V-ADCP: A New Acoustic Doppler Current Profiler for Measuring Water Velocity, Level, and Flow in Open Channels or Large Pipes

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ABSTRACT

A new acoustic Doppler current profiler, V-ADCP, for measuring water velocity, level, and flow in open channels or large pipes was developed recently. V-ADCP uses the broadband pulsed Doppler technology. A numerical model to calculate flow using the V-ADCP measured velocity profile and water level data was developed and implemented in the V-ADCP operation software. The numerical model is appropriate and no calibration is required for a narrow channel. A V-ADCP can also be used as an index-velocity meter for a wide channel. Results from two tests are presented in this paper. The first test was conducted in a 1-m diameter pipe at the National Large Water Flow Meter Test Center in Kaifeng, China. The results indicated that the V-ADCP measured flow agreed well with the standard flow meter measured flow. The second test was conducted in a flume at the Hydraulic Model Test 3 facility, Royal Irrigation Department, in Bangkok, Thailand. The results indicated that the V-ADCP measured flow was consistent with the 90 degree V-notch weir measured flow.

INTRODUCTION

Acoustic Doppler technology has been used in measuring water velocity and flow in open channels or pipes for many years. There are two main types of Doppler systems: continuous wave (CW) Doppler and pulsed Doppler. They differ in transducer design and operating features, signal processing procedures and in the types of information provided. CW Doppler is older, electronically simpler, lower in cost, and less in accuracy. CW Doppler involves continuous generation of ultrasound waves coupled with continuous echo reception. A two-head ceramic transducer accomplishes this dual function with one head devoted to each function. The main disadvantage of CW Doppler is its lack of depth or distance discrimination. That is,

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since CW Doppler is constantly transmitting and receiving from two different transducer heads, there is no provision for range gating. As a consequence, the output from a CW measurement contains Doppler shift data from all scatters reflecting ultrasound waves back to the transducer along the course of the acoustic beam.

A pulsed Doppler system uses transducers that alternate transmission and reception of ultrasound waves. One main advantage of the pulsed Doppler is its ability to provide Doppler shift data from small segments, referred to as the "cells", along the acoustic beams through range gating. Therefore, a pulsed Doppler system is able to measure velocities at multiple cells and it is called acoustic Doppler current profiler (ADCP).

According to pulse transmitting, receiving, and signal processing procedures, ADCPs are classified into three types: narrowband, pulse-to-pulse coherent, and broadband ADCPs. Among the three types of ADCPs, the narrowband ADCP has the lowest precision and resolution; the pulse-to-pulse coherent ADCP has the highest precision and resolution, but its profiling range and velocity range is the least. The broadband ADCP technology was introduced in 90's of the 20th century (RD Instruments, 1997). Its precision is about 3-4 times higher and resolution is about 10 times higher than the narrowband ADCP. Broadband ADCPs have been widely used in river or open channel discharge measurements (e.g., Lipscomb, 1995; Simpson, 2001).

An ADFM (acoustic Doppler flow meter) that employs the broadband pulsed Doppler technology was introduced in later 90's of the 20th century by MGD Technologies (Metcalf and Edelhauser, 1997), a subsidiary company of RD Instruments (now Teledyne RD Instruments). Recently, Teledyne RD Instruments developed a new broadband pulsed Doppler technology based flow meter, named as V-ADCP (vertical acoustic Doppler current profiler). The V-ADCP is to be a replacement of the old model ADFM.

In this paper, we first describe the system components and specification of V-ADCP, followed by flow calculation methods. We then present results from two tests. One was conducted in a 1-m diameter pipe at the National Large Water Flow Meter Test Center in Kaifeng, China. The other test was conducted in a flume at the Hydraulic Model Test 3 facility, Royal Irrigation Department, in Bangkok, Thailand.

SYSTEM COMPONENTS AND SPECIFICATION

Figure 1 shows a photo of the V-ADCP hardware which consists of an electronics housing, a transducer, and an I/O cable. A half of the electronics housing contains electronics boards and the other half is for internal battery. The transducer has four heads: three of them are for velocity profiling and one (in the middle) is for water level measurement. The velocity measurement beams have a beam angle of ±20 degree in the flow direction and ±25 degree in the cross direction. The beam width is 0.95 degree. Each beam may have up to 50 velocity measurement cells so that there may be a total up to 150 measurement points at the cross-section of a channel or pipe. Table 1 shows V-ADCP velocity measurement specification. The acoustic water level sensor has a frequency of 600 kHz. Its measurement range is 0.1-10m with an accuracy of 0.1%±3mm and a resolution of 0.1mm.

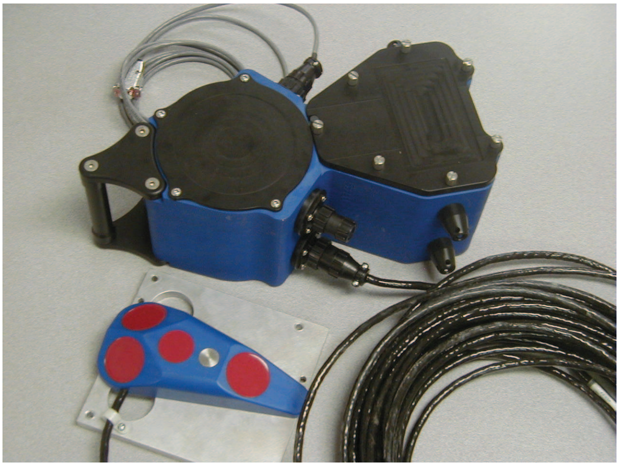

Figure 1. V-ADCP hardware components

Table 1. V-ADCP velocity measurement specification

System frequency	2400 kHz
Number of cells	3-150 （1-50 at each beam）
Cell size	3-20cm
Maximum profiling range	5m
Blanking distance	3cm
Measurement range	±5m/s [default］、±20m/s [maximum]
Accuracy	±0.5% ± 0.2cm/s
Resolution	1mm/s
Maximum data output rate	1Hz

Note: the maximum profiling range depends on temperature, salinity, and solids concentration.

FLOW CALCULATION METHODS

A V-ADCP measures stream-wise velocity profiles and water level. Two methods may be employed to calculate flow using the velocity and water level data. One is a numerical method and the other is index-velocity method. The principle of the numerical method is to generate the whole cross-section velocity distribution using a mathematical model. Flow Q is calculated by:

$$Q = \iint_A u(y,z)\, dydz \tag{1}$$

where $u\ (y,z)$ is the stream-wise velocity (perpendicular to the cross-section) distribution function (i.e., the mathematical model); (y,z) is the cross-section coordinates; A is the wetted cross-section area.

A mathematical model for velocity distribution, developed by HR Wallingford (1992), was used for ADFM. The HR Wallingford model has six unknown coefficients that need to be determined by regression of velocity data. However, the HR Wallingford model was found unstable, sometimes resulting in significant uncertainty in the calculated flow.

We developed a simple mathematical model that has only three unknown coefficients. A numerical scheme was developed to implement the model for flow calculation. The channel cross-section is first divided into a grid with square or rectangular elements. The velocities at all nodes of the grid are then calculated using the model with the coefficients determined by regression analysis of the V-ADCP measured velocities. Finally, a Gaussian numerical integration is applied to Eq. 1 to calculate flow. The numerical flow calculation method does not require calibration. It is appropriate for a narrow channel, i.e., a channel with a small width-to-depth ratio, say, less than 3.

The principle of index-velocity method is to establish a rating for the relationship between the channel mean velocity V and index-velocity V_I. The index-velocity is the averaged velocity of the V-ADCP measured stream-wise velocities at all valid cells. The mean velocity is determined by other flow measurement methods such as a moving boat ADCP method. Therefore, the index-velocity method is a calibration method and a V-ADCP is used as an index-velocity meter in this case. The advantage of the index-velocity method is that it can be used for a wide channel with a large width-to-depth ratio. In using the index-velocity method, flow Q is calculated by:

$$Q = A \times V \tag{2}$$

where

$$V = f(V_I) \tag{3}$$

where f(V_I) is a rating model. Five rating models may be used for index-velocity rating (Table 2).

Table 2. Rating models for index-velocity rating

Rating model	Mathematical expression
Linear (one parameter)	$V = b_1 + b_2 V_I$
Second-order polynomial	$V = b_1 + b_2 V_I + b_3 {V_I}^2$
Power law	$V = b_1 {V_I}^{b_2}$
Compound linear	$V = b_1 + b_2 V_I$ $\quad V_I \le V_c$
	$V = b_3 + b_4 V_I$ $\quad V_I \ge V_c$
Two parameter linear	$V = b_1 + (b_2 + b_3 H) V_I$

Note: b_1, b_2, b_3, and b_4 are rating coefficients; V_c is a critical velocity at which the two linear rating models give the same mean velocity value.

Both of the numerical and index-velocity methods are incorporated into the V-ADCP operation software Q-Monitor-V. The software is used for system set-up, real-time data acquisition and display, and flow calculation. It is also used for data playback and post processing.

TESTS AND RESULTS

This section presents results from two tests. The first test was conducted in a 1-m diameter pipe at the National Large Water Flow Meter Test Center in Kaifeng, China. The second test was conducted in a flume at the Hydraulic Model Test 3 facility, Royal Irrigation Department (RID), in Bangkok, Thailand.

Pipe test. The test in a pipe at the National Large Water Flow Meter Test Center in Kaifeng, China was conducted on March 15 and 16, 2006. The facility has a 20m steady overfall water tower and measures flow using the standard volumetric method with an accuracy of 0.1% of measured flow. The purpose of the test was to collect V-ADCP data and standard flow data for the development and verification of the numerical flow calculation model.

Figure 2 shows the test pipe line and the installation of the V-ADCP transducer on the bottom of the test pipe section. The test pipe line has a diameter of 1m and a length of 40m. During the test, water was pumped from an underground reservoir into the water tower. A constant water head of 20m was kept in the pipe line due to the overfall from the tower. The water in the pipe was flowing and entering into the measurement tank through a commutator or back to the underground reservoir through a by-pass pipe. The flow was adjusted five times at 2.35, 1.62, 1.21, 0.70, and 0.40m^3/s during the test; each flow was kept for about 20mins. Three measurements at each flow were made using the volumetric method.

Figure 2. Test pipe line and installation of the V-ADCP transducer

The V-ADCP was configured with cell size 5cm, number of cells 22, blanking distance 5cm, sampling interval and averaging interval 10s. At these settings, the V-ADCP ping rate was 34 Hz. The V-ADCP run from 22:41:51 to 00:46:31 and collected 748 sets of velocity profile data.

Figure 3 shows a comparison of the V-ADCP measured flow and the standard flow meter (the volumetric method) measured flow. It can be seen from Figure 3 that the V-ADCP measured flow agrees well with the standard flow meter measured flow; the difference is less than 1.3%. It should be mentioned that the flow data for the two low flows were ruled out and not shown in the plot. It was found that the side lobe effect was significant due to less scattering materials at the two low flows, resulting in biased velocities at the middle cells on the two slant beams.

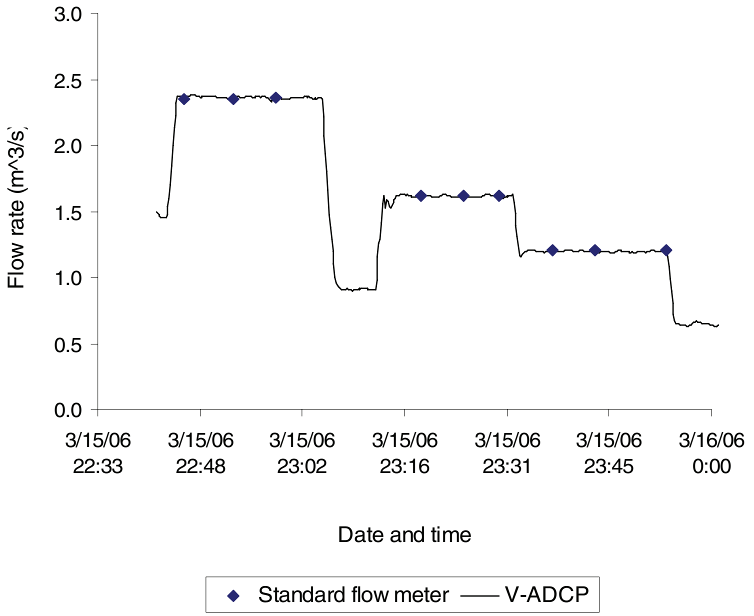

Figure 3. Comparison of the V-ADCP measured flow and the standard flow meter (the volumetric method) measured flow in the pipe test

Flume test. The test in a flume at the Hydraulic Model Test 3 facility, Royal Irrigation Department (RID), Thailand was conducted on June 21, 2006. The test flume was about 50m long, 0.99m wide, and 1m deep. The V-ADCP transducer was mounted on the bottom of the test section of the flume. The downstream of the flume was a pond. The water was pumped out from the pond and transferred through a pipe to the upstream, entering a flow measuring tank. The tank had a 90 degree V-notch installed to measure flow.

The V-ADCP was configured with cell size 3cm, number of cells 30, blanking distance 4cm, sampling interval and averaging interval 5s. Two major data files were collected (other small files were disregarded). The first and second data sets were collected from 10:54:56 to 11:25:36 and 11:42:04 to 12:41:19, respectively.

The test facility supplied a flow calculation equation for the 90 degree V-notch weir:

$$Q = 0.01472\, H^{2.43} / 1000 \qquad (4)$$

where Q is in m^3/s; H is the head on the weir in cm.

On the other hand, according to "ISCO Open Channel Flow Measurement Handbook" (Grant and Dawson, 1995), the flow calculation equation for a standard 90 degree V-notch weir is written as:

$$Q = 1380\, H^{2.5} / 1000 \quad (5)$$

where Q is in m^3/s; H is in meter.

It is noticed that Eq. 4 is slightly different from Eq. 5. Both equations are used. Figure 4 shows a comparison of the V-ADCP measured flow and the V-notch weir measured flow. It can be seen from Figure 4 that the V-ADCP measured flow is in the middle of the V-notch measured flow calculated by Eq. 4 and Eq. 5.

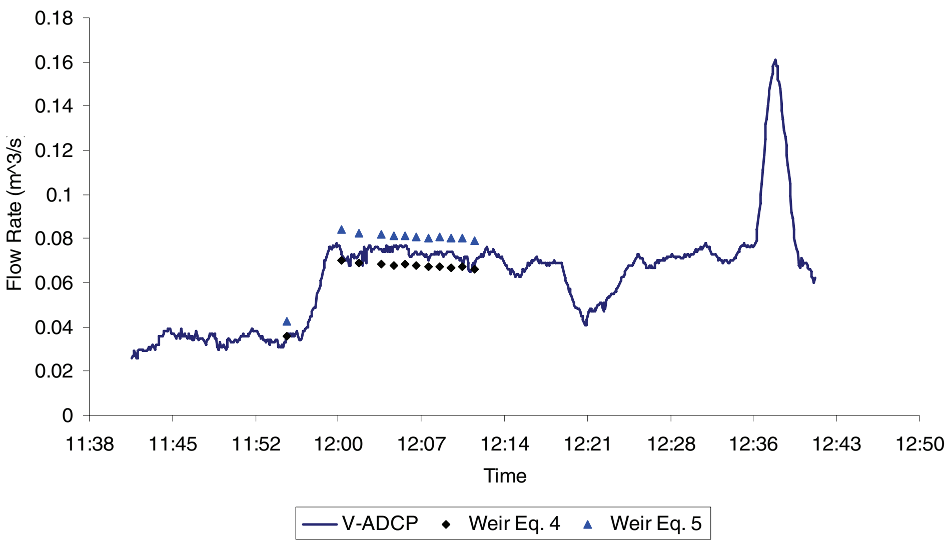

Figure 4. Comparison of the V-ADCP measured flow and the V-notch weir measured flow in the flume test

CONCLUSION

V-ADCP, the recently developed broadband pulsed Doppler system for open channel and large pipe flow measurement, is a replacement of the old model ADFM. V-ADCP can be used in narrow channels as a flow meter without a need for calibration. It can also be used in wide channels as an index-velocity meter. The test results from the 1-m diameter pipe at the National Large Water Flow Meter Test Center in Kaifeng, China indicated that the V-ADCP measured flow agreed well with the standard flow meter measured flow. The test results from the flume at the Hydraulic Model Test 3 facility, Royal Irrigation Department, in Bangkok, Thailand indicated that the V-ADCP measured flow was consistent with the 90 degree V-notch weir measured flow. However, future tests are required to verify V-ADCP flow measurement accuracy in open channels or large pipes at a variety of conditions.

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REFERENCES

Grant, D. M. and Dawson, B. D. (1995). *Isco Open Channel Flow Measurement Handbook*, Fourth Edition, Isco, Inc. Lincoln, NE.

HR Wallingford (1992). *Algorithms for Estimating Flow in Sewers: Beckton/ Crossness Models*, Report EX2538, March, 1992.

Lipscomb, S.W. (1995). *Quality Assurance Plan for Discharge Measurements Using Broadband Acoustic Doppler Current Profilers,* United States Geological Survey, Open-File Report 95-701.

Metcalf, M. A. and Edelhauser M. (1997). "Development of a velocity profiling Doppler flow meter for use in the wastewater collection and treatment industry." *Proc. of the Water Environment Federation: WEFTEC'97,* Chicago.

RD Instruments. (1997). "Broadband acoustic Doppler current profiler." United States Patent: RE35535, 1997-6-17.

Simpson, M. R. (2001). *Discharge Measurements Using a Broad-Band Acoustic Doppler Current Profiler,* United States Geological Survey, Open-File Report 01-1.