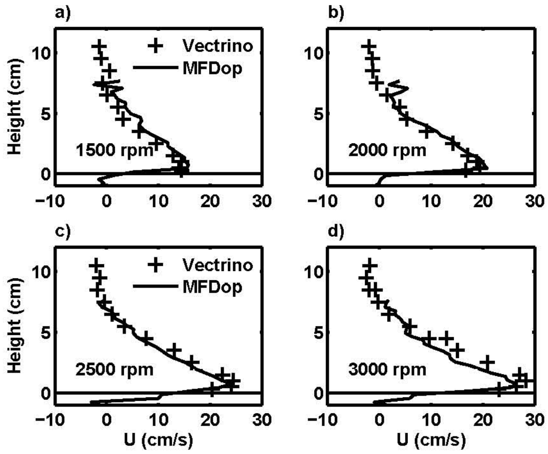

Figure 7: Comparison between mean velocity profiles measured using a Nortek Vectrino ADV (values indicated with a +), and multi-frequency Doppler (indicated by a solid line). Profiles a, b, c, and d correspond to increasing flow speeds as regulated by pump speeds of 1500, 2000, 2500, and 3000 rpm respectively.

very good keeping in mind that the observations were not made simultaneously. It must also be noted that, at some point, as velocity estimates from the Doppler profiler approach the wall, velocities will be biased toward zero because of side-lobe interference. Agreement between the profiler and the Vectrino in the present example suggests that good data are being acquired to within at least 1 cm of the boundary.

V. Summary and Conclusions

We have developed a multi-frequency, coherent Doppler profiling system for use in boundary layer studies. The system operates simultaneously at four frequencies between 1.2 and 2.4 MHz using tuned receiver circuits to separate the four signals. Three component velocity profiles over a 30 cm interval can be generated at a rate of 150 s^{-1} with 3 mm range resolution. The multiple frequencies allow resolution of ambiguity velocity wraps that are the Achilles heal of coherent Doppler systems. Importantly, with the multiple frequency approach, there is no need to rely on knowledge of the flow characteristics or flow time history to recover absolute velocities. In addition, the multiple independent measurements serve to reduce uncertainty in velocity estimates. Multiple frequency data can also be used to invert for the concentration and size distribution statistics of acoustic scatterers. We have presented results obtained with a working system through laboratory tests with a turbulent wall jet. The measured velocities reveal detailed coherent structure within the flow, and agree well in the mean with independent (point measurements) made with a Vectrino ADV.

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