In Search of Easy-to-Use Methods for Calibrating ADCP's for Velocity and Discharge Measurements

Kevin Oberg[1]

[1]U.S. Geological Survey, Office of Surface Water, 221 N. Broadway Ave., Urbana, IL 61801; PH (217) 344-0037; email: kaoberg@usgs.gov

Abstract

Acoustic Doppler current profilers[2] (ADCP's) have become a common tool for measuring streamflow and profiles of water velocity. Despite their widespread use, no standard procedure has been adopted or accepted for calibration of ADCP's. Limitations of existing facilities for testing point-velocity meters, the complexity of ADCP instruments, and rapid changes in ADCP technology are some of the reasons that a standard procedure has not been adopted. This paper outlines various methods for calibrating ADCP's, discusses the advantages and disadvantages of these methods, and presents a simple, cost-effective procedure for calibrating an ADCP in the field.

Standard methods for the calibration of current meters involve towing a meter in a tow tank at various known speeds. This method has also been used to calibrate ADCP's. Disadvantages to this method include lack of adequate and uniform backscattering material, lack of flowing water in the testing facility, and inability to use the ADCP's internal flux-gate compass. Use of flumes for ADCP calibration is not practical for many ADCP's due to width and depth restrictions associated with the instruments. ADCP's and conventional methods for measuring velocity and discharge have also been compared. However, these field comparisons are costly and conventional velocity and discharge measurements may be subject to relatively large uncertainties.

The USGS is investigating a new method for ADCP calibration. This method requires the use of differential global positioning system (DPGS) with sub-meter accuracy and standard software for collecting ADCP data. The method involves traversing a long (400 – 800 meter) course at a constant compass heading and speed, while collecting simultaneous DGPS and ADCP data. This process is repeated several times and the ratio of the course length measured by means of the ADCP to the course length measured by means of DGPS is computed. When this ratio is less than 0.995, measurements made with RD Instruments' Rio Grande ADCP most likely have a negative bias error and when it is greater than 1.003 the ADCP most likely has a positive bias error. It is estimated that this procedure can be completed in 2 hours or less, and can be done by anyone with access to a sub-meter DGPS.

Introduction

Acoustic Doppler current profilers (ADCP's) have become a common tool for measuring water velocity and discharge. At present (2002), the U.S. Geological Survey (USGS) operates

[2] In this paper, the use of the term acoustic Doppler current profiler is intended to refer to a class of instruments rather than any particular brand or model.

approximately 130 ADCP's for measurement of velocity and discharge in streams and estuaries throughout the United States. Many more ADCP's are used throughout the world, especially for the measurement of ocean currents and flows in estuaries. Despite their widespread use, no standard procedure yet has been accepted for calibration of ADCP's. No standard procedure has been accepted because of limitations of existing facilities for testing current meters, the complexity of the instrument, and rapid changes in the technology. Many of the facilities used for testing devices for measuring currents in streams were not designed for use with ADCP's, but rather for mechanical, point velocity current meters. Often physical features of these facilities, such as the width of a tow tank, limit its use for ADCP calibration. When making ADCP measurements, consideration must be given to factors such as adequate backscattering material in the water, interference from sidewalls and the bottom, and the presence of variable magnetic fields. When calibrating mechanical current meters, most of these factors are not important. Much more data are collected during ADCP measurements as compared to mechanical current meters. Interpretation of ADCP data is sometimes challenging and more difficult than data collected with mechanical current meters. Finally, the functionality of ADCP's has changed rapidly over the past 10 years. Scientists and engineers often spend considerable effort to keep abreast of these technological developments, which limits time available for detailed calibration and testing.

The purpose of this paper is to (1) discuss various methods for calibrating ADCP's and advantages and disadvantages of these methods, (2) present results from tow tank tests made by the USGS, and (3) propose a simple method for calibrating an ADCP in the field. The scope of this paper does not allow for a detailed discussion of each of the methods, nor a detailed presentation of the results of such methods as tow tank testing. A more comprehensive report is planned for detailed presentation of these results.

Methods for Calibrating Acoustic Doppler Current Profilers

Engineers and oceanographers have considered various methods and/or facilities for calibrating ADCP's. Not all of these methods and facilities will be discussed in detail. Rather, only the more promising methods are discussed here along with method advantages and disadvantages.

Instrument Comparisons

A common method for evaluating or calibrating new instruments is to conduct measurements with that instrument and compare the results to measurements made simultaneously or nearly simultaneously with other well-calibrated instruments. For example, Lohrmann and others (1994) and Voulgaris and Trowbridge (1998) both compared measurements made with an acoustic Doppler velocimeter (ADV) to measurements made with a laser Doppler velocimeter (LDV). Voulgaris and Trowbridge (1998) found that mean flows and Reynolds stress values from the ADV were within 1 percent of measurements made with the LDV. These comparisons were made in a laboratory setting without using an ADCP. Few comparisons have been made in a laboratory flume, using commercially available ADCP's. Nystrom and others (2002) showed that mean velocities from ADCP measurements were within 1 cm/s of ADV measured velocities. Furthermore, they found that turbulence statistics that were computed based on ADCP measurements usually were biased. Nystrom and others made their comparisons in a 1.8 m wide laboratory flume in 0.9 m deep flow. The advantages of such comparisons are that flow rates and instrument settings can be controlled precisely in a laboratory flume. In addition, it is not difficult to keep enough backscattering material suspended in the flow such that the ADCP will function. However, acoustic interference, caused by reflections from sidewalls and the bottom of the flume, can result in erroneous measurements. Although flow rates can be changed in the laboratory, it is difficult to obtain high velocity measurements because typically the water depths for higher flow rates are such that there is inadequate depth to allow for proper ADCP operation. Furthermore, instrument comparisons must be carefully made because often the instruments being compared do not measure the same volume of water at the same time. The question often arises when making such comparisons, "Which instrument is correct"?

Bos (1991), Lemmin and Rolland (1997) and Appell and others (1985) all have made field comparisons of ADCP's with other instruments or other ADCP's. Simpson and Oltmann (1993) made many detailed velocity profile measurements with mechanical current meters and compared the profiles to those obtained from an ADCP. Many other researchers have made comparisons that are not cited here. Appell's (1985, p. 726) remarks aptly summarize some field comparisons issues. Appell states, "This experiment highlights the difficulty of trying to determine from field intercomparisons. …. It is difficult to estimate uncertainty with any field intercomparison without adequate measurements from reliable, calibrated instruments strategically place at the experiment site." As a result, field comparisons typically are costly and cannot be made with the same degree of reliability as in a controlled laboratory.

Tow Tanks

Tow tanks have been used to calibrate current meters for many years. Many detailed studies have been done in tow tanks, and experience and expertise in the use of such facilities is well developed. Experience has shown that tow tanks are a reliable method for calibrating many types of current meters, especially mechanical meters. It is therefore not unusual that one of the first methods considered for calibration of ADCP's is a tow tank. Appell and others (1988), Lemmin and Rolland (1997), and Shih and others (2000), among others, all have made use of a tow tank to calibrate or evaluate ADCP's.

Tow tanks offer the advantage of providing a very accurate reference velocity. The tow cart velocity can be measured precisely and even be referenced to known standards, such as the National Institute of Standards. The speeds used in tow tank tests also more closely match the range of velocities that will be measured in the field. For example the tow cart at the USGS Hydraulics Lab is capable of obtaining speeds from 0.08 m/s to 3.6 m/s. The primary disadvantage of tow tanks is that the water in the tank has a zero or very small velocity (small currents induced by thermal gradients are not uncommon). As a result backscattering material, essential to ADCP operation, does not stay suspended in the water column and artificial seeding of the water becomes necessary. However, this seeding usually does not result in a uniform distribution of the backscattering material. Other disadvantages of tow-tank facilities are boundary interferences, lack of any shear in the water column, and the presence of large magnetic or electromagnetic fields that cause fluctuations in the heading measured by the ADCP.

Distance Course

Appell and others (1988) others describe the layout and application of a distance course for calibrating ADCP's. Two courses, one 200 meters long and the other, 1000 meters long, were surveyed and established on a lake for the purpose of testing ADCP's. With this method, the ADCP is mounted on a boat and driven over the course at a constant speed and using a constant heading. Usually, two passes with the boat and ADCP are made on reciprocal courses. The distance traveled as measured by the ADCP using bottom tracking then is compared to the known distance. This method can be quickly used to determine whether any bias errors are present and commonly is used by ADCP manufacturers to check for beam alignment errors. It also is possible to use water tracking, by selecting a layer of water at a user-specified depth, as a reference for the boat speed. Use of a water layer as a reference for testing an ADCP is appropriate as long as any ambient currents in the lake are constant while the two passes (on reciprocal headings) are made. There are various disadvantages in using a distance course including, (1) the startup cost of surveying in a distance course at locations convenient to users throughout the U.S. and (2) this method does not test all aspects of ADCP operation.

Discharge Measurement Comparisons

The USGS has made comparisons of discharges measured by the ADCP to discharges as measured by other commonly used equipment, such as Price AA current meters. Morlock (1995) made comparison discharge measurements at 11 locations throughout the U.S. and found that most of the ADCP measured discharges typically were within 5 percent of the discharge measured by Price AA current meters. Mueller (2002) repeated this work using profilers that were not available to Morlock. Such comparisons are important to the USGS because discharge records are the primary product of the USGS national streamgaging program. Furthermore, almost all the ADCP sensors are used in making a discharge measurement and therefore the errors associated with that measurement reflect the performance of these sensors.

However, there are several major disadvantages to such comparisons. A typical mechanical current meter measurement will only sample a small percentage of the flow area (< 3%), whereas an ADCP will sample between 20 – 60% of the flow area. The time period used when making discharge measurements is often significantly different for both kinds of measurements. Furthermore, mechanical current meter measurements are subject to both instrument and human errors. This makes it difficult to accurately determine measurement errors, without resorting to many such comparisons. Finally, discharge measurement comparisons are quite expensive to make.

USGS Tow-Tank Tests

As a part of a joint effort by the USGS and the South Florida Water Management District to evaluate the accuracy of ADCP measurements, the USGS arranged to conduct ADCP testing at the Naval Center for Surface Warfare in the David Taylor Model Basin, in West Bethesda, Maryland. This facility is used regularly by personnel from the National Oceanographic and Atmospheric Administration (NOAA) to calibrate ADCP's used by NOAA. The USGS contracted to use this facility for ADCP testing for the period March 13-16, 2000. The goal of these tests was to evaluate the feasibility of using such a facility to calibrate ADCP's. If these tests were successful and could be done cost-effectively, the procedures used could become an essential part of the USGS streamflow quality-assurance and quality control program.

David Taylor Model Basin

The David Taylor Model Basin consists of several hydraulic facilities, including two towing basins and a circulating water channel (http://www50.dt.navy.mil/facilities/Carriages.html). The towing basins are 760 m long, of which one is 15 m wide and the other is 8 m wide. The 15-m wide basin has been divided into two sections, one section which is 260 m long and the other section is approximately 500 m long. The tests described herein were conducted in the 260-m long section of the 15-m wide basin.

Testing Procedure

The testing procedure for each instrument consisted of the following steps:

1. Mount the ADCP to be tested in dry dock of the towing basin.
2. Seed the tank with powdered limestone.
3. Make calibration runs at specified tow cart speeds. Two measurements were made at various speed, one in an easterly direction and one in a westerly direction. Two passes in opposite directions were made so that any residual current in the basin would cancel out.

Both ADCP data and tow cart velocities were simultaneously recorded on a computer.

When testing acoustic Doppler velocity meters in a towing basin, it is necessary to seed the tank with a backscattering material. Adequate backscattering material is essential to Doppler measurements. If the concentration of backscattering material is too low (< 35 db), the size of the backscattering particles is too small, or the concentration of the backscattering material is highly variable, significant errors in the measured velocities may result. Various approaches to seeding were used during the 4 days of testing. Initially, seeding consisted of broadcasting powdered limestone from the tow cart. This seeding worked fairly well but required a lot of lime and did not provide good backscatter uniformity. Subsequently, a lime slurry was sprayed into the towing basin prior to the commencement of testing. It was hoped that this method would result in more uniform backscatter in the towing basin.

Five ADCP's were tested at the David Taylor Model Basin, a SonTek[3] Argonaut SL ADP, a 3 mHz SonTek ADP, a RD Instruments Rio Grande 600 kHz ADCP, a RD Instruments Broadband 1200 kHz ADCP, and a prototype 3-beam horizontal 600 khz ADCP made by RD Instruments. Only the results from the Rio Grande and Broadband ADCP were available for inclusion in this paper. Data for the other instruments presently are being analyzed and the data and corresponding analyses are planned to be published later. The test results summarized below are for the Rio Grande 600 kHz ADCP, serial number 1189 with firmware version 16.03 and the Broadband 1200 kHz ADCP, serial number 1330, using firmware version 5.47. The Rio Grande ADCP firmware used (version 16.03) is actually firmware from the Workhorse series of ADCP's. This firmware was being used in this instrument as a part of a separate evaluation of new firmware features. Two independent velocity measurements were obtained, the bottom

[3] The use of firm, trade, and brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

track velocity and the water track velocity. The bottom track velocity, or the velocity of the ADCP over the bed, is measured by the ADCP using a long acoustic pulse that is independent of water velocity measurements. A single velocity is recorded for each sample (known as an ensemble). Water-track velocities are measured using a different technique than bottom tracking (Simpson, 2002) that involves the use of short, phase-encoded acoustic pulses.

Test Results

The means of two tow-cart runs, one in the easterly direction and one in the westerly direction, with one exception are shown in table 1. Tow cart velocities were not available for the 1200 kHz ADCP run in the westerly direction at a speed of 41 cm/s. Therefore, only the results from the single run in the easterly direction are shown. All ADCP velocity measurements shown in table 1 were obtained by computing the depth-averaged velocity for all valid velocity measurements over the entire time span of each run. Tow cart velocities were obtained by averaging the speeds from a speed log provided by the David Taylor Model Basin staff.

Table 1.--Selected results of tow tank tests at the David Taylor Model Basin, West Bethesda, Maryland, March 13-16, 2000

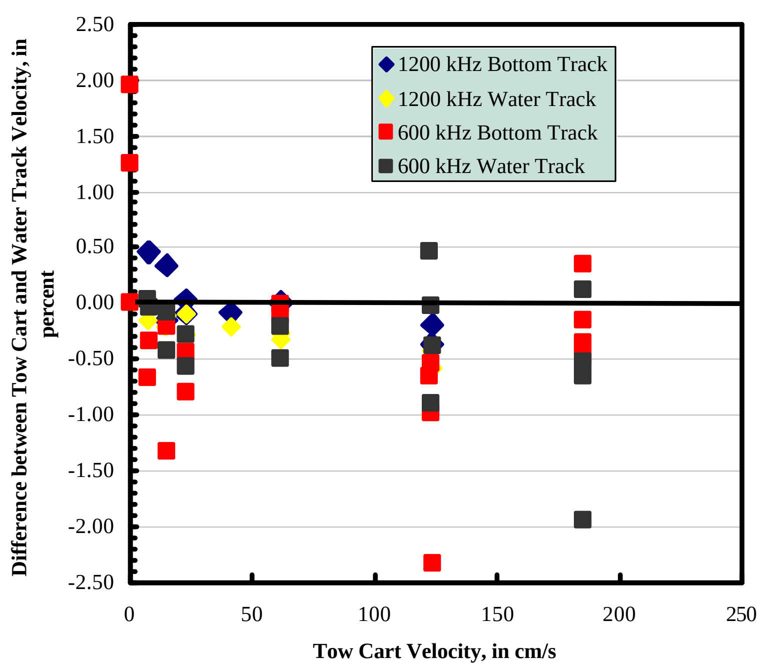
[cm/s, centimeter per second; %, percent; kHz, kilohertz; --, not applicable; bottom track, velocity as measured by the ADCP using a bottom track pulse; water track, velocity as measured by the ADCP using a water track pulse]

	ADCP						
	Mean measured velocity			Mean velocity difference			
	Tow Cart	Bottom Track	Water Track	Bottom Track		Water Track	
ADCP Type	(cm/s)	(cm/s)	(cm/s)	(cm/s)	(%)	(cm/s)	(%)
1200 kHz	7.74	8.20	7.65	0.46	5.9	-0.09	-1.2
1200 kHz	14.9	15.0	14.7	0.09	0.6	-0.16	-1.1
1200 kHz	22.8	22.8	22.6	-0.03	-0.1	-0.19	-0.8
1200 kHz	41.1	41.0	40.9	-0.09	-0.2	-0.21	-0.5
1200 kHz	61.8	61.8	61.5	0.00	0.0	-0.30	-0.5
1200 kHz	123	123	123	-0.28	-0.2	-0.51	-0.4
				0.62	--	0.00	--
600 kHz	0.00	0.62	0.00	-0.50	-6.6	0.00	0.0
600 kHz	7.61	7.10	7.60	-0.77	-5.2	-0.25	-1.7
600 kHz	15.0	14.2	14.7	-0.62	-2.7	-0.42	-1.9
600 kHz	22.8	22.1	22.3	-0.06	-0.1	-0.35	-0.6
600 kHz	61.8	61.8	61.5	-1.13	-0.9	-0.21	-0.2
600 kHz	123	122	123	-0.16	-0.1	-0.76	-0.4
600 kHz	185	185	185	-0.43	-0.2	0.30	0.1
600 kHz	258	257	258	0.46	5.9	-0.09	-1.2

The mean difference between the tow-cart velocity and the measured ADCP velocity was -0.21 cm/s and -0.23 cm/s for bottom track and water track respectively. The mean percent difference was -0.8% and -0.7% for bottom track and water track respectively. These differences are close to the expected error from such instrument. ADCP's will tend to report a measured velocity that is somewhat less than the true velocity due to a number of instrument factors. The average errors described above are about what would be expected for a well-calibrated system (Gary Murdock, RD Instruments, personal communication, 2002). Some versions of firmware (< 10.09 for Rio Grande ADCPs) had bottom tracking errors of about this magnitude. However, it is noticeable that differences between tow cart and bottom-track velocities at slow speeds (15 cm/s or less) are larger than those for water-track velocities. This may be indicative of undetected interference and needs to be investigated further.

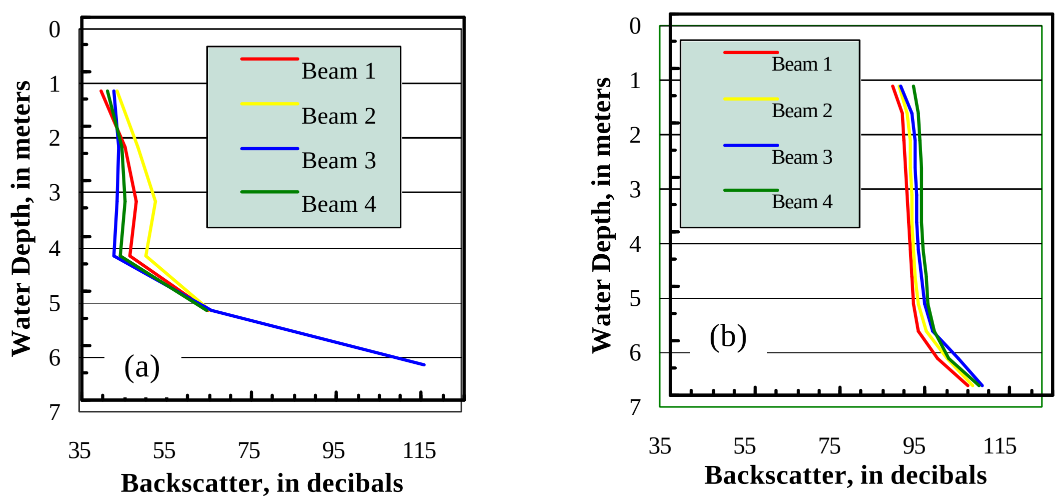
For the 600 kHz ADCP, various tests were conducted in which the tow carriage was not moved while both tow cart and ADCP velocities were recorded (table 1). Interestingly, the bottom track measurements showed a mean error of –0.62 cm/s, whereas the water track velocities had a mean error of zero. Normally, one would expect bottom-track velocity measurements to be more accurate than water-track velocity measurements. The reasons for this difference and for the negative "offset" for bottom track velocities should also be investigated further. Errors do not tend to increase with speed (figure 1). This result is in contrast to results from Appell and others (1988) that showed that some of the early ADCP's manufactured by RD Instruments had errors that increased with speed.

Figure 1. Graph of showing differences between tow cart velocity and ADCP measured velocity.



Although these results appear promising, a number of practical difficulties were encountered during these tests. First, the large amount of metal in the towing basin introduced some errors into the measurements. For data analysis, the compass heading had to be ignored and values for the heading, pitch, and roll fixed to a constant value. Although assigning a constant value for heading can be done easily in the laboratory, and in fact, heading, pitch and roll values were constant during the measurements, field measurements made with an ADCP require the use of the compass and are subject to pitch and roll changes that must be applied throughout the measurement. Second, the surfaces (bed and sidewalls) of the tow tank acoustically are quite reflective. It is likely that side-lobe interference from reflections off of the bed could account for observed variability in bottom track velocity measurements. Finally, and most importantly, the intensity of signal returned to the ADCP (referred to here as backscatter) appreciably varied in space and time. The average backscatter for one of the tow-tank measurements are shown in figure 2a. For one of the depth cells, backscatter ranges from 43 db for beam 3 to 52 db for beam 2. Backscatter for beams 3 and 4 are similar because they are in the same vertical plane. In contrast, for a typical river measurement, variation in backscatter among the 4 beams is no more than 3 db (figure 2b).

Figure 2. Graphs showing the variation in backscatter with depth for (a) tow tank measurements and (b) typical field measurements.



In addition, the backscatter changed appreciably between runs and with depth for a given run. For example, the average backscatter for beam 2 dropped 7 db in about 25 minutes, for measurements made in the same area of the tow tank.

Field Method for Calibrating ADCP's

The USGS is investigating use of a new method for calibration of ADCP's, originally suggested by Gary Murdock (RD Instruments, personal communication, 2002). This method requires the use of a differential global positioning system (DPGS) with sub-meter accuracy and standard software for collecting ADCP data. It is essentially a variation of the distance course method referred to above. Calibration measurements using this method should ideally be made on a lake where the currents are relatively small and there is little or no wave action. The method involves traversing a long (400 – 800 meter) course at a constant compass heading and speed, while simultaneously recording both DGPS and ADCP data. Then a course of the same length is traversed at a heading approximately 180 degrees from the previous pass. This is repeated for a total of 4 times, (8 passes altogether), while rotating the ADCP 45 degrees between each pair of courses. Rotating the ADCP helps to insure that no directional bias is introduced by a moving bed or other unexpected problems. The ratio of the straight-line distance traveled (commonly called the made-good distance) as measured by means of bottom tracking with the ADCP and the straight-line distance traveled as measured by means of DGPS can be computed. This ratio is referred to herein as BC/GC. When BC/GC is less than 0.995, measurements made with RD Instruments' Rio Grande ADCP most likely has a negative bias error and when it is greater than 1.003 the ADCP most likely has a positive bias error. Values for BC/GC were selected based on work done by RD Instruments (G. Murdock, RD Instruments, personal communication, 2002). A value for BC/GC of 0.995 corresponds to a -0.5% error in bottom-track velocity measurements. A value for BC/GC of 1.003, corresponding to a +0.3% error in bottom-track velocity measurements, was chosen because most RD Instruments Rio Grande ADCP's with firmware 10.14 or greater will tend to under-report bottom track velocities by about 0.1% (Gary Murdock, RD Instruments, personal communication, 2002). Well-calibrated Rio Grande ADCP's should have BC/GC values of approximately 0.998 or 0.999. It is estimated that this procedure can be completed in 2 hours or less, and can be done by anyone with access to a sub-meter DGPS. This time estimate does not include setup time and the time required to drive to the lake.

The primary drawback to this technique is that the full capability of the profiler to measure discharge is not fully tested. In particular, this method primarily tests the bottom-track measurements and not water-track measurements. However, experience has shown that the major sources of bias errors are often in beam alignment errors which will be present in both water-track and bottom-track velocity measurements. Bias errors are a primary concern in using ADCP's to measure streamflow. With proper measurement techniques, random errors can often be reduced to an acceptable level by obtaining more samples (measurements). However, bias errors cannot be eliminated by this means. The above method will provide a good overall check of ADCP performance and it can be done in a cost-effective manner.

During the next 6-12 months, the USGS will document a protocol for this method and will have the protocol evaluated by various offices throughout the country. During this period, appropriate values for BC/GC will be determined for SonTek profilers. After any necessary adjustments to the protocol are made, it is likely that a policy will be implemented within the USGS in which every acoustic profiler will be calibrated using this procedure at fixed intervals in time and after any factory repairs or upgrades.

Summary

Various approaches for calibrating ADCP's have been outlined in this paper, along with brief discussions of the advantages and disadvantages of each approach. Tow tanks, in which an ADCP is towed in a towing basin at known speeds, have been used by Appell and others (1988) and Shih (2000) to calibrate ADCP's. Nystrom (2002) evaluated the ability of ADCP's to accurately measure mean velocities, turbulence intensities, and Reynold's stresses in a flume.

ADCP's and conventional methods for measuring velocity and discharge have also been compared and distance course have been used to evaluate ADCP performance. However, each of these methods have significant drawbacks, such as inadequate and non-uniform backscattering material in tow tanks, width and depth restrictions associated with use of flumes, and field calibrations are costly and often subject to relatively large uncertainties.

The USGS conducted tow tank calibration tests in a large towing basin using five ADCP's in March 13-16, 2000. Results of these tests for two ADCP's show that the mean difference between the tow cart velocity and the ADCP velocity measured was 0.21 cm/s for bottom track data and 0.23 cm/s for water track data. The mean percent difference was 0.8% for bottom track and 0.7% for water track. ADCP bottom tracking measurements made at zero cart speed showed a mean error of –0.62 cm/s. While this is still quite small, the cause for this error should be investigated further.

A new method for calibration of ADCP's is proposed in this paper. This method requires the use of a differential global positioning system (DPGS) with sub-meter accuracy and an ADCP to collect data on a course with a fixed heading. The ratio of the straight-line distance traveled (commonly called the made good distance) as measured by means of bottom tracking with the ADCP and the straight-line distance traveled as measured by means of DGPS can be computed. When this ratio is less than 0.995, measurements made with RD Instruments' Rio Grande ADCP most likely have a negative bias error and when it is greater than 1.003 this ADCP most likely has a positive bias error. It is estimated that this procedure can be completed in 2 hours or less, and can be done by anyone with access to a sub-meter DGPS (not including setup and driving time). It is believed that this technique will be useful in helping detect significant bias errors in ADCP's cost-effectively. The USGS is exploring implementation of this method nationwide.

References

Appell, G.F., Mero, T.N., Sprenke, J.J., and Schmidt, D.R. (1985) "An intercomparison of tow acoustic Doppler curren profilers." *Proc. Of Oceans '85*, New York, NY, 723-730.

Appell, G.F., Gast, J., Williams, R.G., and Bass, P.D. (1988) "Calibration of acoustic Doppler current profilers." *Proc. Of Oceans '88--Conference and Exposition October 31-November 2, 1988*, Baltimore, MD, 346-352.

Bos, W.G. (1991) "A comparison of two Doppler current profilers." *J. Oceanic Eng.*, AMS, 16, 374-381.

Lemmin, U., Rolland, T. (1997) "Acoustic velocity profiler for laboratory and field studies." *J. Hydr. Eng.*, ASCE, December 1997, 1089-1098.

Lohrmann, A., Cabrera. R., and Kraus, N.C. (1994) "Acoustic-Doppler Velocimeter (ADV) for laboratory use." *Proc. Conf. On Fundamentals and Advancements in Hydraulic Measurements and Experimentation*, Buffalo, NY, ASCE, 351-365.

Morlock, S.E. (1995) *Evaluation of Acoustic Doppler Current Profiler Measurements of River Discharge*: U.S. Geological Survey Water Resources Investigation Report 95-4218, 41 p.

Mueller, D.S. (2002) "Field Assessment of Acoustic Doppler Based Discharge Measurements." *Proc. Hydraulic Measurements & Experimental Methods 2002*, Estes Park, CO, ASCE.

Nystrom, E.A., Oberg, K.A., Rehmann, C.R. (2002) "Measurement of Turbulence with Acoustic Doppler Current Profilers - Issues and Laboratory Results." *Proc. Hydraulic Measurements & Experimental Methods 2002*, Estes Park, CO, ASCE.

Shih H. H., Payton C., Sprenke J., and Mero T. (200) "Towing Basin Speed Calibration of Acoustic Doppler Current Profiling Instruments", *Proc. 2000 Joint Conference on Water Resources Engineering and Water Resources Planning and Management*, Minneapolis, MN, ASCE.

Simpson, M. (2002) *Discharge Measurements Using a Broad-Band Acoustic Doppler Current Profiler*: U. S. Geological Survey, Open-File Report 01-01, 128 p., http://water.usgs.gov/pubs/of/ofr0101/

Simpson, M.R., and Oltmann, R.N. (1993) *Discharge measurement using an acoustic Doppler current pro?ler*: U.S. Geological Survey Water-Supply Paper 2395, 34 p.

Voulgaris, G., and Trowbridge, J.H. (1998) "Evaluation of Acoustic Doppler Velocimeter (ADV) for turbulence measurements." *J. Atmos. Oceanic Tech.*, AMS, 15, 272-289.