Leadership in Sustainable Infrastructure
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Vancouver, Canada
May 31 – June 3, 2017/ *Mai 31 – Juin 3, 2017*

LABORATORY AND FIELD MEASUREMENTS OF TURBULENCE USING AN ACOUSTIC DOPPLER CURRENT PROFILER

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Abstract: Acoustic Doppler current profilers (ADCPs) have been used widely in river engineering applications, in particular for measuring discharge and bathymetry along open channels. Reduced measurement time and simple deployment techniques are among the advantages of such devices compared to Acoustic Doppler Velocimeters (ADVs). While the measurement accuracy of ADCP discharge measurements has been proven in several studies, there are few studies that have focused on using ADCP data to calculate turbulent flow characteristics within open channels, which is the focus of this paper. A four-beam M9 Sontek ADCP was used to measure and calculate stationary velocity profiles, turbulent kinetic energy (TKE), and Reynolds stress (RS) in a flume in the Hydraulics Research & Testing Facility at the University of Manitoba and within the Assiniboine River in the City of Winnipeg. Vertical profiles of velocity, TKE, and RS as well as depth-averaged values of these parameters were calculated under different flow conditions using measured ADCP data. Laboratory and field results were evaluated and compared with corresponding measurements using a Sontek MicroADV under the same flow conditions. Results showed that a four-beam ADCP can be used to calculate turbulent flow characteristics with a reasonable accuracy in a very short period of time compared to ADVs. It is anticipated that these field-based measurements of river turbulence will be helpful in predicting the type of river ice that may occur during freeze-up on rivers in cold regions.

1 Introduction

Turbulent flow characteristics significantly affect open channel flow hydraulic processes. Measuring or calculating turbulence characteristics are essential to understand river morphodynamics, mixing, and energy dissipation. Turbulence is also a primary variable that influences the type of ice that will form on a river during freeze-up. Field measurements of turbulence can be a costly and time-consuming task depending on measurement techniques and expected resolution. Acoustic Doppler Velocimeters (ADVs) are a common measurement device used in hydraulics laboratories to quantify turbulence; however, using such devices in the field is time consuming and costly due to the single point velocity measurement of ADVs and special deployment arrangements such as preparing an appropriate traversing mechanism. Moreover, offshore measurement of turbulent flow characteristics requires the use of a boat. Acoustic Doppler Current Profilers (ADCPs) can measure velocity profiles over depth and along a cross section easily and quickly with a simple deployment technique and using a hydro-board. A few recent studies focused on evaluation of turbulence measurements using different ADCPs; however, more studies and experiments are required to evaluate the ability of these devices to measure turbulence under different flow conditions.

During discharge measurements using an ADCP, several other flow parameters are measured such as signal-to-noise ratio and beam velocity components. Studies have been shown that these parameters can be used to calculate several flow characteristics such as sediment concentration and turbulence characteristics (Kimiaghalam et al. 2016; Kimiaghalam et al. 2015; Stacy 2000). Three and four beam

ADCPs have recently become the most common devices that are used for discharge measurements of large rivers. Nystrom et al. (2007) conducted an experimental study to evaluate turbulence measurements using the 1.5 MHz three beam Nortek ADCP and the 600 kHz four beam RD Instrument Rio Grande ADCP. They used beam coordinates velocity data to calculate the time-averaged streamwise velocity component ($\bar{u}$), turbulent kinetic energy (TKE), and Reynolds stress ($\overline{u'w'}$). They concluded that the calculated velocity and Reynolds stress profile using the four-beam ADCP had a good agreement with ADV measurements; however, corrections are required to calculate TKE. The mean velocity varied between 20-30 cm/s in their experiments and they suggested to perform further field measurements to evaluate turbulence measurements and calculations.

Several error sources were identified while using an ADCP for turbulence measurements (Nystrom et al. 2002). Sidelobe interference can affect near-bed velocity measurements and cause errors in measured velocity (Appell et al., 1991). Moreover, flow disturbance and ringing can cause errors in measurements near ADCP transducers (Gartner and Ganju 2002). In addition, extra assumptions were considered to calculate turbulence parameters using ADCPs since all calculations were conducted based on three or four measured velocity components along beams.

Recently a group of researchers have started to conduct a study on river ice processes in collaboration with Manitoba Hydro and the Natural Sciences and Engineering Research Council of Canada (NSERC). There was a need to understand the effects of turbulent flow characteristics on ice formation, freeze-up, and break-up processes. A Sontek River Surveyor M9 that is a four-beam ADCP was used to collect flow data within the Assiniboine and Red Rivers. It was essential to evaluate turbulence measurements and calculations using this ADCP since there was no study regarding the ability of this ADCP to measure turbulence, in particular in the field. This study focused on field and experimental evaluation of turbulence measurements using an M9 ADCP. Results from this study will be helpful for the ongoing research in the field of river ice engineering.

2 Measurements

Velocity profiles were measured using the 16 MHz Sontek MicroADV and the M9 Sontek ADCP in a flume in the Hydraulic Research & Testing Facility (HRTF) of the University of Manitoba and at two locations within the Assiniboine River in the City of Winnipeg. The flume is 13 m long, 0.95 m wide, and 0.7 m deep. The flume has glass sidewalls and a smooth bed with approximate slope of 0.0053. Water level can be regulated using a gate at the downstream end of the flume. Preliminary measurements demonstrated that at a location 8 m downstream of the flume inlet the flow was fully developed; therefore, measurements were performed at this location at the center of the flume. Velocity profiles were collected at the centerline when flow rates were 42, 120, 200, and 295 L/s and the water depth ranged between 0.45-0.48 m. Field measurements were performed within the Assiniboine River at the Hugo Dock and the Forks where performing measurements were possible without having a boat (Figure 1). Measurements were conducted on November 15, 2016 when the discharge was around 155 m^3/s and water depth varied between 0.8-1 m at the measurements locations. The first set of measurements were performed at a sampling rate of 50 Hz using the 16 MHz Sontek MicroADV. Three minutes of velocity data (9000 samples) were collected for each measurement points over depth and the ADV was moved in 3-5 cm intervals to cover the water depth. The sampling distance for this ADV was 5 cm from the probes. For field measurement, the ADV was mounted to a metal pole (4 cm by 4 cm in cross-section) that was long enough to reach the river bed. The second set of measurements were performed at a sampling rate of 1 Hz using the River Surveyor M9 ADCP. Ten minutes stationary velocity profile data (600 samples) were collected for each measurement cell over depth. The ADCP was mounted to a hydro-board during the measurements.

3 Data processing and calculations

Measured ADCP velocity data from the experimental and field measurements were exported to MATLAB files in beam coordinates and XYZ coordinates. A modified version of the Goring and Nikora (2002) method was used to remove noise and spikes from the raw measured ADCP and ADV velocity data. $\bar{u}$, TKE, and ($\overline{u'w'}$) were the turbulent flow characteristics that were measured and calculated using both ADV and ADCP data. The ADCP has four beams with symmetrical orientation in the Janus configuration and each beam

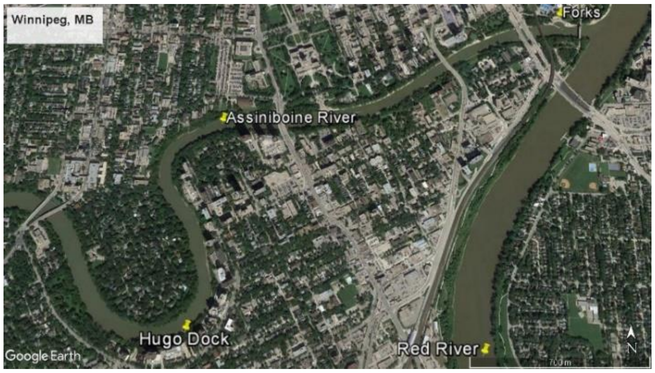

Figure 1: Field measurements location within the Assiniboine River in Winnipeg (Google Earth Pro, 2017)

has an angle of θ (25° for the M9) with the vertical plane (Figure 2). With the assumption of beams 3 and 4 being aligned with the stream-wise axis and homogeneity in the mean and variance of the velocity signals (Stacy et al. 1999):

[1] $u_3 = usin\theta - wcos\theta$

[2] $u_4 = -usin\theta - wcos\theta$

where u_3 and u_4 are the measured velocity in beam 3 and 4 respectively, u is the stream-wise velocity component, and w is the vertical velocity component. For both ADV and ADCP field data in XYZ coordinates, the turbulence parameters were calculated. Using Equation 3 and 4, $\bar{u}$ and $\overline{u'w'}$ can be calculated as follows using data in beam coordinates:

[3] $\bar{u} = \frac{\overline{u_4} - \overline{u_3}}{2\,sin\theta}$

[4] $\overline{u'w'} = \frac{\overline{{u_4}'^2} - \overline{{u_3}'^2}}{4\,sin\theta\,cos\theta}$

where $\overline{u_3}$ and $\overline{u_4}$ are the measured time-averaged stream-wise velocity components in beam 3 and 4, respectively, u'_3 and u'_4 are the turbulent intensities in beam 3 and 4, respectively. For data in beam coordinates, TKE was calculated using the following equation with the assumption of instantaneous homogeneity (Nystrom et al. 2007):

[5] $TKE = (TKE)_{error} + 0.5\left(1 + \frac{1}{4}tan^2\theta\right)S^2 + \frac{1}{16cos^2\theta}[\overline{u'_1u'_3} + \overline{u'_1u'_4} + \overline{u'_2u'_3} + \overline{u'_2u'_4}) + (1 + 4cot^2\theta)(\overline{u'_1u'_2} + \overline{u'_3u'_4})]$

where $S^2 = \frac{1}{4sin^2\theta}\sum_{i=1}^{4}\overline{{u_i}'^2}$.

A sensitivity analysis was performed to calculate the effects of having the ADCP beams misaligned from the stream-wise and span-wise axis based on Equations 1 and 2 (Table 1). This analysis is important, in particular for field measurements and the results showed that the accuracy of the measurements are reasonable if the misalignment is less than 10°.

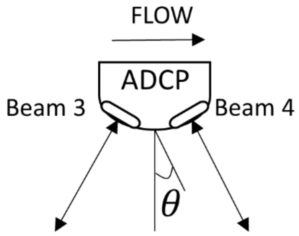

Figure 2: ADCP configuration

Table 1: Uncertainty in measured flow parameters with respect to the ADCP misalignment from the stream-wise axis

Δα (°)	Δu (%)	Δw (%)	Δu'w' (%)	ΔTKE (%)
5	0.4	0.4	0.1	0.1
10	1.5	1.5	2.4	2.4
15	3.5	3.5	12.4	12.4
20	6.4	6.4	41.2	41.2

4 Results

Figures 3a, 3b, 3c, and 3d show the turbulence characteristics measured and calculated using both the ADCP and the ADV in the laboratory. Table 2 shows depth-averaged turbulent flow characteristics with an error percentage. There was a good agreement between measured time-averaged stream-wise velocity profile using the ADCP and the ADV with 3% average error . Depth-averaged Reynolds stress error varied between 12-69% for different flow rates and always the average calculated Reynolds stress using the ADCP was less than the ADV. The depth-averaged TKE error varied between 9-47% and with increasing the flow rate, error decreased (Table 2).

Figures 4a and 4b show the turbulent flow characteristics measured and calculated using both the ADCP and the ADV in the field within the Assiniboine River in the City of Winnipeg. There was a good agreement between measured time-averaged stream-wise velocity with average error around 3%. There was a good agreement between calculated TKE using the ADCP and the ADV and also error in the depth-averaged TKE varied between 3-24%. ADCP's and ADV's calculated Reynolds stress were different with 56-61% error in depth-averaged Reynolds stress. Also, similar to the experimental results, the ADCP's calculated Reynolds stress were less than the ADV's calculated Reynolds stress.

While results showed that the calculated Reynolds stress based on the ADCP had a high error compared to the ADV measurements; the calculated Reynolds stress based on the ADCP measurements still showed the same trend; ie. that there is a range of Reynolds stresses that were a function of flow rate. For example from Figure 3, clearly one can understand that when the discharge were 42, 120, 200, and 295 L/s, $\overline{u'w'}$ varied between 0-0.06, 0.1-0.6, 0.2-2, and 1-12 cm^2/s^2, respectively. Also, the same trend can be found between calculated TKE using the ADCP and the ADV.

The experimental study by Nystrom et al. (2007) using the four-beam 600 kHz RD Instruments Rio Grande ADCP showed that the four-beam ADCP can be used to calculate Reynolds stress profile with a high accuracy. However, the present study suggests that the Sontek M9 ADCP can be used to calculate TKE profile with a reasonable accuracy but calculated Reynolds stress accuracy varied with different flow rates, in particular, field measurements showed that error in calculating Reynolds stress is higher than error in calculating TKE in the field. Since there was a good agreement between the measured ADCP and ADV stream-wise velocity profile, it can be concluded that the source of error in $\overline{u'w'}$ is the measured vertical velocity component. Moreover, since the stream-wise velocity component has the most significant effect on TKE compared to the vertical velocity component, the error in TKE was decreased with increasing flow rate and stream-wise velocity. For steady, uniform, and turbulent flow friction velocity (u*) can be calculate as follows:

[6] $-\overline{u'w'} = \mathrm{u}^{*2}(1-\frac{z}{h})$

where z is the distance from the measurement location from the bed and h is the water depth. Results from this study suggests that using Equation 6 to calculate u* in the field using the ADCP results in a high inaccuracy in the calculated u* and bed shear stress. Therefore, the log-law (Equation 7) based on the measured stream-wise velocity is the best way to calculate u* since there was a high accuracy in the measured stream-wise velocity component:

[7] $\frac{u}{u^*} = \frac{1}{k}(\frac{30z}{k_s})$

Where k is the Von Karman's constant and k_s is the bed roughness.

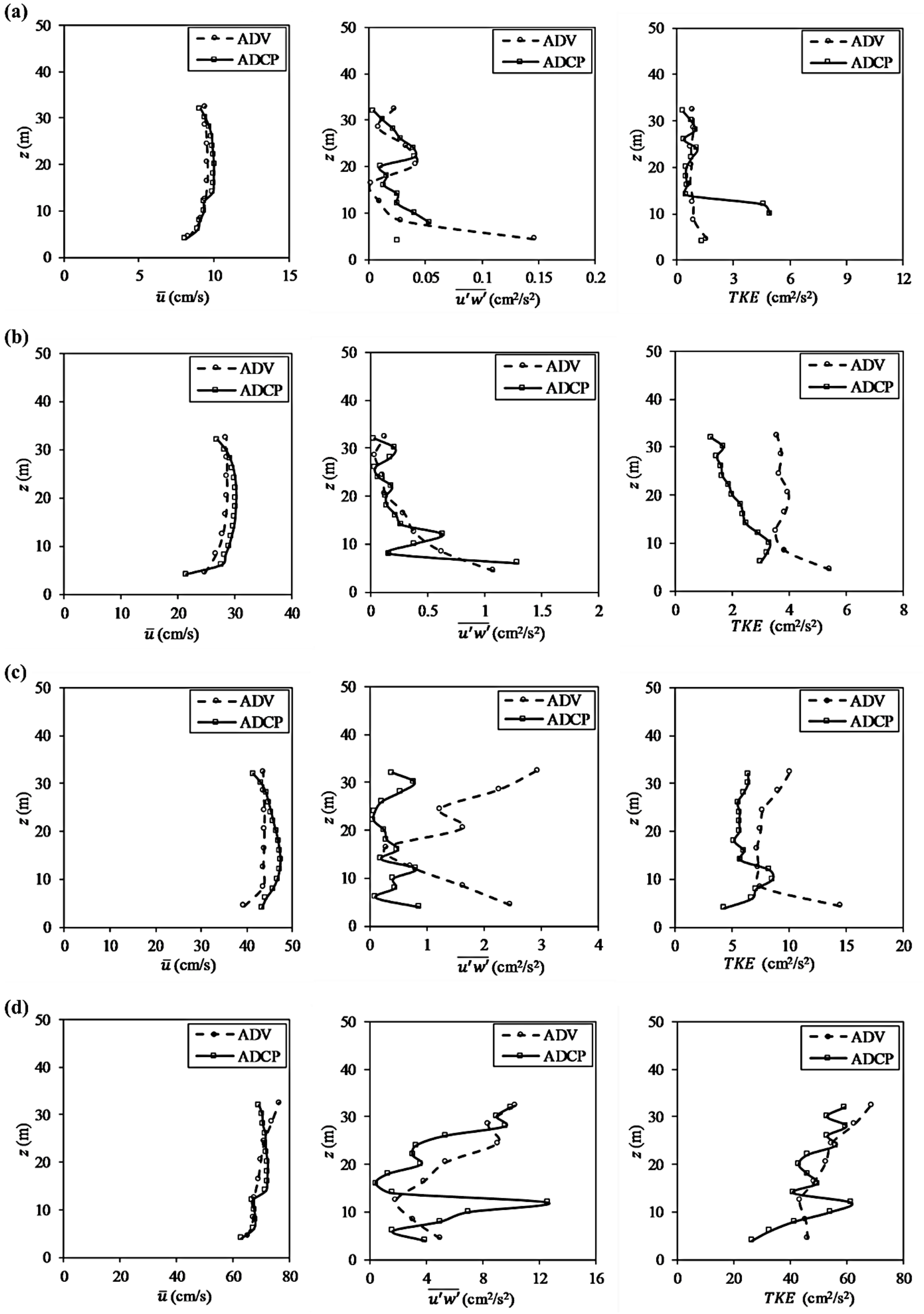

Figure 3: measured and calculated stream-wise velocity, Reynolds stress, and TKE using both the ADCP and the ADV in the HRTF: (a) Q=0.042 m^3/s; (b) Q=0.12 m^3/s; (c) Q=0.2 m^3/s; (d) Q=0.295 m^3/s

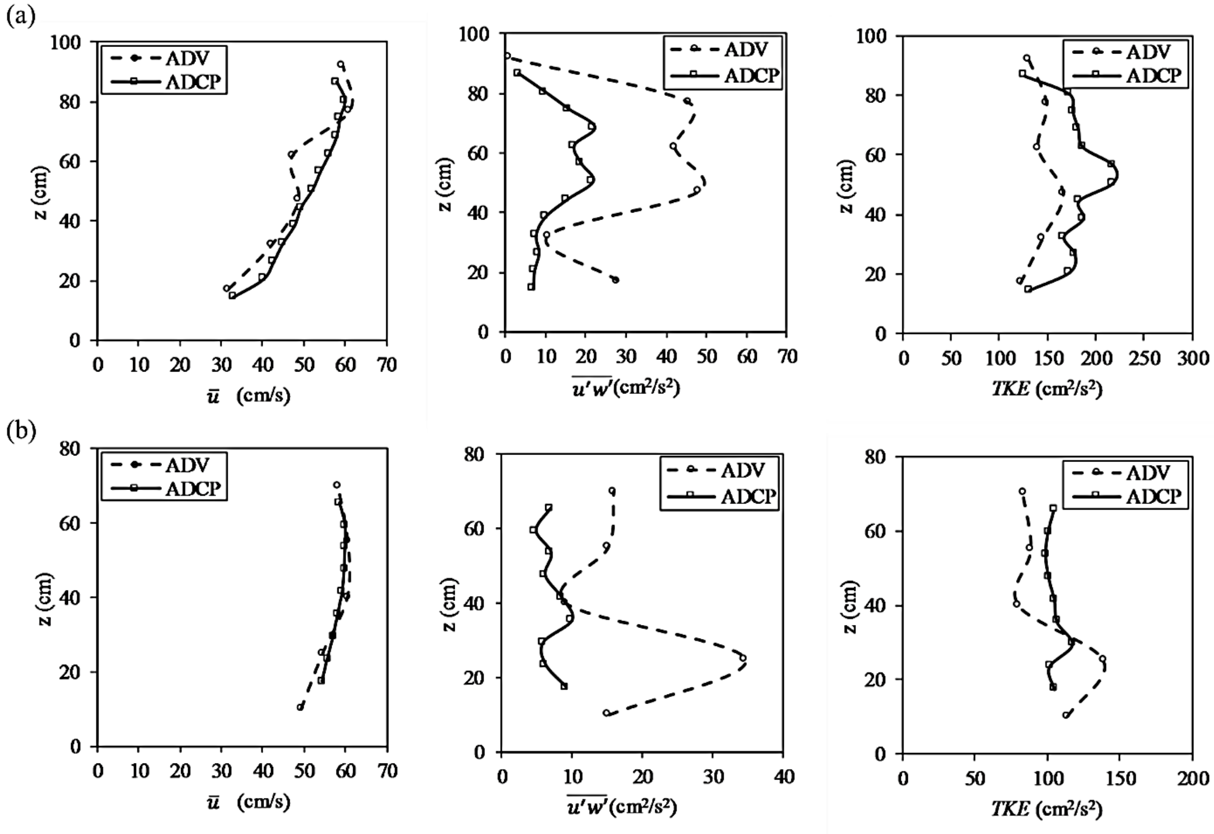

Figure 4: measured and calculated stream-wise velocity, Reynolds stress, and TKE using both the ADCP and the ADV in the field (Q=155 m³/s): (a) Hugo Dock; (b) Forks

Table 2: Comparison of the depth-averaged stream-wise velocity (U), Reynolds stress (U'W'), and TKE

		Laboratory Testing				Field Testing		Average Error
	Q (m³/s)	0.042	0.12	0.2	0.295	150	150	
U	ADV (cm/s)	9.3	27.8	42.4	70.1	56.7	48.4	3.0
	ADCP (cm/s)	9.5	28.6	45.4	69.7	58.2	50.3	
	Error (%)	2.2	2.9	7.1	-0.6	2.6	4.1	
U'W'	ADV (cm²/s²)	0.0	0.4	1.7	5.9	1.8	29.0	-41.6
	ADCP (cm²/s²)	0.0	0.3	0.5	5.2	0.7	12.7	
	Error (%)	-30.6	-20.0	-69.7	-11.9	-61.1	-56.2	
TKE	ADV (cm²/s²)	0.9	4.0	8.9	52.8	101.2	142.5	26.0
	ADCP (cm²/s²)	1.3	2.3	6.3	48.2	104.9	176.7	
	Error (%)	47.3	-41.9	-29.2	-8.7	3.7	24.0	

5 Summary and conclusions

Experimental and field measurements were conducted to evaluate turbulence measurements using the Sontek River Surveyor M9 ADCP. The purpose of this study was to understand possible uncertainty and error in the measured and calculated turbulence parameters using the ADCP including stream-wise velocity component, Reynolds stress, and TKE. Calculated Reynolds Stress using the ADCP was always underestimated compared to the ADV; however, the ADCP can be used successfully to find a range for Reynolds stress as a function of discharge. TKE was successfully calculated using the ADCP with a reasonable error, in particular, in the field. It can be expected that the uncertainty of the turbulence measurements would decrease if the measurements were performed off shore due to the distance from riverbanks and deeper water. Riverbanks can cause the similar signal interference in the results as a flume sidewalls. Moreover, deeper water will reduce the effect of sidelobes near the bed and ringing near the transducer; therefore, the agreement between the turbulence parameters would improve.

Generally, the Sontek River Surveyor M9 ADCP can be used to measure and calculate turbulence parameters to save time and cost of ADV measurements for practical purposes; however, considerations from this study may be applicable in terms of accuracy of the reported results.

Acknowledgements

This research was supported by Manitoba Hydro and the Natural Sciences and Engineering Research Council of Canada.

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