Determining minimum numbers of transects for accurate flow measurements using moving-vessel ADCPs

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Acoustic Doppler Current Profilers (ADCPs) are widely used for flow measurements in field. A moving-vessel ADCP application decreases the measurement duration compared to stationary measurements. The minimum number of required transects at each cross section for accurate velocity and discharge measurements under different flow conditions is a fundamental question. This study addresses this question by conducting ADCP measurements in different field sites with 2D/3D fast and 2D slow flow conditions. The results show that for discharge measurements, averaging four and eight transects results in average errors of less than ±2% at 2D and 3D fast flow conditions with a streamwise velocity higher than $U > 10$ cm/s, respectively. The error increases to ±5% at 2D slow flow conditions despite averaging of nine transects. For accurate streamwise velocity profiles, a minimum number of four and eight transects is needed for fast and slow flow conditions, respectively. To determine secondary currents, averaging a minimum of eight and ten transects with ±10% error is required for 2D and 3D fast flow conditions, respectively. For 2D slow flow conditions, averaging of nine transects results in ±10% error for secondary currents. Overall, the flow conditions strongly affect the quality of the measurements.

Keywords: Acoustic Doppler Current Profiler, discharge measurements, secondary currents, velocity profile, 2D and 3D flows

1. Introduction

Acoustic Doppler current profilers (ADCP) measure three-dimensional (3D) velocities simultaneously through a vertical profile in a water column. Such velocity profiles are used to calculate discharge in waterways, rivers, lakes and estuaries. They are particularly useful for large flow regions where the measurements are affected by time limitation and study costs, and unsteady flow. There are several studies reporting a boat-mounted application of ADCPs (moving-vessel) for discharge measurements [1] and mapping of velocity fields in river reaches including primary and secondary flow structures in meandering bends [2], confluences [3] and around hydraulic structures [4]. ADCPs are also used to investigate turbulent flow structures [5] and tidal flow assessments [6].

Despite the wide range of application, ADCP velocity measurements are subject to large velocity fluctuations of around 76% of the mean velocity [7,8], which is not related to turbulent flow structures and hence reduces the accuracy of final results in terms of velocity profiles, discharge and primary and secondary flow structures. Averaging multiple transects is a way to smooth the velocity fluctuations and reduce the errors [9]. Many studies recommend from 1 to 16 transects at each cross-section to obtain accurate discharge measurements [2-4, 7].

ADCPs on a moving platform have more applications than discharge measurements, such as determination of secondary flow structures, flow field components and in-depth velocity profiles for the calculation of shear velocity. Szupiany *et al.* [8] studied these in the Parana River, Argentina, by conducting fixed and moving boat flow measurements with an ADCP. They found out that the results of horizontal flow velocities averaged from 5 moving boat transects compared well with those from 10 minutes fixed boat measurements. Furthermore, they recommended an average of five transects to study finer details of secondary currents.

Although past studies cover a wide range of ADCP applications for both fixed and moving-vessel ADCP under various flow conditions in relation to the discharge measurements, there is still a lack of knowledge and clear-cut criteria on the required number of transects for both discharge and velocity measurements under 2D and 3D flow conditions as well as for very low to high flow velocities. Accurate measurements of velocity fields are of prime importance to advance in the understanding of 3D large-scale turbulent flow structures, sediment transport, deposition processes and to address other hydraulic problems. Therefore, we aimed at determining the adequate number of transects for accurate measurements of (i) discharge, (ii) vertical velocity profile distribution, and (iii) secondary flow pattern for different flow and site conditions. To this end, we conducted 28 cross sectional ADCP measurements at four field sites in Switzerland by covering low flow velocities in a reservoir, highly turbulent and 3D flow structures at the inlet and outlet of turbines as well as 3D narrow channel and 2D flow in a straight wide channel. Herein, we focus on the results of three measurement campaigns at two study sites.

2. Study Sites and Methodology

In the following, the two selected study sites, methodology, instrumentation and data processing are described.

2.1 Study sites

Solis Reservoir

The first study site is Solis reservoir, located on the Albula River in the eastern Swiss Alps and commissioned in 1986 (Figure 1a). Further information is available in Müller-Hagmann [10]. At Solis, ADCP measurements with 10 transects were conducted at two cross-sections. The cross-section A was located at the inlet of the reservoir with elevated flow velocities, while section B was further downstream inside the reservoir with low flow velocities (Figure 1, Table 1). In addition, at the center of each cross-section, a stationary velocity measurement was conducted with a duration between 5 and 10 min at a sampling frequency of 1.5 Hz. During stationary measurements, it was difficult to keep the boat carrying the ADCP at a steady state and hence it shifted inside a circle with radius of less than 5 m.

Stroppel Hydropower Plant

The second case study is the hydropower plant Stroppel located on River Limmat 36 km downstream of Lake Zurich. The measured rectangular cross section is located upstream of the turbine intake with an aspect ratio of around 5 representing 3D narrow open channel flow conditions [11,12].

Table 1 lists the hydraulic conditions at the measured cross-sections. In this table, b and h are channel width and cross-sectionally averaged water depth, respectively. Q and U are discharge averaged over the number of transects and cross-sectionally averaged streamwise velocity, respectively. SF and FF stand for 'Slow Flow' with $U \leq 0.10$ m/s and 'Fast flow' with $U > 0.10$ m/s, respectively, characterizing the flow conditions at the corresponding study site. This threshold value was determined based on the velocity measurements from 28 cross-sections.

Table 1: Cross sections and flow characteristics at presented case study sites

Cross section	Solis A	Solis B	Stroppel A
Number of transects	10	10	12
h (m)	2.50	3.44	2.90
U (m/s)	0.32	0.06	0.61
Q (m^3/s)	25.52	14.25	26.8
b/h	12.70	18.88	5.49
Flow des.	2D/FF	2D/SF	3D/FF

2.2 Instruments, data collection and processing methods

The ADCP used in this study is River Pro 1200 kHz including a piston style four-beam transducer oriented at 20° to the vertical with a 5th, independent 600 kHz vertical beam mounted on a Q-Boat supplied by Teledyne Marine, USA. The sampling configuration for all measurements is: blanking distance 0.25 m; automatic water mode; ADCP depth from the water surface 0.12 m. Q-Boat positioning and velocity were obtained using RTK-GPS, which was interfaced with the ADCP. The Q-Boat velocity and track position were held as constant as possible along predetermined cross sections. During all measurements, the Q-Boat velocity was less than the flow velocity and maximum lateral deviations from the cross section lines were ±5 m. Velocity data were collected with the WinRiver II software. Data were processed with MATLAB based toolbox VMT [13]. Due to the beam angle separation, the flow velocities within individual profiles are spatially averaged to different degrees with depth. This spatial averaging therefore implies an assumption of temporal and spatial flow homogeneity both across and through the measured volumes, which becomes particularly large at greater distances from the ADCP head [8].

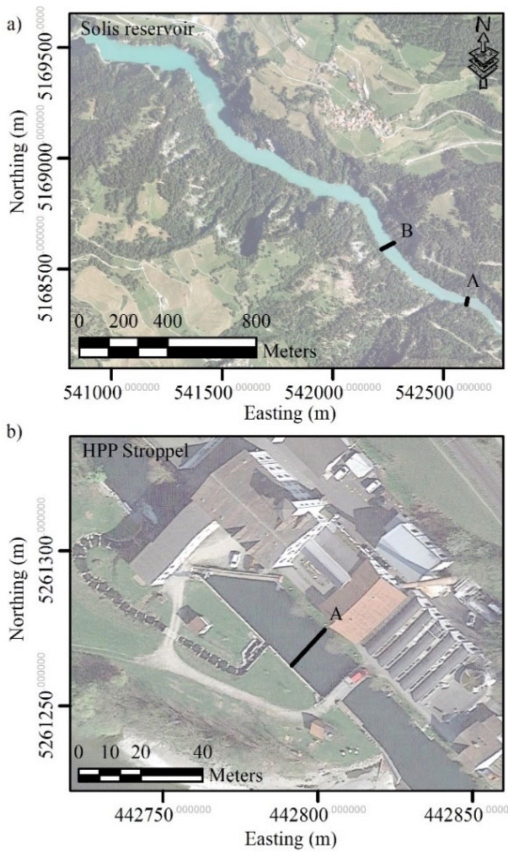

Figure 1: The measurement locations (cross sections) at a) Solis reservoir and b) hydropower plant Stroppel

3. Results and Discussion

Discharge measurements

Velocity measurement were conducted under different flow conditions. The real discharge is assumed to be the average of all transects' discharges [14]. Figure 2 illustrates the discharge measurement error as a function of the number of averaged transects for each cross-section. The errors, N_e are calculated as:

$$N_e = 100 * \frac{Q_i - Q}{Q} \tag{1}$$

Where index i represents the number of averaged transects and Q is the real discharge.

The results show that for 2D FF conditions at Solis A (Figure 2a), averaging 4 numbers of transects reduces the error to less than 2%. At Solis A, averaging more transects does not have a significant effect on the error reduction since the error remains in the range of ±1-2%. Red dots in Figure 2 show the measurements with a duration of more than 720 seconds, while black dots represent the measurement with a duration less than 720 seconds. Figure 2a also shows that for 2D and high flow conditions, the number of averaged transects is more important than the duration of the measurements. For 3D FF conditions at Stroppel A (Figure 2b), averaging 4 numbers of transects involves errors of around ±3% while by increasing the numbers of transects to 8, the error reduces to less than 2%. At this cross section, it takes 720 seconds to measure 7 transects, but this number of transects features an error of more than 2%. Once again, the number of transects at this site is more important than the measurement duration (Figure 2b). Finally, at the 2D SF conditions occurring at Solis B, increasing the number of transects significantly reduces the error to around 10% at 6 transects, while a further increase of the transects only slightly reduces the error down to less than 5% at 9 transects (Figure 2c). The present results from three study locations reveal that the mean flow velocity has a stronger impact than the flow complexity, i.e. 2D or 3D flow conditions, on discharge measurement errors. The higher error at the slow flow conditions at Solis B possible stems from the wind effect and noise caused by the boat engine and movement and the instrument noise. Accurate discharge measurements under such flow conditions with $U \leq 10$ cm/s requires considerably more averaging than under 2D/3D FF conditions. These findings are in a good agreement with previous studies [15]. Huang [15] divided the data into the groups of low flow velocity and high flow velocity with the threshold of 35 cm/s, while in this study the threshold is even lower with less than 10 cm/s.

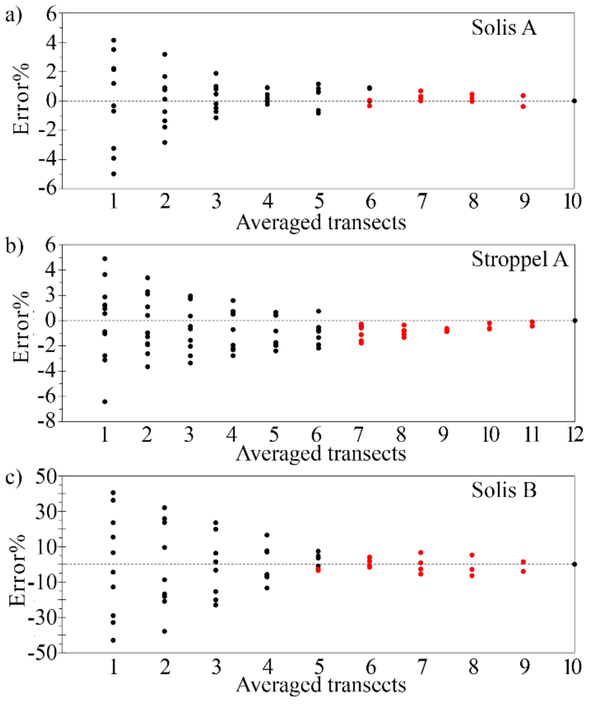

Figure 2: Discharge measurement error at each cross section for a) 2D FF, b) 3D FF and c) 2D SF conditions.

Vertical velocity profile

Streamwise velocity profiles are required in many studies such as for monitoring purposes, estimation of sediment transport, scouring processes, eco-habitat restoration, energy dissipation and for validating numerical simulations [7]. Instantaneous velocity measurements over an extended time span at a single point using a fixed ADCP clearly show that there is a good agreement between measurements and theoretical fluid mechanics velocity profiles [7]. Stationary measurements are time consuming and require great efforts, especially in wide channels. Therefore, we investigate how many transects from moving-vessel measurements are required for accurate mean velocity profiles under different flow conditions. Figure 3 compares the velocity profiles derived from different numbers of transects with the profiles obtained from fixed ADCP measurements.

Figures 3a and b show that for 2D and 3D FF conditions, one transect results in an error of ±15%. By increasing the number of averaged transects to four, the resulting velocity profile matches with stationary measurements. Further increasing the number of transects does not have a significant effect on the error reduction. For 2D SF conditions, the velocity profile extracted from averaging different numbers of transects fluctuates in the range of ±60% from stationary measurements (Figure 3c). Although increasing the averaged transects to 8 makes the velocity profile closer to the stationary measurement, it still features an error of around ±10%.

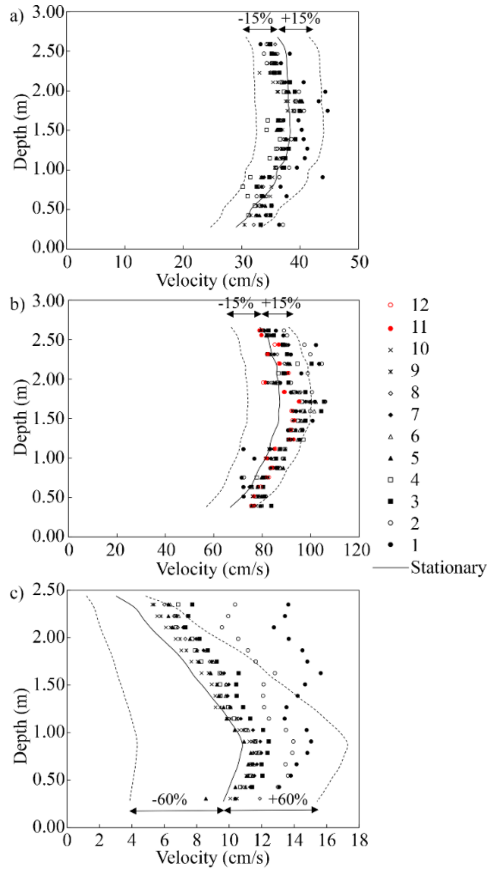

Figure 3. Effects of different number of transects on velocity profiles in a) 2D FF, b) 3D FF and c) 2D SF conditions.

Secondary flow pattern

For secondary flow patterns, accurate measurement of transverse and vertical velocities is important. Herein, it is assumed that the pattern obtained from averaging the maximum number of the measured transects is real and the difference between this pattern and the pattern obtained from lower number of transects is the measurement error. To this end, the direction of secondary flows was interpolated for the measured areas (bin size) of the cross sections and a Digital Elevation Model (DEM) was created for each averaging the numbers of transects. The created DEMs are categorized in 2 groups with negative and positive values, representing secondary flow direction to the left or right bank (group I) and to down and up (group II), respectively. The ratio of different DEMs to the real pattern of secondary flow for transverse and vertical directions is calculated. The areas with negative values in the resulting map show that the direction of the secondary flow, in transverse or vertical direction, is opposite to the real direction. Therefore, the fewer the areas with negative values, the smaller the error is. To calculate the error for each set of averaging transects, the percentage of the area with negative values is calculated. Figure 4 shows the error for transverse and vertical direction in the measured cross sections. For 2D and 3D FF conditions, increasing the number of transects sharply reduces the error, whereas for 2D SF condition the error reduces more mildly. The results indicate that the minimum required number of transects for secondary flow measurements with an error of ± 10%, are 8 and 10 for 2D and 3D FF conditions, receptively, and at least 10 for 2D SF conditions.

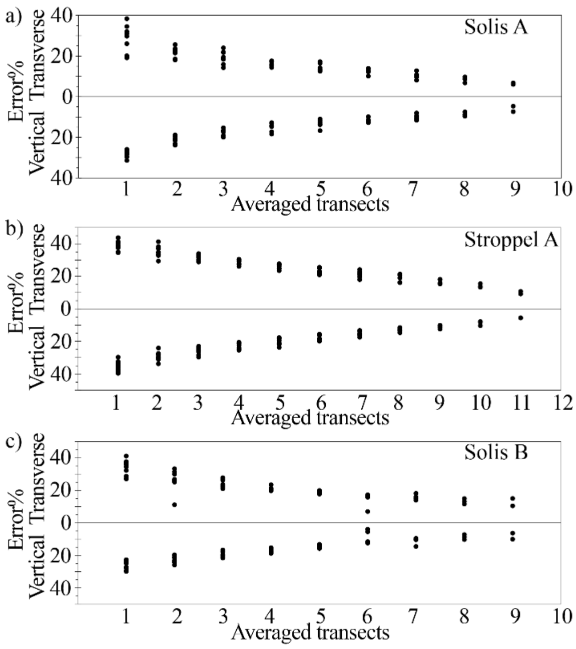

Figure 4. Effects of different number of transects on secondary currents in a) 2D FF, b) 3D FF and c) 2D SF conditions.

6. Summary

The present findings indicate that the moving-vessel ADCP application is capable to measure different parameters under different flow conditions. Flow velocity is the dominant parameter to determine the required numbers of transects for discharge measurement and velocity profiles. For slow flow conditions, a minimum number of 6 and 9 transects are recommended with errors of 10% and 5%, respectively. Accurate streamwise velocity profiles require minimum numbers of 4 and 8 transects for fast and slow flow conditions, respectively. To determine secondary flow patterns accurately, it is recommended to measure at least 8 transcets.

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References

[1] Mueller DS, *et al.*: Measuring discharge with acoustic Doppler current profilers from a moving boat, U.S. Geological Survey (2013).

[2] Petrie J, *et al.*: Combining fixed- and moving-vessel acoustic Doppler current profiler measurements for improved characterization of the mean flow in a natural river, Water Resour. Res., 49 (2013), 5600-5614.

[3] Tsubaki R, *et al.*: New 3-D flow interpolation method on moving ADCP data, Water Resour. Res., 48 (2012), 1-15.

[4] Jamieson EC, *et al.*: Evaluation of ADCP bed velocity in a large sand bed river: Moving versus stationary boat conditions, J. Hydraul. Eng., 137 (2011), 1064-1071.

[5] Le TB, *et al.*: Large-eddy simulation of the Mississippi River under base-flow condition: hydrodynamics of a natural diffluence-confluence region, J. Hydraul. Res., (2018).

[6] Hale R, *et al.*: Observations and scaling of tidal mass transport across the lower Ganges-Brahmaputra delta plain: implications for delta management and sustainability, Earth Surface Dynamics, 7 (2019), 231-245.

[7] Muste M, *et al.*: Practical aspects of ADCP data use for quantification of mean river flow characteristics. Part I: Moving-vessel measurements, Flow Meas. Instrum., 15 (2004), 1-16.

[8] Szupiany RN, *et al.*: Comparison of fixed- and moving-vessel flow measurements with an aDp in a large river, J. Hydraul. Eng., 133 (2007), 1299-1309.

[9] Gunawan B, *et al.*: Comparing fixed-vessel and moving-vessel ADCP measurements in a large laboratory flume, J. Hydraul. Eng., 143 (2017).

[10] Müller-Hagmann M: Hydroabrasion in high-speed flow at sediment bypass tunnels, VAW-Mitteilung 239 (R. Boes, ed.), ETH Zurich (2017).

[11] Nezu I & Nakagawa H: Turbulence in open-channel flows, IAHR monograph series, Balkema, Netherlands (1989).

[12] Auel C, *et al.*: Turbulence characteristics in supercritical open channel flows: Effects of Froude number and aspect ratio, J. Hydraul. Eng., 140 (2014), 04014004.

[13] Parsons DR, *et al.*: Velocity mapping toolbox (VMT): A processing and visualization suite for moving-vessel ADCP measurements, Earth Surf. Processes Landforms, 38 (2012), 1244-1260.

[14] García C, *et al.*: Variance of discharge estimates sampled using acoustic Doppler current profilers from moving platforms, J. Hydraul. Eng., 138 (2012), 684-694.

[15] Huang H: Estimating bias limit of moving-boat ADCP streamflow measurements, J. Hydraul. Eng., 144 (2018), 04018024.