DESIGN AND IMPLEMENATATION OF A 3-AXIS COHERENT DOPPLER VELOCITY PROFILER

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Abstract: *Coherent Doppler velocity profiling is playing an increasing role in ocean scientific research. One area of application is near-bed sediment transport studies, as part of coastal erosion and shelf edge monitoring. Here, a coherent Doppler velocity profiling system designed at POL for sediment transport studies in the bottom 1 metre above the seabed, is discussed from a practical point of view. The system uses a central vertically downwards pointing transducer to transmit acoustic pulses into the water column. This transducer, plus two orthogonal receiving transducers, are used to record the acoustic return signal scattered from particulates in suspension. The system records coherent "in-phase" (I) and "quadrature-phase " (Q) signal components of the detected return signal from which Doppler phase shift and hence velocity can be calculated. Additionally, acoustic backscatter signal strength can be calculated allowing measurement of the suspended particulate concentration. Profiles are formed by recording I and Q components from each transducer at co-located range bins in the water column above the sea-bed. Results from deployments and issues, for example "phase wrap around", are discussed. To combat phase wrap around, a dual PRF technique is employed and is also discussed along with future developments planned.*

Keywords: *Coherent, Acoustic, Doppler, Velocity, Profiler, sediment, transport.*

1. INTRODUCTION.

Sediment transport forms a major part of coastal erosion and process studies (Zedel and Hay [1], Thorne and Haynes [2][3], Betteridge et-al [4]). Different instruments are available for use in these studies e.g LISST developed by Sequoia Scientific to quantify suspended particulate size distribution from optical backscatter. Of interest here is the development and application at POL of acoustic Coherent Doppler Velocity Profiling (CDVP) technology.

Taking a profile of water velocity in the near-bed 1m boundary layer forms a key measurement. At POL various instrument frames are used for this, fitted with a combination of instruments including Acoustic Doppler Velocimeter (ADV) units, Acoustic Backscatter (ABS) recorders and LISST units. Using the ADV units as an example, the systems cannot fit closer together than their physical dimensions allow providing a limited ‘pseudo-profile’. Typically three instruments are used (Fig 1), providing a three point profile. It is far more desirable to take a profile consisting of many points located closer together. One approach would be to use a commercially available ADCP (Acoustic Doppler Current Profiler) from a company like RDI, but these systems use divergent acoustic beam patterns which do not provide sufficiently co-located measurements. For the small scale processes, co-located measurements from small volumes close together are needed. In the absence of suitable commercial instruments, POL has invested resources in developing Doppler profiling technology of it’s own.

Discussed within this paper is the technology developed at POL for a 3-axis pulse to pulse CDVP providing three-dimensional velocity vector profiles within 1m of the sea-bed. Also discussed are practical problems facing the system designer.

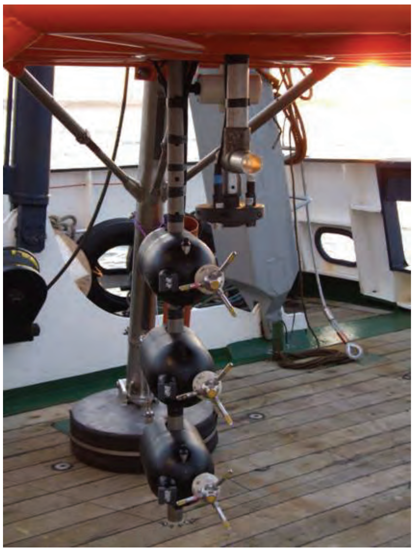

Fig 1 - photograph of Sontek ADV sensors arrangment measuring a three point pseudo-profile

2. ESSENTIAL COHERENT DOPPLER THEORY.

The pulse-pulse coherent Doppler method is based around a number of key equations ([4][5][6][8][9]) which describe Doppler shift and hence water velocity in terms of phase-shift detection.

$$v_d = \left(\frac{c f_d}{2 f_o} \right) \quad \textbf{(1)}$$

where, v_d is Doppler velocity, c is speed of sound in water, f_d is Doppler shifted frequency and f_o is transmitted frequency.

$$R_m V_m \leq \left(\frac{c^2}{8 f_o} \right) \quad \textbf{(2)}$$

R_m is maximum unambiguous profile distance (range), V_m is maximum unambiguous velocity.

$$f_d = \frac{1}{2\pi\tau} \tan^{-1}\left(\frac{X}{Y} \right) \quad \textbf{(3)}$$

where X and Y (not related to vector axes labels) are given by

$$X = \langle I(t)Q(t+\tau) - Q(t)I(t+\tau) \rangle \quad \textbf{(4)}$$

$$Y = \langle Q(t)Q(t+\tau) + I(t)I(t+\tau) \rangle \quad \textbf{(5)}$$

τ is time between profiles, I is discretely sampled In-Phase Doppler component and Q is discretely sampled Doppler Quadrature (90° phase shifted) component.

These equations describe the relationship between Pulse Repetition Frequency (PRF – the rate at which pulses are transmitted = $1/\tau$), transmit frequency and water velocity. The Acoustic Backscattered Signal strength can also be calculated (6).

$$ABS = \sqrt{X^2 + Y^2} \quad \textbf{(6)}$$

Determining Doppler shift in terms of phase, means that at certain velocities the phase shift exceeds 2π radians leading to aliasing. Hence a phase-shift detected could be the result of one of a number of different water velocities. Fig 2 illustrates the problem.

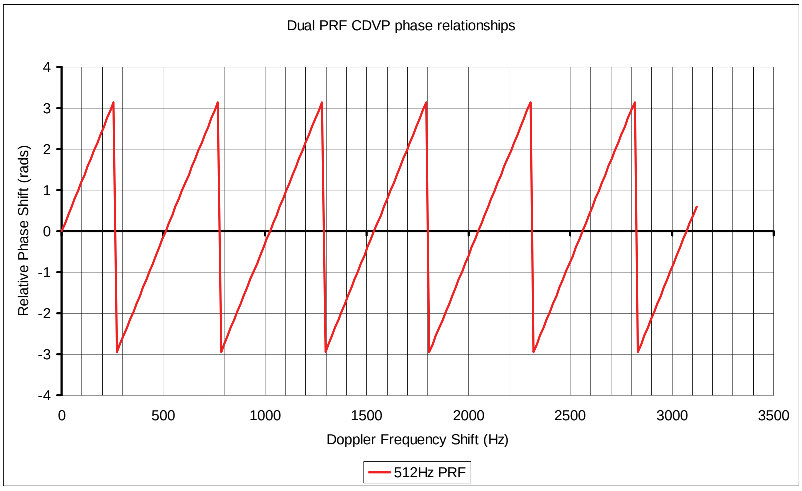

Fig 2 - Example of phase shift aliasing with increasing water velocity

A solution is to use dual-PRF whereby two interleaved transmit repetition rates (Fig 3) are used and resolved into a single phase shift. Fig 4 shows the graphical result of dual-PRF.

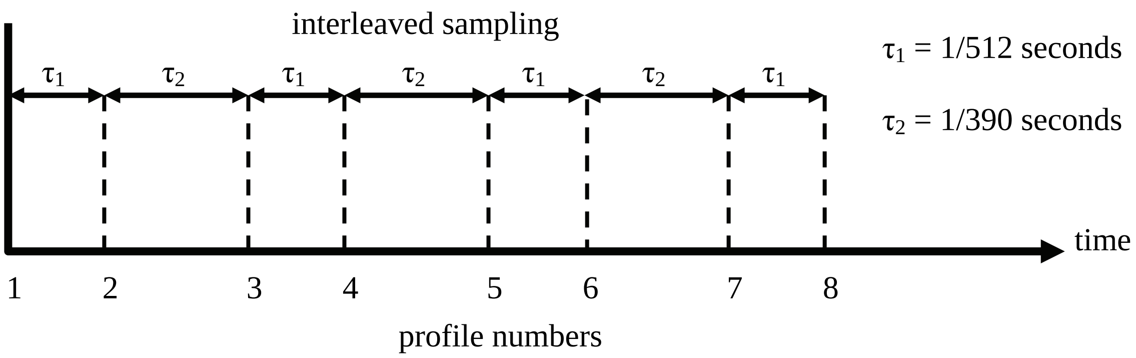

Fig 3 - sketch showing interleaving of dual-PRF

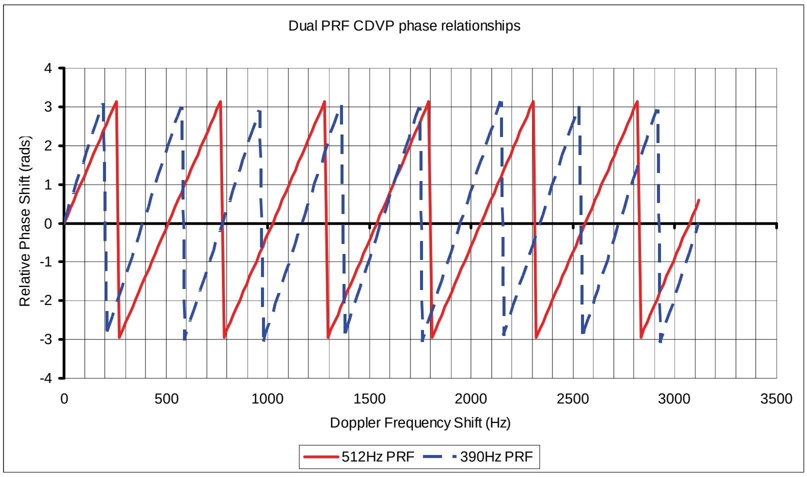

Fig 4 - graphical example of phase shift with dual-PRF

Using this dual-PRF technique and (3) results in two equations which can be solved simultaneously to 'de-alias' the Doppler shift leading to higher measured water velocities

3. RESOLVING THE DATA.

All the above is interesting but how do we detect the Doppler shift and resolve into useable orthogonal velocity vector components u, v and w (Zedel[6], Betteridge[4]) ?

Doppler shift is calculated from two phase components – In-phase (I) and a 90° phase delayed Quadrature (Q) component. The backscattered signal received by the system can be thought of as the transmitted pulse modulated by Doppler shift. By taking the received signal and coherently demodulating it using the transmit frequency and the transmit frequency shifted by 90°, Doppler shift is recovered in terms of I and Q. Doppler shift can then be calculated over 'n' profiles using equations (7)(8)(9).

$$X = (I_1Q_2 - I_2Q_1) + (I_2Q_3 - I_3Q_2) + \dots\dots + (I_nQ_{n+1} - I_{n+1}Q_n) \qquad \textbf{(7)}$$

$$Y = (Q_1Q_2 + I_1I_2) + (Q_2Q_3 + I_2I_3) + \dots\dots + (Q_nQ_{n+1} + I_nI_{n+1}) \qquad \textbf{(8)}$$

$$f_d = \frac{PRF}{2\pi}\tan^{-1}\left(\frac{X}{Y}\right) \tag{9}$$

To form a profile I and Q are recorded at different distances from the transducers using range gating. This gives us the Doppler shift at the point I and Q where taken from and as it is calculated over ‘n’ profiles, is a time-averaged result reducing the effects of system noise.

To calculate X and Y, two sets of results are produced ; $X_{\tau1}$, $Y_{\tau1}$ and $X_{\tau2}$, $Y_{\tau2}$. These are calculated using data at the start and end of each τ_1 period to calculate $X_{\tau1}$ and $Y_{\tau1}$ and similarly for τ_2 w.r.t. $X_{\tau2}$ and $Y_{\tau2}$. For example in Fig 3 for PRF of 512Hz, I_1Q_1 paired with I_2Q_2 would be taken from profiles 1 and 2 respectively but I_2Q_2 paired with I_3Q_3 would be taken from profiles 3 and 4 respectively.

The above has been explained for one transducer and gives one radial velocity from the ‘viewpoint’ of that transducer. To form three dimensional velocity vectors, at least three transducers are used resulting in three sets of I and Q, hence three radial velocities are calculated. Work carried out by Zedel and Hay[6] uses three transducers but Stanton[13][15], Lemmin[16] use four and five transducers. The technology developed at POL uses one transducer to transmit and receive, plus two orthogonal transducers to receive only as shown in Fig 5.

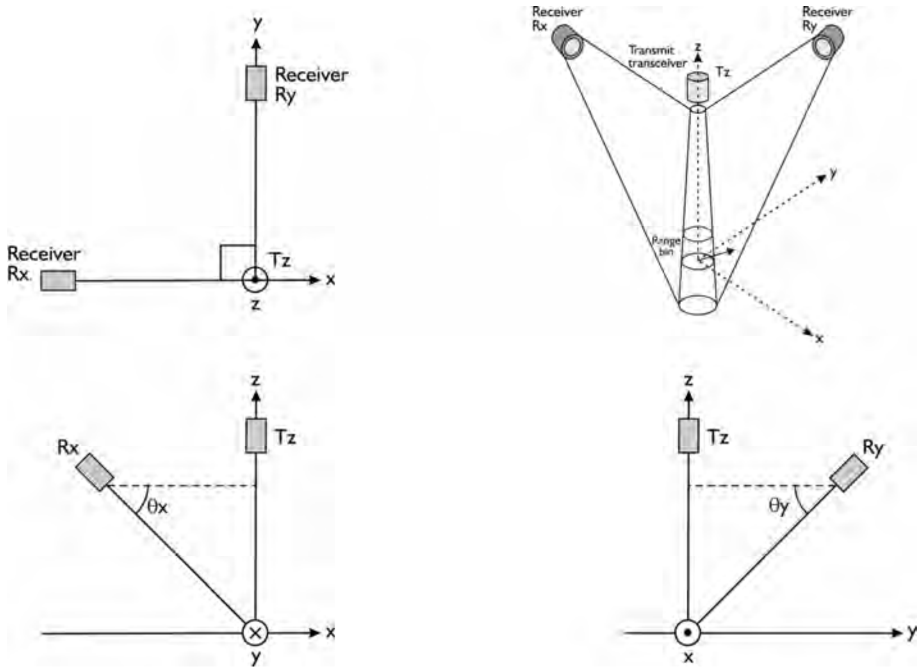

Fig 5 - diagram of POL CDVP system three transducer arrangement

We can designate the three transducers Rx, Ry and Tz in reference to their orthogonal positioning with velocities measured respectively as Vx, Vy, Vz. The orthogonal velocity vectors u, v, w in the x, y, z axes (Fig 5), are then calculated using (10)(11)(12).

$$w = V_z \tag{10}$$

$$v = \tan\theta_y\left(\frac{V_y}{\sin\theta_y} - V_z\right) \tag{11}$$

$$u = \tan\theta_x \left(\frac{-V_x}{\sin\theta_x} + V_z \right) \quad \textbf{(12)}$$

4. HOW THE TECHNOLOGY WORKS.

Fig 6 shows a block diagram of a 3-axis CDVP system, which POL's systems are based around.

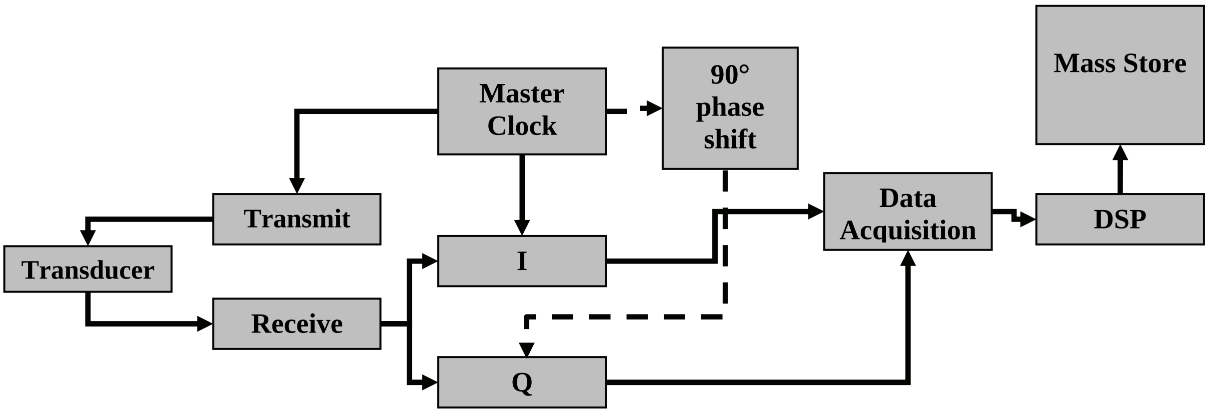

Fig 6 - simplified block diagram of POL CDVP system

A system consists of one central transmitter with receiver, plus two receive only sections.

Using the central transmit and receive section as an example, coherence is maintained throughout using a single master clock. The transmitted signal is generated from the master clock as are two receive signal timebases. The first is in-phase with the transmitted signal the second is phase-delayed by 90°, forming the in-phase and quadrature timebases. Backscattered acoustic signals received by the transducers after being amplified and bandpass filtered, are demodulated using the I and Q timebases. This leaves us with the Doppler phase shift in the form of In-phase (I) and Quadrature (Q) component signals. These two component signals are then sampled by a data acquisition system. Further processing is performed by applying equations (7)(8) to the recorded data, from which velocity and ABS components are calculated using (6)(9). Remember, this is for the central transmitter and receiver. The process is repeated simultaneously for the central transducer and two side receiver sections resulting in calculated velocity components along the transducer axes for each PRF used. These are then dealiased (Fig 4) and the velocity components u, v, w calculated (equations (10)(11)(12)).

POL has one cabled CDVP system operating with a fixed transmit frequency of 524KHz. Profiles consist of 32 range bins, each 46mm long giving a total range of about 1.5m. The dual-PRF rates are set at 512Hz and 410Hz yielding profile averages of n=25 and 16 respectively before dealiasing. The data acquisition system consists of a PC fitted with a data acquisition board equipped with 16-bit A/D converters controlled by two Texas Instrument's Digital Signal Processors. This CDVP does present problems as a cabled system only offers limited deployment ability but no commercial system matches fieldwork requirements.

To solve this issue, an autonomous version is been under development. This system makes use of updated technology to provide a better field deployable solution. This new system takes advantage of recent developments in low power technology to allow use of battery packs for power. It's specifications when the system is completed, will be 1MHz transmit frequency with a profile range consisting 10mm range bins over a 1.28m range. PRF's will be programmable via software. Maximum deployment time will depend on available battery power and recording parameters but is expected to typically be 20 to 30 days.

5. CALIBRATION, DEPLOYMENTS, AND DESIGN TRADEOFFS.

One of the immediate issues is that of calibration. Two of the more popular methods are to mount a system on a frame of some description and either (a) place it in a tow-tank so water flow is simulated by pulling the system along at a known rate [10][15], or (b) place a system on a frame in a flume or wave tank along side other instruments for comparative measurements[6][8]. The second approach has been used with the POL cabled CDVP system with ADV units for comparison. The new POL autonomous system will probably use a combination of both approaches during it's performance testing and initial fieldwork trials.

The POL cabled system has been deployed a number of times during fieldwork as reported in [2][3][4][5][7][9]. The cabled system results do correlate with those from the other instruments but one performance issue has been highlighted. Even with the system recording at an overall profile rate of 16Hz, noise within data limits useful turbulence power spectra to 2Hz maximum [9]. It is believed this is mainly due to low signal to noise ratio as a result of insufficient large particle concentrations for the 524KHz transmit pulses to backscatter from. This is one of the reasons why the new autonomous system uses 1MHz. It also highlights the tradeoffs in system design between transmit frequency, the need for sufficient suspended particles to backscatter from and particle size – a point also noted by Nortek[12].

The affect of noise on dealiasing was noted during analysis of cabled CDVP datasets. This required software to be developed incorporating spike detection routines and statistical filtering to ensure the correct dealiased velocities are selected[4].

Other trade offs in system design relate to the range-ambiguity function (2). The choice of system transmit frequency needs to be balanced against maximum unambiguous profile range and maximum unambiguous velocity. Changing one affects the other three variables, e.g. increase frequency, decrease max velocity for a desired profiling distance. In addition to this as Lhermitte and Serafin [11] point out, the range-ambiguity function also represents a trade off between max profile distance, pulse-repetition frequency and maximum unambiguous velocity. The system designer also needs to bear in mind the increase in sampling volume with distance from the transducers due to the geometry of the transducer beams. Velocities measured at distance come from a much larger volume of water than those closer up, contributing to measurement error.

8. SUMMARY/CONCLUSIONS AND FUTURE DEVELOPMENTS.

To summarise, the coherent Doppler approach has it's advantages but also it's disadvantages. One of the aims of this paper was to give the reader a more summarised practical insight into such systems as well as POL's work on the topic.

Future plans for the new autonomous system are to have it ready for field trials by the end of 2007 and then to start work on a version using three transmit frequencies to augment acoustic backscatter technologies used during sediment transport studies. With the new system being programmable and close to completion the possibility for other research for example, investigating the use of tri-PRF instead of dual-PRF, is made possible. Although Lemmin and Rolland [8] argue that averaging over less than 16 profiles increases statistical uncertainties.

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