MULTI-BEAM DOPPLER SONAR FOR MEASURING 2-D VELOCITIES IN A SWATH: SWATHDOP

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Abstract: *Doppler sonar profiling systems normally employ an array of diverging acoustic beams and measure velocity profiles subject to assumptions about flow homogeneity over the sampled volume. On smaller length scales where homogeneity cannot be assumed, bistatic beam geometries are employed to create (near) coincident component measurements that allow velocity profiles over a limited range. For either approach, measurement of flow spatial structure in more than one dimension requires the use of multiple instruments or requires physically scanning with a single instrument with the assumption of flow stationarity. We are interested in understanding sediment transport over bedforms where flow evolves continuously both in time and space. For this purpose we are developing a pulse-to-pulse coherent swath Doppler system by combining a steerable receiver array with fan beam transmitters in a bistatic configuration. The system operates at 500 kHz with 10% bandwidth sampling transmit pulses at 1.5 ms intervals. The software-defined radio data acquisition and control system limits us at present to 8 independent receiver channels, giving a sample domain that measures 2-D velocities in a ~0.8 m by ~0.8 m region and allows a resolution of about ~3 cm in the plane of the swath. A coherent sonar simulation model was used to test beamforming algorithms and data inversion methods. We report on prototype trials made at the St. Anthony Falls Laboratory main flume facility with observations of 1-m deep unidirectional flow at speeds of order 1 m* s^{-1} *over evolving bedforms.*

Keywords: *Doppler Sonar; Velocity; Pulse-to-pulse; Coherent; Bistatic; Multi-beam; Beamforming*

1. INTRODUCTION

Doppler sonar used for oceanographic purposes normally employs a series of diverging acoustic beams where each beam is able to measure a single velocity component. By arranging a number of beams with different orientations, multiple velocity components can be measured and these observations can be inverted to determine the 3-component velocity. The trade-offs between measurement accuracy and profiling range result in practical systems with 3 to 5 acoustic beams tilted at angles of between 20 and 45° away from vertical. An essential assumption in this configuration is that the flow is homogeneous over the volume sampled by the diverging beams so that all of the beams are measuring components of the same velocity [1]. In the context of measuring ocean current profiles, this assumption is easily met.

In smaller scale flow environments, the velocity will not be homogeneous over the span of the diverging acoustic beams and the conventional Doppler profiler geometry is not suitable. For such applications, velocity measurements are made using Doppler velocimeters where the multiple acoustic beams are oriented to converge on a single sample volume. These systems provide high precision velocity measurements but can provide velocity profiles over a comparatively short distance interval along one spatial dimension (Nortek Vectrino [2], MFDop [3], Sontek Argonaut-ADV [4], ADVP [5]).

The sampling of structures that evolve in both time and space using standard Doppler beam geometries requires multiple synchronised instruments in a spatially-distributed array [6], [7]). An acoustic geometry capable of simultaneous measurements at multiple locations in 2d space is provided by multi-beam sonar (see for example [8], [9]), which can be configured to extract Doppler velocity estimates [10]. We have configured such a system – the SwathDop -- to enable velocity measurement in near-bottom flow for the purpose of studying sediment transport processes.

2. SYSTEM CONFIGURATION

The SwathDop consists of two fan-beam transmitters mounted 0.568 m to either side of an 8-element receiver array (see Fig. 1). Operating at 500 kHz, pulses are transmitted alternately from each transmitter and recorded by the central receiver array. The beam pattern of the receiver array has a ~4.9° (3 dB) beam width in the xz plane. The 2d measurement domain is sampled using steer angles between +20° to -20° in 4° increments. The measurement domain extends nominally 0.8 m below the instrument with a horizontal extent of 0.8 m but the velocity and spatial resolution vary with position.

In order to extract two component velocities, measurements from the two (essentially independent) bistatic sonar systems must be combined. In addition, the individual sample volumes for the two sonars do not overlap and so data must be interpolated to a common sample space. The actual velocity magnitude is determined by combining bistatic measurements u_1 and u_2 as follows:

$$\alpha_1 = \tan^{-1}\left[\frac{1}{\sin\gamma}\left(\frac{u_2}{u_1} - \cos\gamma\right)\right] \tag{1}$$

$$\alpha_2 = \tan^{-1}\left[\frac{1}{\sin\gamma}\left(\frac{u_1}{u_2} - \cos\gamma\right)\right] \tag{2}$$

$$\gamma = \alpha_1 + \alpha_2 = \psi_1 + \psi_2 \tag{3}$$

$$U = \frac{1}{2}\left(\frac{u_1}{\cos\alpha_1} + \frac{u_2}{\cos\alpha_2}\right), \tag{4}$$

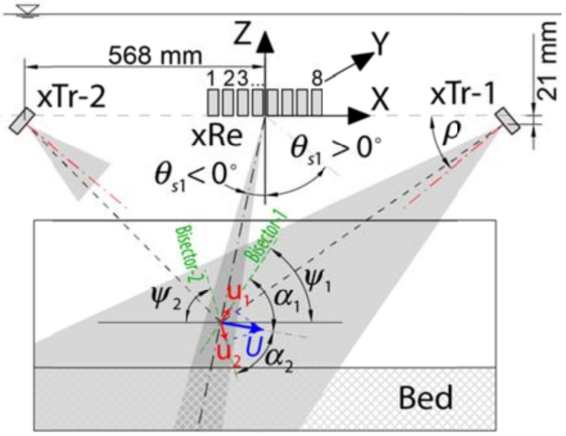

Fig. 1: SwathDop geometry.

here, angles α_1, α_2, ψ_1, ψ_2, and γ are defined in Fig. 1. The cartesian components are then given by:

$$\begin{aligned} u &= U\cos\varphi \\ w &= U\sin\varphi \\ \varphi &= \psi_1 - \alpha_1 \end{aligned} \tag{5}$$

3. MODEL EVALUATION

The expected performance of the SwathDop concept was investigated by using a model of coherent Doppler operation [11]. The model was used to develop beamforming methods and to test the required signal processing algorithms and velocity extraction algorithms (Equations 1-5). Transducer sidelobes are a challenge for multibeam sonar operation and ultimately limit the range of sample volumes that can be resolved by the system. Fig. 2 presents the bistatic beam intersection predicted by the model for a 12° steer angle.

As a demonstration of system sampling, the model was used to simulate velocity measurements with a logarithmic velocity profile over a boundary located at 0.7 m below the receiving array (see Fig. 2). Sampled velocities (black dots) are shown in comparison to the input velocity profile for steer-angles of -12, -4, 4, and 12° in Fig. 3. In general there is pleasing agreement through the profile with noticeable deviations near bottom and at the top of the sample domain.

4. LABORATORY TRIALS

Based on the model results, a design geometry was chosen and implemented on a prototype SwathDop system. The prototype was tested in the St. Anthony Falls Laboratory main flume facility; the main flume is 84 m by 2.75 m by ~ 1m (length by width by depth) and allows a discharge of order 1 $m^3 s^{-1}$ with flow speeds of order 1 m s^{-1} (see Fig. 4).

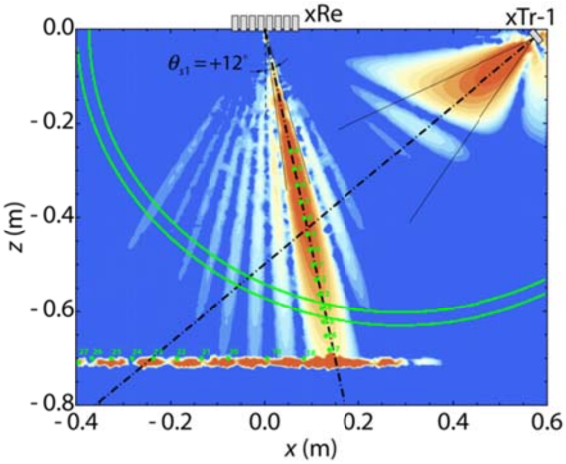

Fig. 2: SwathDop bistatic beam pattern. Here, the beam for the receive array (centered at x=0, z=0) has been steered to 12° off axis. . Warmer colours indicate higher amplitude response. The high amplitude signal at z = -0.7 m is caused by the bottom return.

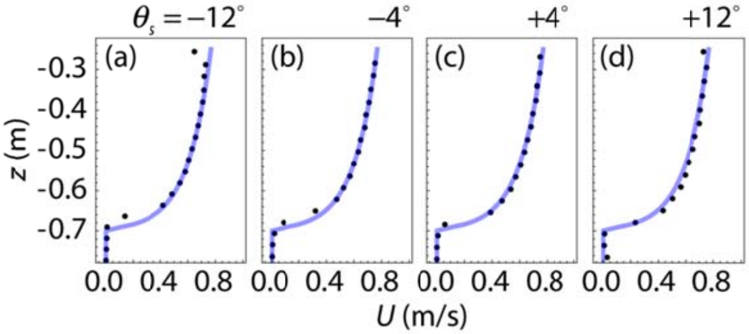

Fig. 3: Model results from sampling logarithmic velocity profile.

The SwathDop was positioned so that the transducers were ~0.7 m above a mobile sand bed with median particle diameter of 0.4 mm. For the results presented here, dunes with length of about 2 m and amplitudes of about 0.10 m were present and moving through the test area. Additional flow speed measurements were made with a Nortek Vectrino ADV. A rotary pencil beam was used to determine bedforms. In addition, independent (although not concurrent) measurements of velocity profiles were made using the MFDop velocity profiler [3].

Despite high concentrations of acoustic scatterers in the water column, the SwathDop system realised low signal levels giving rise to low signal to noise ratios in the phase measurements required for Doppler velocity processing. Only data from one of the two transmitters provided data of an adequate quality to extract data and as a result, it was not possible to extract flow direction information. In order to generate velocity profiles from the resulting data, it was assumed that the flow was horizontal. Given the presence of significant bedforms (where slopes on the lee-side of dunes were as high as 30°) the assumption of horizontal flow could result in substantial bias especially near the bottom.

5. SYSTEM PERFORMANCE

System performance was evaluated by generating averaged velocity profiles at different steer angles. An example set of profiles for steer angles of 0, 4, 8 and 12° is shown in Fig. 5 (red dots). A somewhat uniform velocity of about 0.8 m s^{-1} is seen down to about 0.1 m above bottom where there is a rapid decrease to 0 m s^{-1}. The profile shape does not match the typical law-of-the-wall profile that was used in the model simulation trials, but comparison with the MFDop profiles collected during similar flow conditions validates this profile shape (see solid lines in Fig. 5); this profile shape is consistent with theory for flow over bedforms presented by [12].

Fig. 4: St. Anthony Falls Laboratory main flume.

6. SUMMARY/CONCLUSIONS

This paper has reported on development of a new multi-beam sonar system that enables the measurement of velocity profiles over a swath; the SwathDop. The instrument operates by using two fan beam acoustic projectors offset to either side of a central 8 element receiver array. By transmitting pulses alternately from each projector, 2-D velocity estimates can be constructed from the two independent bistatic velocity fields. Simulations of the system indicated that reasonable measurements were possible using steer angles ranging over ±12° (see Fig. 2). Field scale laboratory trials of the system were undertaken in St. Anthony Falls Laboratory in a 1.0 m deep flow at 0.8 m s^{-1} over a mobile bed of 0.4 mm diameter sediment. Operating in this environment we struggled to achieve an adequate signal level in the receiving array. This problem was caused by the need for greater amplifier gain in the receive circuits and also by limits to the transmit power of the projectors; this is an area of system operation that needs to be improved. Even when working with the low signal levels, measured profiles provided good agreement over steer angles from 0-12° and these profiles agreed with independent velocity profiles collected during similar flow conditions, and with the predicted vertical structure of flow over dune fields.

7. ACKNOWEDGEMENTS

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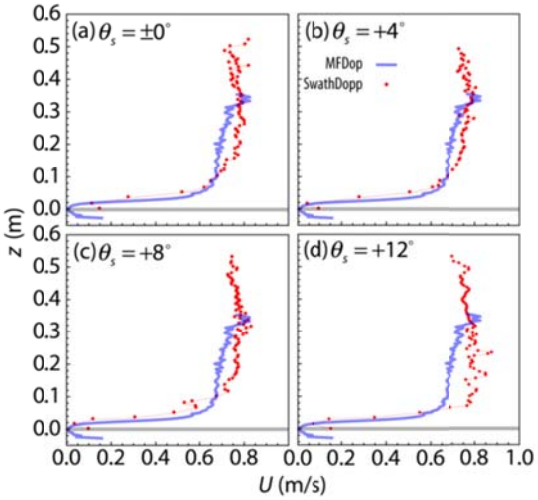

Fig. 5 SwathDop Velocity profiles measured at selected steer angles compared to independent observations from MFdop.

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