SwathDop: Multibeam Pulse-Coherent Doppler Sonar for Scanning 2D Velocity Sections near the Sediment–Water Interface

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ABSTRACT

This paper considers the problem of accurately measuring the sediment transport over bedforms where flow evolves continuously both in time and space. For this purpose, we have developed a pulse-to-pulse coherent Doppler sonar system designed in bistatic geometry with two fan-beam transmitters symmetrically positioned on each side of a multielement receive array. The system resolves 2D velocity components within a $\pm 20^\circ$ (~ 0.5 m by ~ 0.5 m) swath. The software-defined radio data acquisition and control system limited us at present to eight independent receiver channels, and consequently the azimuthal resolution of the system is 4° . As a preliminary test of the sonar system, the system operation was simulated using a model developed to predict coherent sonar performance. The uncertainties with respect to the prescribed values and mean measurements in the model results were confined to 0.35 and 0.23 cm s^{-1} , respectively, in the presence of strong shear (~ 150 s^{-1}) and 50 cm s^{-1} horizontal flow. An important thing is that the model allowed us to test and develop the signal processing algorithms necessary to invert the multibeam sonar data. Using sand of 0.4 -mm median diameter, the laboratory trials were carried out in active sediment transport conditions over dunes with 2 -m wavelength and ~ 0.90 m s^{-1} unidirectional flow velocities. The results presented here focus mainly on 2D velocity field and indicate an average 4% deviation from the wake law and 8% from independent observations made with the wide-band multifrequency coherent Doppler profiler (MFDop) instrument under similar flow conditions.

1. Introduction

Accurate measurement of bedload transport has long been a goal of river and coastal scientists and engineers (Postma 1961). However, measuring bottom stresses is a challenging problem as both the elevation and the shape of the sediment–water interface can undergo major changes through time (Hay et al. 2012a). Several studies have suggested that macroturbulence associated with dune bedforms is important in both the entrainment and transport of sediment, and in controlling

the formation and hydraulic stability of dunes (Jackson 1976; Grass 1983; Drake et al. 1988; Best 1992; Zedler and Street 2001; Garcia et al. 2007; Hanmaiahgari et al. 2017). In general, sediment suspension events seem to be strongly correlated with large turbulent eddy motion (Zedler and Street 2001). Research in fluvial systems has shown that ejection and sweep events and larger macrostructures (e.g., kolks and boils) are often associated with enhanced sediment entrainment and transport via suspension (Jackson 1976; Grass 1983; Drake et al. 1988; Garcia et al. 2007). During burst–sweep events low-momentum fluid is ejected toward the outer regions of the flow to be replaced by high-momentum fluid that sweeps the bed, then sediment is exported downstream. Therefore, the flow structure in a vertical slice of the boundary layer, oriented parallel to the flow, over a rough

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bed is of fundamental interest. There is therefore a need to make observations as close as possible to the bottom without disturbing the flow. In a laboratory context, such measurements can be made using established laser Doppler sampling methods (Nezu and Rodi 1986). However, in field conditions when dealing with high levels of suspended sediment, laser methods are not effective because of the high light attenuation. As a result, over the past decades, coherent Doppler velocimetry has been an attractive alternative for boundary layer studies (e.g., Hurther and Lemmin 2000; Hurther et al. 2007; Hay et al. 2012c,b,a). The lack of suitable technologies for making measurements of flow and sediment transport within the bottom boundary layer encouraged development of a variety of coherent Doppler instruments [i.e., acoustic Doppler velocimeters (ADV) and acoustic Doppler current profilers (ADCPs)] that are commercially available (Lohrmann et al. 1995; Thurnherr 2010; Craig et al. 2011). Custom-built systems have been developed (Stanton 1996; Zedel et al. 1996; Hurther and Lemmin 1998; Thosteson and Hanes 1998; Hay et al. 2012b) to address specific measurement demands. In most of these developments, high-resolution velocity profilers with bin size of $O(1)$ cm have an advantage over point measurement techniques (ADV), because the spatial resolution is provided over some range and therefore can accommodate vertical movement of the bottom. Furthermore, as the sample volume is outside the zone of instrument flow disturbance, this technique is less intrusive than point measurement devices, an important consideration in sediment transport measurements.

For measurements of near-bottom turbulent flow, the conventional Doppler geometry with multiple divergent beams is unsuitable because the assumption of flow uniformity between sample locations is invalid (Gordon 1996). This problem is overcome for modest profile intervals by using a bistatic geometry. The bistatic geometry with intersecting narrow beams has been used since the 1990s (Kraus et al. 1994; Lohrmann et al. 1994) to produce a single point measurements in the intersection zone. This approach avoids the issues associated with estimating Cartesian velocity components from spatially separated radial velocities that are in particular problematic for flow over boundaries with high geometric roughness (Hay et al. 2012c). However, a drawback of bistatic systems with narrow beams is that the sample volume, which is defined by the intersection of the two beams, is too small for signal range gating. To achieve measurement profiles in bistatic geometry, a narrow-beam transmitter and fan-beam receivers can enable profiles of multiple velocity components (Rolland and Lemmin 1997; Hurther and Lemmin 1998, 2000; Zedel and Hay 2002; Hay et al. 2008; Smith 2014); however, the region that can

be sampled is still limited to a (relatively) narrow line along which the two acoustic beams intersect.

The principal motivation for developing the new instrument introduced here, SwathDop, is to enable the measurement of the velocity structure in the near-bottom boundary layer within a plane. This sampling is achieved by replacing the single-element receiver with a uniform linear array (ULA) and employing fan-beam transmitters to add spatial selectivity to the design introduced by (Zedel and Hay 2002). While restricted to only resolving two components of velocity on a segment of a 2D plane, it has the capacity to resolve spatial structure that is hard to capture with a finite number of individual velocity profilers.

The paper is organized as follows. The system configuration and beam-forming theory are outlined in section 2. This section also describes the way data from the two transmitters are combined to make clear the connections between the geometry of the velocity measured by each of the bistatic systems and the Cartesian velocity components to lay the basis for simulating the behavior of SwathDop, presented in section 3. A laboratory setup is described together with the data analysis results in section 4. The conclusions and summary remarks are presented in section 5.

2. SwathDop description

a. System configuration

The SwathDop geometry is sketched in Fig. 1. Two single-element transmitting transducers, xTr-1 and xTr-2, are symmetrically positioned on each side of a multielement receive array, indicated by xRe. The transducer assembly is located about 1 m above bottom. The transmit frequency is $f_c = 500$ kHz with an achievable bandwidth (BW) of 10%. The transmitters ping alternately, and therefore the system is in fact composed of two independent bistatic sonars. SW-1 designates the xRe/xTr-1 sonar, and SW-2 is the xRe/xTr-2 sonar. The receiver array consists of $N = 8$ elements uniformly spaced at a pitch of $d = 3.75$ mm. All transmit and receive elements are rectangular with nominal 3.8° by 30° beamwidths in the x - z and y - z plane, respectively. The beam steer angle θ_s for each sonar is positive if the beam is steered toward the corresponding transmitter and negative if steered away, as illustrated for θ_{s1} in Fig. 1; the subscript 1 refers to the SW-1 system.

b. Beam forming and sample domain

The primary function of a ULA is to control the beam pattern (in 2D space) so that the main beam points in the desired direction, and to control the sidelobe levels and directions of the nulls. This control is determined by the

FIG. 1. Schematic layout of the SwathDop. Projections of the flow along the bisectors are indicated by the arrows labeled u_1 and u_2 . The resolved flow velocity U makes an angle α with the respective bisector.

values of the complex weights associated with each array element. The weighting scheme depends on the bandwidth of the acoustic system (Allen and Ghavami 2006). An array is said to be narrowband if the signal bandwidth is only a small fraction of the center frequency (Trigg et al. 1991), that is, if the propagation delay across the array is much smaller than the reciprocal of the signal bandwidth. Given the SwathDop design specifications, a typical sound speed of $c = 1450 \text{ m s}^{-1}$, and a maximum steer angle of $\theta_s = 20^\circ$, the largest delay between the first and last element in the array is $\tau_{\max} = (N - 1)d \sin \theta_s / c$. For SwathDop $\tau_{\max} = 1/160 \text{ ms}$, which is considerably smaller than $1/BW = 1/50 \text{ ms}$ and much larger than the reciprocal of the carrier frequency ($1/500 \text{ ms}$). Thus, SwathDop is a narrowband system.

For a narrowband system, $W_n = w_n e^{i\alpha_n}$ is the general form of the steering vector components, where $i^2 = -1$, w_n is the amplitude weight of the n th element, $\alpha_n = 2\pi(d/\lambda)(n - 1)\sin \theta_s$ is the phase, and λ is the wavelength. Here, the Dolph–Chebyshev window (Lynch 1997; Duda 2011) is utilized to suppress the sidelobes. This window controls the sidelobe level by optimizing for the narrowest mainlobe width for a given number of elements, and gives sidelobe equiripple attenuation. For SwathDop design parameters, amplitude weights are calculated with a -40-dB nominal sidelobe suppression to control the trade-off between the main-beamwidth and the sidelobe level (e.g., Fig. 2). The weights used in processing the data are listed in Table 1.

The detected volumes in the SwathDop sampling domain are defined in a polar coordinate system centered at the receiver (Fig. 1). The azimuthal angle corresponds to the beam steer angle, and the range coordinate

is determined by the ellipsoidal equal travel time surfaces with the transmit and receive points at the ellipse foci (Fig. 2). The size of the range cells along each steer angle is determined by the duration of the transmit pulse and the overlap of the transmit and receive beams. Figure 2 shows the effective bistatic beam pattern that is made up from a beam pattern weighted sum (Zedel and Hay 2002; Hay et al. 2008) for the $\theta_{s1} = +12^\circ$ steer angle. Several undesired sidelobes with varying intensity are evident. Although sidelobes can be controlled to some extent by employing window functions, their intensity and width vary strongly with the steer angle. At zero steer angle, the largest sidelobe (located at far left of the swath) occurs at approximately $\pm 51^\circ$, and is $\sim 18 \text{ dB}$ down from the mainlobe at 40-cm range. However, at $|\theta_s| > 20^\circ$ the intensity becomes comparable to or larger than that of the main beam. Therefore, the sampling domain is ultimately restricted to $-20^\circ \leq \theta_s \leq +20^\circ$ steer angles.

The azimuthal resolution of the system is determined by the dimensions of the transducer array in terms of the wavelength. Hansen (1990) showed that the array beamwidth, θ_{BW} , can be estimated from the half-power (-3 dB) points of the main beam or by equating the array factor to $N/2^{1/2}$, which yields $\theta_{BW} = 0.8858\lambda/(Nd)$. For the SwathDop, the latter equation gives a beamwidth of $\theta_{BW} = 4.9^\circ$ in the measurement plane, leading us to select a uniform azimuthal resolution of 4° for the swath. Also shown in Fig. 2a are the centers of the sample grid points along the mainlobe of the bistatic beam pattern. The range resolution depends on the effective signal bandwidth (i.e., pulse duration), steer angle, and bistatic range. The cell size decreases by an average of $\sim 24\%$ with bistatic range and the average cell size increases $\sim 19\%$ (from 2.9 ± 0.09 to $3.5 \pm 0.33 \text{ cm}$) as the receive beam steers from -20° to $+20^\circ$.

c. Coordinate and velocity transformation

Because the bistatic beam patterns for each beam pair are mirror images, the range bins for each pair are collocated in space only for a zero-degree beam steer angle. To combine the bistatic velocities registered by each pair, a unified polar grid centered at xRe is defined, in which the steer angle sign follows that for SW-1. This grid is illustrated in Fig. 3 for cell ranges along the steer angle of $+12^\circ$. Also, the bins are equisized along each steer angle and their number is the minimum of available bins from each of the sonars over the range interval for which data from both bistatic systems exist.

To project either scalar or vector values from the SW-1 and SW-2 range cells onto the unified coordinate system, the inverse distance weighting (IDW) interpolation method (Shepard 1968) with unit power parameter is applied. At each steer angle, for a given cell range in

FIG. 2. Sectional view of the effective beam pattern at $\theta_{s1} = +12^\circ$ and xTr-1 fan beam in (a) the x - z plane, (b) the y - z plane along the $\theta_{s1} = +12^\circ$ line, and (c) the x - y plane at $z = -0.5$ m [shown by the dotted horizontal white line in (a)]. Also shown in (a) is the sample range-cell geometry together with two travel time surfaces used to determine the location of range cell 14. The dashed lines denote the axes of the mainlobe of the beam former and transmit fan beam.

the unified grid, all the data from SW-1 or SW-2 within $1.25L_{RC}$ from the center of the cell are included (Fig. 3) to ensure at least one and at most two range cell(s) from each of the individual sonars contribute to the interpolated value. The L_{RC} is the length of the range cell, which varies slightly with steer angle and range, and the 1.25 factor is selected empirically to ensure the incorporation of a maximum four bins (two from each bistatic sonar) in the interpolation process. The velocities registered by each sonar are combined vectorially to obtain flow velocity magnitude $\mathbf{U}$ using the relations

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

$$\gamma = \alpha_1 + \alpha_2 = \psi_1 + \psi_2, \quad \text{and}$$

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

where u is the velocity component registered by the sonar: that is, the projection of the vector $\mathbf{U}$ along the unit vector bisecting the receiver/transmitter beam intersection (i.e., the bisector velocity). The ψ angles (see Fig. 1) define the bisector directions and are based on the

positions of the unified bins. Each α is the angle between the vector $\mathbf{U}$ and the respective bisector unit vector. The vector $\mathbf{U}$ can be decomposed into (u, w) Cartesian components using

$$u = \mathbf{U} \cos \varphi, \quad w = \mathbf{U} \sin \varphi, \quad \text{and} \quad \varphi = \psi_1 - \alpha_1. \quad (2)$$

Note that in the case that only one sonar is available (single-sonar mode) it is necessary to assume that the flow is horizontal in order to generate velocity profiles from the resulting data. This assumption reduces Eqs. (1) and (2) to $\mathbf{U} = u_1$ and $u = u_1 / \cos \psi_1$, respectively

3. Simulation approach

In this study, we have made enhancements to the model for a fixed bistatic beam geometry presented by

TABLE 1. SwathDop array propagation vector as a function of steer angle. The phase weight for $n = 5-8$ should be multiplied by -1 .

n	1, 8		2, 7		3, 6		4, 5	
Weight	w_n	α_n	w_n	α_n	w_n	α_n	w_n	α_n
	0.15	28.44	0.42	20.31	0.76	12.19	1.00	4.06

FIG. 3. Sample geometry of the unified polar grid. The centers of the range cells along $\theta_{s1} = +12^\circ$ and $\theta_{s1} = -12^\circ$ are also shown by the times signs and the open circles, respectively. For comparison, the centers of the range cells attributed to the uniform grid for the steer angle of $+12^\circ$ are marked by red dots. The light-blue shading denotes the distance over which IDW interpolation was performed for the cell (from the uniform grid) marked by the arrow. The planar bottom is at $z = -0.7$ m as shown by the thick gray line. The inset indicates the cells from SW-1 and SW-2 grids that contribute to that particular uniform cell range. Mirroring this figure about the z axis yields the range-cell geometry for the steer angle of -12° in the unified grid system.

Zedel (2008) to incorporate narrowband beam forming. In that model, acoustic backscatter is simulated by summing up contributions from a random distribution of point scattering targets that are distributed through the model domain. The transmit pulse used here is a linear chirp with a length of 70 ms. Figure 4a shows the transmit pulse filtered with a Chebyshev (type I) bandpass filter (BPF).

The acoustic return from a single scatterer is assumed to be an amplitude-scaled, bandwidth limited version of the transmitted signal. The weights for scaling the amplitudes are obtained from the effective beam pattern, while accounting for attenuation due to pure water absorption (Francois and Garrison 1982) and spherical spreading. The backscatter signal from the sample volume is obtained by coherent linear summation of the contributions from all scatterers received at the same time. Although the root-mean-square (RMS) of velocity estimates decreases asymptotically as the number of scatterers is increased to a certain limit (Zedel 2008), to prevent incurring unnecessary computations an average of 7.5 scatterers per sample volume (0.13 mm^{-3}) is chosen. This density meets the requirements for stable second-order statistics determined by Dillon et al. (2012). Furthermore, by excluding the contribution of particles whose backscatter amplitude is less than 2% of the largest backscatter amplitude in each summation, computation

FIG. 4. (a) Pulse template sampled at 8 MHz used in the simulation for insonifying the model domain. (b) Sample realization of acoustic return for element 5 of the receiver array without any noise. The received signal is filtered with a Chebyshev (type I) BPF. Backscattered returns are calibrated against the laboratory-based trials by a uniform scale factor SF. Strong backscatter at $\sim 600 \mu\text{s}$ indicates the high-amplitude bottom return.

time is significantly reduced without sacrificing accuracy. To model the backscatter from the bottom, the bed was divided into two layers: a 1-cm-thick layer representing the sediment–water interface, and below that a 40-cm-thick layer representing the sediment column beneath. Backscatter from particles in the deeper layer was treated in the same way as from particles in the water column (but with zero velocity). Backscatter from the particles in the interfacial layer is scaled up by a factor of 3.1 to obtain signal-to-noise (SNR) levels at the bed comparable to values observed in laboratory-based trials. The bottom is assumed to be centered at $z = -0.7$ m in the model. No attempt was made to simulate the geoaoustic properties of the bed or underlying layers. Illustrated in Fig. 4b is one realization of the model backscatter signal for receiver element 5. The strong backscatter at $\sim 600 \mu\text{s}$ indicates the high-amplitude bottom return.

The accuracy of velocity estimates in a pulse-coherent Doppler system is strongly linked to the ping-to-ping interval, which also has a profound influence on correlation between two successive returns. Zedel et al. (1996) report that for a single pulse pair the accuracy of the system improves proportionally with τ^{-1} up to certain

FIG. 5. Velocity profile used in the numerical model. It is assumed that the bottom is at $z = -0.7$ m and is not moving.

extent. However, as τ becomes smaller, the maximum achievable data rate increases, allowing for increased accuracy by averaging over larger number of ping pairs. Hence, the accuracy for a given data rate is notionally proportional to $\tau^{-1/2}$. Herein, with τ set to 15 ms (666.7 pings per second) the model achieves the desired coherency and more importantly this rate is practically achievable with the SwathDop hardware. Figure 5 presents the laminar velocity profile used for model validation purposes. The discontinuities in the profile were used to examine the spatial response of the swath sampling, while evaluation of model sensitivity to a range of velocities was sought through the velocity gradient. The horizontal velocity gradually increased from zero to 0.5 m s^{-1} , corresponding to a maximal bisector velocity component of 0.35 m s^{-1} , which is still much less than the maximum resolvable ambiguity velocity of $v_r = 0.48 \text{ m s}^{-1}$, calculated from Eq. (3) (see, e.g., Hay et al. 2008):

$$v_r = \frac{c}{4f_c \tau}. \quad (3)$$

The value of τ can be substituted by $(R_T + R_R)/c$, which yields

$$v_r (R_T + R_R)_{\max} = \frac{c^2}{4f_c}, \quad (4)$$

where R_T and R_R are, respectively, the distance of a target from the transmitter and center of the receiver array. According to Eq. (4), the maximum profiling range corresponding to $v_r = 0.48 \text{ m s}^{-1}$ falls along the $\theta_{s1} = -20^\circ$ when the distance of the receiver from bottom is 1.9 m. This range is consistent with the geometry of the system and width of the fan-beam transmitters.

Model test of sonar

As a validation test of the sonar model, the acoustic backscatter signal was simulated for the parameters listed

TABLE 2. SwathDop simulation parameters.

Parameter	SW-1/SW-2	Units
Central frequency	500	kHz
Chirp bandwidth	50	kHz
Chirp duration	70	μs
Total no. of pulses for single-sonar/dual-sonar mode	5000/2500	—
Pulse repetition interval	666.67	Hz
Receive bandwidth	50	kHz
Sampling frequency	8	MHz
Pulse pairs per ensemble	20	—
Ensemble acquisition rate	33.33	Hz
Range resolution	2.6–4.0	cm
Angular resolution	4	$^\circ$
Highest achievable range resolution	1.45	cm
Total no. of beams	11	—

in Table 2 and the velocity profile shown in Fig. 5. The basic configuration used is shown in Fig. 1 with angle $\rho = 40^\circ$. No noise is added to the backscatter data. Data quality is tracked by monitoring the ensemble-average correlation coefficients for a specified number of pulse pairs. Using angle brackets to denote the ensemble average, the ensemble-average correlation coefficient as implemented in the SwathDop $\langle s \rangle$ takes the form

$$\langle s \rangle = \frac{\sum_{p=1}^P s_p^* s_{p+1}}{\sum_{p=1}^P |s_p^* s_{p+1}|}, \quad (5)$$

where s_p is the complex amplitude of the return from the p th pulse, the asterisk represents the complex conjugate, and $p = 20$ is the total number of pings per ensemble.

With a purely horizontal velocity as input, the symmetry of the two bistatic geometries allows data to be collected for both transmitters at the same time. We simulated 5000 sets of backscatter signals in single mode (SW-1 only). In dual mode (both sonars), all of the odd or even ensembles are respectively assigned to SW-1 or SW-2. The synthetic data were “cleaned” by removing ensembles with correlations less than 0.5, resulting in 1.6% of the total number ensembles being discarded. The figures shown in this section demonstrate data averaged over all the remaining ensembles.

The reduced correlations associated with high steer angles are further degraded by the presence of the strong shear (see Fig. 6a). The low correlations at the upper left of the swath are mainly due to the large sample volume and the resulting wide range of bistatic velocities for the individual scatterers in the sample volume. Furthermore, the low correlations at the right edge of the swath for $z < -0.5$ m can be attributed

FIG. 6. Model results showing spatial variations of (a) correlation and (b) intensity of the backscattered signal for SW-1. The horizontal dashed gridlines denote the peak shear, and the thick solid line indicates the planar bed in the model. To generate the swaths in this figure, data are drawn from beam forming in the span from -20° to $+20^\circ$ with 4° resolution and averaged over the entire simulation length.

to degradation of the mainlobe at high steer angles. For the single-sonar mode, two regions of relatively high backscatter intensity stand out. The one along $z = -0.7$ m is the bottom reflection. Since subbottom particles are treated the same as those in the water column, some high intensities are smeared into the layer below the bed level. The second region is

slightly above the intersection point of the receiver and transmit beams (see Fig. 2a) where the bistatic beam sensitivities are highest.

The distribution of the bisector velocities extracted from the model for the SW-1 system averaged over all the ensembles is shown in Fig. 7a. The corresponding horizontal velocities, computed

FIG. 7. (a) Component of flow velocity extracted from the single-sonar (SW-1) simulation results, (b) flow velocity $\mathbf{U}$ calculated from u_1 by assuming a purely horizontal velocity field, (c) horizontal velocity computed from dual-sonar simulations as described in section 2c, and (d) the error velocity that appears in dual mode. All of the units are meters per second.

FIG. 8. Horizontal velocity resolved in single and dual mode at different steer angles, averaged over the simulation length. The reference velocity data are shown by solid thick lines for comparison. The red arrows denote the cell ranges used to investigate the sensitivity of velocity uncertainty to the number of ensembles over which averaging is performed.

assuming zero vertical velocity, are shown in Fig. 7b. The erroneous velocities, particularly at the bottom-right and top-left edges of the swath, are consistent with regions where correlations are typically below 0.8 (see Fig. 6a).

Figure 8 exhibits the model measured horizontal velocity U at different steer angles. Also shown are the prescribed velocity profiles (thick lines) for comparison. The simulated profiles track the prescribed profiles closely for $|\theta_s| \leq 12^\circ$. The effect of smearing errors from high negative steer angles onto the counterpart positive angles is apparent in these profiles for $|\theta_s| > 16^\circ$; for example, while the velocities at $z > -0.4$ m for $\theta_s = +20^\circ$ are well resolved by a single sonar, when the two systems are combined, velocity deviates from the expected values. The anomalies can be distinguished better in Fig. 7b; particularly at higher positive steer angles, the occurrence of false extremes indicates that these spurious values are a likely consequence of geometric scaling under the $w = 0$ assumption that reduces Eq. (1) to $u = u_1/\cos\psi_1$. The angle ψ increases proportional to the inverse of bistatic distance and as the beam former is steered toward the transmitter; angle ψ is larger than 80° for $\theta_s \geq +16^\circ$.

To investigate the effect of number of the ensembles, n_{ens} , over which averaging is performed on velocity uncertainty, the standardized root-mean-square, RMS_{std} , of deviations from the input values—given in Fig. 5—is calculated as

$$\text{RMS}_{\text{std}} = \sum_{n_{\text{cls}}} \frac{\text{RMS}(u_i - u_{\text{in}})/\sqrt{n_{\text{ens}}}}{n_{\text{cls}}}, \quad i = 1, \dots, n_{\text{ens}}, \quad (6)$$

where $n_{\text{cls}} = N_{\text{ens}}/n_{\text{ens}}$ with N_{ens} being the total number of available ensembles (500 for the single- and 250 for the dual-sonar modes). The results shown in Fig. 9 indicate that the velocity uncertainty rapidly decreases

for $n_{\text{ens}} \leq 50$; however, the rate of improvement diminishes for larger n_{ens} .

The deviation from the prescribed velocity and the measured values averaged over 250 and 125 ensembles for, respectively, single and dual sonar is quantified by evaluating the absolute and relative uncertainties in the predicted horizontal velocity as illustrated in Fig. 10. A quantitative summary is also given in Table 3. The advantage of the dual-sonar configuration is clear in lowering the uncertainty, in particular the maximum absolute and relative RMS values are reduced by 28% and 33%, respectively. The artificial nonzero

FIG. 9. The standardized absolute uncertainty of velocity averaged over n_{ens} ensembles at three different cell ranges for single- and dual-sonar modes for $\theta_{s1} = -12^\circ$. The cell range numbers are indicated by boldface font followed by the corresponding coordinate (m) in the swath. The positions of the range cells in the profile are also marked in Fig. 8.

FIG. 10. The run-averaged (a),(b) absolute and (c),(d) relative RMS of horizontal velocity resolved by (left) SW-1 and (right) the dual mode.

vertical velocity components, here referred to as “error velocity,” u_e , are shown in Fig. 7d. The magnitude of such error for $|\langle s \rangle| \geq 0.5$ is 0.013 cm s^{-1} , that is, $\sim 2.5\%$ of the largest velocity in the water column. The magnitude of the error velocity grows with the inverse of correlation and, for poorly correlated data, $|\langle s \rangle| < 0.5$, the magnitude of the error velocity reaches as high as $\sim 0.1 \text{ m s}^{-1}$.

4. Laboratory experiment

The SwathDop system was deployed in the main flume at St. Anthony Falls Laboratory (SAFL), Minneapolis, Minnesota. The flume is 84 m long with a cross section 2.75 m in width by 1.8-m height and is equipped with a sediment recirculation system (Fig. 10). The bed was covered with sand of 0.4-mm median diameter to a thickness of 40 cm throughout the 55-m-long test section. For the data presented here, the mean flow velocity was 0.88 m s^{-1} , which built the bed into three-dimensional dunes with approximately 2-m wavelengths and 15-cm heights.

The prototype SwathDop was positioned ~ 0.7 meters above bed in the SAFL flume to register 60 s of

backscatter at 1.5-ms sampling interval. Concurrent measurements included a Nortek AS model Vectrino⁺ ADV, a rotary pencil beam sonar, and two pressure/temperature (PT) sensors as sketched in Fig. 11.

For this experiment only one transmitter and seven receive channels could be implemented in SwathDop. Through the experiment, data quality varied widely because of variable suspended sediment and bubble concentrations in the water. Here, only results from a run with higher backscatter levels that resulted in better data quality (indicated by higher correlations) are

TABLE 3. Uncertainty in horizontal velocity [RMS (m s^{-1})] resolved by the model for the single- and dual-transmitter cases. Statistics are drawn from the entire swath.

	Min	Mean	Max
Absolute			
Single	0.007	0.021	0.452
Dual	0.007	0.021	0.347
Relative			
Single	0.003	0.017	0.327
Dual	0.002	0.014	0.230

FIG. 11. Sketch of the SAFL main channel and instrumentation layout. Except for the PT sensors, all instruments were located relative to the same reference location; the flow cross section (section A–A) was 15.2 m upstream of the flume outlet.

presented. The SwathDop configuration for this run was the same as the simulation (see Table 2) except with a shorter chirp duration of 20 ms.

Spatial structure of the flow

The results for the selected run are presented in Fig. 11 only for SW-1. The $|\langle s \rangle| < 0.5$ criterion led to rejection of 53.3% of the data before averaging. The run-averaged values of correlation and SNR based on the cleaned data are shown in Figs. 12a and 12b. The values of $|\langle s \rangle|$ mostly fall below ~ 0.7 . The very high values of SNR near $z = -0.7$ m on the right side of the swath indicate reflection of the mainlobe off the bed. The high values on the left side of the swath trending upward from $z = -0.7$ to -0.6 m are caused by a sidelobe reflection from the bottom. Relative to these bottom-reflected signals, the background correlation—associated with the water column—is low (< 0.65). The SNR values shown in Fig. 12b range from 6.5 to 10 dB in the water column with a spatial distribution more or less the same as for the correlation values. In general, the system capability was reduced relative to the model results because of low SNR levels and the availability of only one transmitter (xTr-1).

The horizontal velocity field shown in Fig. 12d is obtained from the measured component of flow velocity plotted in Fig. 12c—that is, the projection of the actual velocity onto the bisector—assuming that flow was largely horizontal in entire depth. One might expect to see inconsistencies in velocity due to the reduction of

SNR with range and beam pattern, and certainly some of the anomalies can be attributed to the reduced SNR. However, the correlation ultimately determines the data quality (Brumley et al. 1991). Thus, the less reliable estimates of $\mathbf{U}$ in Fig. 11d are at the edges and particularly in the left half of the swath where the mean correlations are less than 0.65. In the right section of the swath where the correlations are higher, the values of $\mathbf{U}$ are much more uniform, which is expected for steady flow over dunes (see below).

Figure 13a demonstrates spatiotemporal variability of u_1 at four positive steer angles. The measured velocities are consistent through the time at each steer angle. The peak velocity magnitude gradually decreases with steer angle as the angle bisector makes with the horizon becomes larger toward larger positive steer angles. The bottom is marked by velocities smaller than 0.02 m s^{-1} . There is a slight slope in the bottom that is attributed to the movement of the dunes over the time.

In the presence of bedload, Hurther and Thorne (2011) identified the bed using its immobility and strong backscatter characteristics. However, the position of the bottom in both correlation and intensity values in the present data was masked by the interference of the sidelobes, and the strong footprint of the bottom itself particularly at negative steer angles and at the edges of the swath. Thus, in this study, the bed was determined as that locus of points for which the run-average bisector velocity is smaller than 0.02 m s^{-1} (see Fig. 13b). In general, for the positive

FIG. 12. The run-averaged distributions of (a) correlation, (b) SNR, (c) measured velocity, and (d) computed horizontal velocity obtained from a single sonar during one experiment at SAFL. The low-quality data associated with $|\langle \zeta \rangle| < 0.5$ were removed before averaging. The bed (white dots) is tracked using the measured component of velocity.

steer angles (except $\theta_s = +20^\circ$) the bottom geometry seems to be well resolved appearing to depict part of a dune. The small patch of velocities smaller than zero at the extreme negative steer angles are a result of

sidelobe interference and were neglected in the bottom-detection process.

Flow over dunes and ripples has been extensively studied in field experiments and laboratory experiments

FIG. 13. (a) Spatiotemporal variability of the component of velocity measured by SW-1 (u_1) at four steer angles as indicated above each plot. The white line denotes $u_1 = 0.02 \text{ m s}^{-1}$. (b) Run-average profiles of u_1 for all steer angles used to track the bed.

TABLE 4. Averaged hydrodynamic parameters of flow through SwathDop and representative MFDop runs; Re is calculated by assuming water temperature was constant at 15°C.

	Q_F (m ³ s ⁻¹)	h (m)	d_H (m)	$\bar{u}_{ADV}$ (m s ⁻¹)	Re	C_D
SwathDop run	1.83	0.88	0.54	0.81	3.8×10^5	0.010
MFDop run	1.96	1.15	0.63	0.73	4.0×10^5	0.008

with fixed 2D dunes, as well as through theoretical studies. Omidyeganeh and Piomelli (2013) and Best (2005) give a thorough review of the literature. To predict the flow velocity profiles we consider two approaches: the standard model for boundary layer structure given by the log law (Hussain and Reynolds 1975; Nezu and Rodi 1986) and the wake-law model developed by McLean and Smith (1986) and Nelson and Smith (1989, hereinafter NS89) for channel flow over periodic bedforms.

The classic log law can be written as

$$\mathbf{U}(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right), \quad (7)$$

where z is height above bottom, u_* is the shear velocity associated with bed, $\kappa \cong 0.41$ is the von Kármán constant, and z_0 is the roughness length. In our data, the shear velocity was estimated from

$$u_* = \sqrt{C_D \bar{u}_{ADV}^2},$$

where $\bar{u}_{ADV}$ was the flow velocity registered by the ADV and averaged over 120 s. The bottom drag coefficient $C_D = 0.010$ was calculated from the vertically integrated momentum equation for steady flow assuming a balance between shear stress and the pressure gradient; for further details see Zedel et al. (2018, manuscript submitted to *J. Geophys. Res. Earth Surf.*).

The wake-law velocity distribution used here is based on the model first developed by McLean and Smith (1986) for low Froude number flow over spatially periodic finite-amplitude 2D bedforms, and later extended by NS89, to include bedforms with wavelengths less than the flow depth. In NS89 the vertical structure of the flow at heights well above the bedform crest is modeled by accounting for the wakes from successive bedforms upstream. The net effect locally is represented by a vertical stack of these wakes above the boundary layer immediately adjacent to the bed. For a given bedform with wavelength Λ and height H , the origin of the horizontal coordinate x is chosen at the point of re-attachment, and the vertical coordinate z is defined to be height above an arbitrary datum and positive upward. For the i th wake in the stack, the mean horizontal velocity is given by

$$\mathbf{U}(z) = B_i \beta \mathbf{U}_\delta \left\{ 1 + \frac{2\pi}{\Lambda} \eta \frac{\cosh\left[\frac{2\pi(z-h)}{\Lambda}\right]}{\sinh\left(\frac{2\pi h}{\Lambda}\right)} \right\} \times \left\{ 1 - g_i(x) f\left[\frac{z-\eta}{b_i(x)}\right] \right\}, \quad i = 0, 1, \dots, M, \quad (8)$$

where h is the water depth and $z = \eta$ is the elevation of the bed. The function $b_i(x)$ represents the height of the i th wake; B_i is defined by using the model of Smith and McLean (1977) such that the spatially averaged flow over the bedform is given approximately by a logarithmic profile. The M is selected such that the wakes stack up to the free surface. The remaining terms are briefly summarized in the appendix.

Setting $M = 15$ yields $\zeta_M = 0.87$ m, which is slightly less than the mean water depth of 0.88 m. The bedform field was mapped with the SAFL sonar survey system. The results from several surveys are reported in Zedel et al. (2018, manuscript submitted to *J. Geophys. Res. Earth Surf.*). However, none of the bathymetry mappings were concurrent with the SwathDop runs. Hence, the required geometrical characteristics of the dunes and near-bed reference velocity profile recorded by a wide-band multifrequency coherent Doppler profiler (“MFDop”; Hay et al. 2012a–c) are drawn from a run with similar hydrodynamic and channel resistance conditions. The hydrodynamic similarity is based on the parameters given in Table 4, where d_H is the hydraulic diameter used as the characteristic length scale.

A rotary pencil beam sonar centered at the MFDop position (see Fig. 11b) was used to collect along-flume bed elevation profiles. These nominally 5-m long profiles were acquired approximately every 10 min. The bed elevation profile associated with the abovementioned MFDop run discussed here was acquired ~ 74 min earlier and is shown in Fig. 14. Based on the hydrodynamic similarity between the two runs, characteristic values of $\Lambda = 2$ m and $H = 15$ cm are used to establish the NS89 model velocity profile. The time difference between the pencil beam measurement of bottom profile not to mention the offset in cross-channel position between the two measurements (see Fig. 11) preclude an accurate evaluation of bottom detection with the SwathDop system. If the dune defined by the SwathDop is the one

FIG. 14. The bed transect detected by the pencil beam ~ 74 min before the SwathDop run. Transect data are plotted vs range from the pencil beam transducer. The position of the SwathDop receiver is denoted by the vertical solid line, and the pencil beam transducer position is indicated by the vertical dashed line.

captured by the pencil beam, we can assume that the dune traveled ~ 0.55 m over 74 min time difference between pencil beam and SwathDop. A geometric estimate of bedload transport rate of $0.22 \text{ kg s}^{-1} \text{ m}^{-1}$ is obtained by multiplying the active dune cross-sectional area by its migration rate, assuming that the dune did not change in form and a bed packing density of 0.65 and sediment density of 2650 kg m^{-3} . This rate is 2 times that ($\sim 0.1 \text{ kg s}^{-1} \text{ m}^{-1}$) reported by Zedel et al. (2018, manuscript submitted to *J. Geophys. Res. Earth Surf.*). Cross-channel structure in the dunes can easily account for a few tens of centimeters in offset. All that we can say is that a bottom detection at around 75 cm is at least consistent with the conditions seen by the pencil beam data.

Figure 15 presents example velocity profiles from the SwathDop system at four positive steering angles. For these particular steering angles, to adjust the vertical coordinate of the velocity profiles such that $z = 0$ stands for the bottom, immobility and maximum backscatter intensity criteria are utilized. There is very good agreement among the velocity profiles resolved at different steer angles; that is, the average difference among the four velocity profiles shown in Fig. 15 does not exceed 10% of the corresponding averaged measured value at each level. Also shown are the near-bed velocity profiles recorded by MFDop (for details, see Zedel et al. 2018, manuscript submitted to *J. Geophys. Res. Earth Surf.*) as well as the typical velocity profiles predicted using the logarithmic law and wake law. The NS89 theory predicts a range of profile forms referenced in relation to the reattachment point on the dune. The SwathDop profiles do not extend far enough to identify the reattachment point and so it is not possible to set the distance of the profiles from that point. In Fig. 15, we show one representative profile from the

FIG. 15. Examples (on the right side) of ensemble-average velocity profiles centered at $t =$ (a) 9.45 and (b) 61.65 s. On the left side, the corresponding ensemble averages of backscatter intensity used for adjusting the vertical coordinate of the velocity profiles are plotted. All data are drawn from single-sonar (SW-1) records.

NS89 theory that is consistent with the observed ADV velocity. This profile is more uniform in depth compared to the standard law-of-the-wall profile and this structure is also consistent with the observations from the MFDop system.

The velocity profiles averaged over the entire run duration for steer angles of 0° , 4° , 8° and 12° are shown in Fig. 16. Outside this range of steering the profiles deteriorate rapidly due to availability of only one transmitter. The average quantities are well converged and exhibit a favorable consistency among the profiles deduced from different steer angles. The NS89 model and SwathDop observations indicate that the flow is well developed after the crest of the first dune ($\xi_2 = 0.1$ m). The average difference between the MFDop and SwathDop profiles is $\sim 8\%$, which can be attributed partially to the fact that MFDop profiles were collected during a different trial, and partially to the ~ 0.9 m cross-channel separation between the two instruments. The deviation between observations and the boundary treated by far-field wake theory is related to the position of the profile along the wake and or assumptions we had to make to construct the NS89 profile. Also, given the presence of significant bed-forms (where slopes on the lee side of dunes were as high as 30°) the assumption of horizontal flow could

FIG. 16. Instantaneous flow velocity for the entire run duration (small light-red dots) and the corresponding mean values (thick red dots) deduced at four steer angles. All velocities were resolved in single-sonar mode (SW-1). The velocity profiles registered by MFDop at a different run with similar flow conditions and the mean velocity recorded by underway ADV measurements are also shown. The profiles calculated from theory (wake and logarithmic law) are shown for comparison.

result in substantial bias especially near the bottom. The quantitative differences among the three techniques are presented in Table 5. On average the observations do not depart more than $\sim 4\%$ (except SwathDop at $\theta_s = +12^\circ$). Larger deviations are seen in comparisons between the MFDop and the SwathDop (mean value 11%).

5. Summary and conclusions

We have reported on the modeling and testing SwathDop, a 500-kHz multibeam Doppler sonar operating in a pulse-to-pulse coherent mode. SwathDop is capable of resolving 2D velocity components in vertical swaths near the sediment–water interface. A narrow-band beam-forming scheme is adopted to steer the receiver array within $\pm 20^\circ$ at 4° angular resolution. The $\pm 20^\circ$ steer angle is the limit beyond which the sidelobe intensity becomes comparable to

or larger than that of the main beam. Due to hardware constraints we were restricted to no more than eight elements in the receiver array, which limited the directivity of the receiver array.

A point scatterer model capable of simulating the performance of coherent Doppler sonar operation was used to test and develop the signal processing algorithms necessary to invert the multibeam sonar

TABLE 5. Deviation of the Swath velocities from MFDop and NS89. MFDop deviation from NS89 theory is as well calculated for $z > 0.1$ m. All deviations are normalized against the corresponding MFDop record at each level and averaged over the available depth. Values are in percent.

	SwathDop				MFDop
	$\theta_s = 0^\circ$	$+4^\circ$	$+8^\circ$	$+12^\circ$	
NS89	3.3	2.3	3.4	8.6	4.2
MFDop	9.3	8.6	11.7	14.7	

data and combine the two independent sonar systems together. From the model results, it was concluded that combining data from the two sonars reduces the absolute and relative uncertainties in horizontal velocity measurements; for example, the peak absolute and relative RMS in the horizontal velocity measurements reduce from 0.45 and 0.33 m s^{-1} to 0.35 and 0.23 m s^{-1} , respectively, in $\sim 3\text{-cm}$ range cells at a rate of 33.3 profiles per second. Nevertheless, the high uncertainties arise from strong shear ($\sim 150 \text{ s}^{-1}$) in the corresponding range cells. Also, for a horizontal flow field, artificial nonzero vertical velocity components materialized. The magnitude of such errors was on average 0.013 cm s^{-1} , that is, $\sim 2.5\%$ of the largest velocity (0.5 m s^{-1}) in the water column for data associated with correlations larger than 0.5.

Through laboratory-based trials data were collected with only one transmitter because of hardware failure. The data were processed using the algorithms developed through the modeling efforts. Due to available amplifier gain and limits to transmit sound levels the SNR values did not exceed 10 dB except for the strong bed backscatter signal. Quality control was achieved by detecting low correlation values; with a threshold of $|\langle s \rangle| < 0.5$, 53% of data in the 120-s long run presented in this paper had to be discarded. The correlation for the remaining data was in general lower than 0.7 with some strong influence of the main- and sidelobe patterns in the distribution. Despite all the shortcomings, the velocities resolved by SwathDop along different steer angles were in excellent agreement in the span of $\theta_s = 0^\circ - 12^\circ$. Also, with an average of 8% difference, the SwathDop velocities were in excellent agreement with independent measurements made with the MFDop system. The average deviation of SwathDop results from the wake law was $\sim 3.5\%$, we believe because of the assumptions made to obtain the wake-law profiles. Future work certainly requires addressing the shortcomings in the hardware design to improve SNR levels. Then we can explore the time/space flow structures that the system can resolve. Also, modulating the transmit signal and developing the required hardware and software lead to an increase in sampling frequency that would be an asset for turbulence studies.

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APPENDIX

A Brief Summary of the Terms in the Wake-Law Velocity Profile Equation

In Eq. (8),

$$\begin{aligned} b_i(x) &= 2A_1 C_{DW} H \left(\frac{x + x_{0b} + i\Lambda}{C_{DW} H} \right)^{1/2}, \\ g_i(x) &= A_2 \left(\frac{x + x_{0g} + i\Lambda}{C_{DW} H} \right)^{-1/2}, \\ f(\iota) &= (1 - \iota^{3/2})^2, \quad \text{and} \\ \beta &= \left(\left\{ 1 + \frac{2\pi}{\Lambda} \eta \frac{\cosh \left[\frac{2\pi(\delta - h)}{\Lambda} \right]}{\sinh \left(\frac{2\pi h}{\Lambda} \right)} \right\} \times \left\{ 1 - g_i(x) f \left[\frac{z - \eta}{b_i(x)} \right] \right\} \right)^{-1}. \end{aligned} \quad (\text{A1})$$

The horizontal structure function $g(x)$, the wake height $b(x)$, and the similarity function $f[(z - \eta)/b]$ are set from the [Schlichting et al. \(1955\)](#) wake solution, as are the constants $A_1 = 0.4$ and $A_2 = 1.38$. Here, x is the horizontal coordinate, the origin of which is chosen at the point of reattachment, z is defined to be height above an arbitrary datum and positive upward, and $z = \eta$ is the elevation of the bed. In the expressions for the wake height and the horizontal structure function x_{0b} and x_{0g} are the virtual origins of the wake and the momentum deficit. The velocity must be zero at the bottom of the wake formed in the lee side of the dune, so by definition $x_{0g} = C_{DW} H A_2^2$. The C_{DW} is a drag coefficient taken as 0.6 following [NS89](#), who reported values between 0.5 and 0.7 from direct evaluation of the momentum integral over cement sand bedforms with ripple index of 20° and 30° slip face for the lee side; x_{0b} should be set such that the wake height at the crest is equal to the thickness of the separating internal boundary layer. The near-bed velocity in the eddy is roughly symmetrical about a point midway between the bedform crest and the reattachment point. To satisfy the symmetry argument, $g_0 = 1 - 4\vartheta\xi(1 + \xi)$ is used in [NS89](#), which returns unit values at the crest and reattachment point and a value of about +1.20 at the point midway between them. Here, ϑ is the ratio of the maximum upstream directed velocity to the velocity above the lowest wake, and $\xi = x/x_r$; x_r is the reattachment distance. For steady flow, this length is fairly well constrained between 3 and 8 times

the obstacle height h , with a typical value of $6h$ (Fredsoe and Deigaard 1992). We used a value of $4h$ for x_r in the calculations presented here; β is a scaling function ensuring that the velocity structure in turbulent layer matches with that inside the internal boundary layer. The reader is referred to NS89 for further details.

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