Validation of Streamflow Measurements Made with Acoustic Doppler Current Profilers

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Abstract: The U.S. Geological Survey and other international agencies have collaborated to conduct laboratory and field validations of acoustic Doppler current profiler (ADCP) measurements of streamflow. Laboratory validations made in a large towing basin show that the mean differences between tow cart velocity and ADCP bottom-track and water-track velocities were −0.51 and −1.10%, respectively. Field validations of commercially available ADCPs were conducted by comparing streamflow measurements made with ADCPs to reference streamflow measurements obtained from concurrent mechanical current-meter measurements, stable rating curves, salt-dilution measurements, or acoustic velocity meters. Data from 1,032 transects, comprising 100 discharge measurements, were analyzed from 22 sites in the United States, Canada, Sweden, and The Netherlands. Results of these analyses show that broadband ADCP streamflow measurements are unbiased when compared to the reference discharges regardless of the water mode used for making the measurement. Measurement duration is more important than the number of transects for reducing the uncertainty of the ADCP streamflow measurement.

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Introduction

Since the early 1990s, the U.S. Geological Survey (USGS) and other agencies around the world have used acoustic Doppler current profilers (ADCPs) to measure discharge in inland waterways and in estuaries (Oberg and Mueller 1994). Pelletier (1988) reported that Water Survey Canada personnel make about 19,000 streamflow measurements annually, and thousands more are made throughout the world each year by government agencies and engineering firms. During the period from October 1, 2005, to September 30, 2006, USGS personnel made 65,766 discharge measurements in the United States, 14% of which were made with ADCPs. ADCPs are widely used for streamflow measurement, but are also increasingly used for mapping velocity fields (Wagner and Mueller 2001; Jacobson et al. 2004), geomorphic research (Dinehart and Burau 2005; Kostachuk et al. 2004), measurement of bed-load velocity (Rennie et al. 2002), and many other applications. Many investigators have studied the accuracy of current-meter streamflow measurements over the years; see Pelletier (1988) for a comprehensive review of this accuracy. Even recently, Hubbard et al. (2001) published information on new Price AA current-meter ratings because of the widespread use of these instruments in the engineering community. However, few comprehensive validations of commercially available ADCPs for streamflow measurements have been made to date (2007).

Purpose and Scope

The purpose of this paper is to present results of laboratory and field validations of streamflow measurements made with ADCPs to ensure that there are no changes in long-term streamflow records caused by changes in equipment and measurement technology. ADCP validations were made by comparing velocities measured by ADCPs to those measured with a tow cart in a towing basin and by comparing streamflow measurements made with ADCPs to concurrent mechanical current meter measurements and streamflow computed from stable stage-discharge rating curves. Tests in towing basins are the standard method for calibrating and validating mechanical current meters (ISO 1976). However, the use of towing basins imposes limitations that are not representative of field measurement conditions (no turbulence, artificial backscatter material, smooth bed, negligible or zero-velocity gradients in the sample volume, and other conditions). Beginning in 2001, the USGS and other agencies undertook field validations for all available water modes at sites in the United States, Canada, Sweden, and The Netherlands. This paper presents the results of these field validations using bottom-tracking profilers.

Previous Work

Many investigators have compared ADCP velocity measurements to measurements made simultaneously or nearly simultaneously with other well-calibrated instruments. Comparisons of ADCP-measured velocities to tow-cart velocities by Shih et al. (2000) and Appell et al. (1988), showed that the ADCPs performed at or close to the manufacturer's specifications. Nystrom et al. (2002) showed that mean velocities measured by commercially available ADCP measurements were within ±1 cm/s of acoustic Doppler

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velocimeter (ADV) measured velocities. Lemmin and Rolland (1997) compared velocity measurements from a custom-made stationary ADCP to hot film and pitot tube velocity measurements in a laboratory flume and to velocity measurements in a shallow river (30–60 cm deep) and found excellent agreement. Bos (1991) compared a commercially available ADCP to the Sonar Work Station built by The Netherlands' Rijkswaterstaat, and found good correspondence between the two instruments except in rapidly changing flows (as much as 2.5 m/s). The differences observed could be explained in part by different depth cell sizes, sampling time, and because the two instruments sampled alternately, not concurrently. Simpson and Oltmann (1993) compared many detailed velocity profile measurements with mechanical current meters on the Sacramento River at Freeport, Calif. to profiles obtained with an ADCP. González et al. (1996) concluded that ADCP velocity profile measurements in the center of a 49-m wide, 8-m deep canal were in good agreement with theoretical fluid mechanics. Although ADCP velocity comparisons are useful, they do not address all of the potential errors in measuring streamflow.

Morlock (1996) evaluated 1,200- and 600-kHz broadband ADCPs manufactured by Teledyne RD Instruments, Inc. (TRDI) at 12 geographically diverse sites in the United States and found that the ADCP discharges compared favorably with discharge measurements made with Price AA current meters and standard USGS techniques (Rantz et al. 1982). Morlock (1996) used water mode 4, which is no longer commonly used. Preliminary results of discharge measurement comparisons at five field sites using water modes 1 and 5 by Mueller (2002) indicated that ADCP-measured discharges were within ±5% of concurrent current-meter measurements. However, the data set was too small to demonstrate whether or not significant biases between ADCP and current-meter measurements were present. Since 2001, new water modes for velocity measurement have been introduced. Some data collected by Mueller (2002) are included in analyses in this paper.

Laboratory Validation

The use of towing basins for current-meter calibrations are common and procedures for these calibrations are well established (ISO 1976). The USGS, in cooperation with the South Florida Water Management District, tested ADCPs at the Naval Center for Surface Warfare, David Taylor Model Basin (DTMB), in Carderock, Md., during March 13–16, 2000. The DTMB was chosen because the towing basin is much deeper and wider than the USGS facility and because the National Oceanographic and Atmospheric Administration routinely uses this facility to evaluate performance of ADCPs for use in its monitoring programs. The purpose of the measurements at DTMB in March 2000 was to evaluate the feasibility of using a large, indoor towing basin for validating ADCPs and to then validate ADCP velocity measurements for various ADCPs.

Instruments Tested

Five ADCPs were tested at the DTMB, a 1,500-kHz SonTek/YSI Argonaut SL, a 3,000-kHz SonTek/YSI acoustic Doppler profiler (ADP), a 600-kHz TRDI Rio Grande, a 1,200-kHz TRDI Broadband, and a TRDI prototype 3-beam horizontal 600-kHz capable of bottom tracking. Of these ADCPs, only the 3,000-kHz SonTek/YSI ADP, the 1,200-kHz Broadband, and the 600-kHz Rio Grande are now commonly used for streamflow measurements. Therefore, only the results obtained from these three ADCPs are presented in this paper. All of the ADCPs used, except the Argonaut SL, were capable of making two independent velocity measurements, a bottom-track (BT) velocity and a water-track (WT) velocity measurement (Simpson 2001). The BT velocity, or the velocity of the ADCP over the bed, is measured by the ADCP using separate acoustic pulses that can be much longer than the water pulse (typically 20–30% of the water depth) and is typically used to measure the velocity of the vessel used for making ADCP measurements. WT velocities are measured using short acoustic pulses (5–50 cm) and backscattered sound returned to the ADCP from small particles moving with the water (Gordon 1996; Simpson 2001). The techniques used to measure velocities vary by ADCP manufacturer. SonTek/YSI uses narrow-band techniques (SonTek/YSI 2001), whereas a broadband technique is used by TRDI (Gordon 1996). Regardless of the techniques employed, BT measurements in rivers are generally more accurate than WT measurements, because of the much stronger acoustic reflections from the river bed.

Data Collection and Processing Methods

The towing basin at the DTMB used in this study is approximately 363 m long; 15.5 m wide, and varies in depth from 3 to 6.7 m (Naval Sea Systems Command 2004). Shih et al. (2000) describe the towing basin and the test procedure used. For valid WT measurements, adequate backscattering material is essential. Towing basins do not retain material in suspension because of negligible turbulence in the basin. It was necessary, therefore, to seed the basin with a backscattering material. The procedures used to ensure adequate backscattering for these measurements are described by Oberg (2002).

Results

Limitations associated with the use of acoustics in towing tanks for validating acoustic profilers were realized during these tests. The compass heading had to be ignored due to magnetic interference and values for the heading, pitch, and roll fixed to a constant value for analysis. The bed and sidewalls of the towing basin are acoustically reflective and acoustic reflections from these surfaces are present in the data. Acoustic interference, if present, is often difficult to detect and eliminate, and usually results in a negative bias. The intensity of signal returned to the ADCP (backscatter) appreciably varied in space and time. The beam-to-beam variation in the intensities for a given depth indicated incomplete mixing of the backscattering material, which is difficult to achieve in a towing basin. In addition, after seeding the tow tank, intensities tended to decrease as seeding material dropped out of the water column, until such time as there was not enough intensity for valid velocity measurements. For one depth cell, the average backscatter for one of the tow-tank measurements ranged from 43 dB in beam 3 to 52 dB in beam 2. In contrast, for a typical river measurement, variation in backscatter among the four beams is usually less than 3 dB [see Fig. 2 in Oberg (2002) for more details]. Acoustic backscatter changed appreciably between measurements. For example, the average backscatter for one beam dropped 7 dB in about 25 min for measurements made in the same region of the towing basin.

The mean tow cart, BT, and depth-averaged WT velocities for 24 comparisons are shown in Table 1. For 5 of the 24 validation runs, only one pass was available for analysis because of prob-

Table 1. Selected Results of Tow-Tank Validations at the David Taylor Model Basin, Carderock, Md., March 13–16, 2000

		Velocity (cm/s)			Difference (%)	
Manufacturer	Model	Tow cart	Bottom track	Water track	Bottom track	Water track
TRDI	Broadband-WM1	7.74	8.20	7.65	5.94	−1.16
TRDI	Broadband-WM1	14.9	15.0	14.7	0.74	−1.28
TRDI	Broadband-WM1	22.8	22.7	22.5	−0.44	−1.32
TRDI	Broadband-WM1	41.1	41.0	40.9	−0.29	−0.54
TRDI	Broadband-WM1	61.8	61.8	61.5	0.03	−0.53
TRDI	Broadband-WM1	123	123	123	−0.24	−0.41
			Mean		0.96	−0.87
TRDI	Broadband-WM5	5.13	5.20	5.00	1.36	−2.60
TRDI	Broadband-WM5	7.71	8.05	7.70	4.36	−0.18
TRDI	Broadband-WM5	14.8	14.9	14.8	0.88	−0.47
TRDI	Broadband-WM5	22.5	22.4	22.4	−0.31	−0.31
TRDI	Broadband-WM5	61.7	61.7	61.5	−0.05	−0.37
TRDI	Broadband-WM5	82.4	82.1	82.1	−0.35	−0.35
			Mean		0.99	−0.70
TRDI	Rio Grande-WM1	7.60	7.10	7.60	−6.58	0.00
TRDI	Rio Grande-WM1	15.0	14.2	14.7	−5.08	−1.74
TRDI	Rio Grande-WM1	22.8	22.1	22.4	−2.64	−1.76
TRDI	Rio Grande-WM1	61.9	61.8	61.5	−0.16	−0.57
TRDI	Rio Grande-WM1	124	121	123	−1.71	−0.45
TRDI	Rio Grande-WM1	185	185	184	−0.04	−0.69
TRDI	Rio Grande-WM1	309	308	308	−0.15	−0.23
			Mean		−2.33	−0.78
SonTek	ADP	7.78	7.60	7.36	−2.34	−5.44
SonTek	ADP	22.7	23.0	22.6	1.45	−0.37
SonTek	ADP	61.9	59.8	60.3	−3.32	−2.53
SonTek	ADP	123	121	121	−2.34	−1.87
SonTek	ADP	308	305	304	−0.95	−1.48
			Mean		−1.50	−2.10

Note: WM=water mode; bottom track=velocity as measured by the ADCP using bottom tracking; and water track=velocity as measured by the ADCP using water tracking.

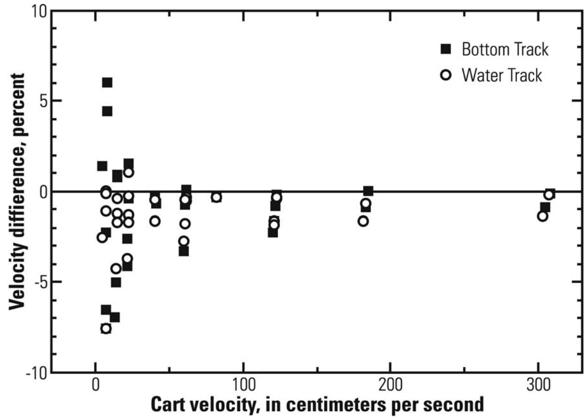

Fig. 1. Differences between tow-cart velocity and ADCP measured velocity

lems encountered in recording the tow-cart velocities. Examination of the reciprocal passes for the remaining 19 comparisons did not indicate any significant variation as a result of the direction of travel in the towing basin, therefore, the single-pass measurements are assumed to be unbiased and valid.

The mean of the differences between the tow-cart velocity and BT velocity ranged from −2.33 to 0.99%. The mean of the differences between the tow-cart velocity and WT velocity ranged from −2.10 to −0.70%. The mean differences between tow cart velocity and ADCP BT and WT velocities for all instruments and tow-cart velocities were −0.51 and −1.10%, respectively. The variability of the differences between BT and WT velocities and tow-cart velocity (Fig. 1) is significantly greater at lower tow-cart velocities (<40 cm/s) as observed by Shih et al. (2000). WT velocities showed a small negative bias. At higher velocities, BT velocities also seemed to exhibit a small negative bias. However, at lower velocities, this bias was not as evident. The distribution of the percent difference between BT and tow-cart velocities was more uniform about zero at lower velocities. Greater variability at slower velocities is expected as the uncertainty in the velocity measurement relative to the cart velocity is greater at these slower speeds. For tow-cart velocities greater than 40 cm/s, velocity differences were significantly less.

Normally, BT velocity measurements are more accurate than WT measurements primarily because the streambed is a good reflector of acoustic energy. However, analysis of measurements at DTMB with TRDI ADCPs indicated a greater absolute error in BT than in WT. This result can be explained by the difference in the scattering of sound energy from a natural streambed and a smooth concrete towing basin. Terrain bias in BT measurements is exacerbated over smooth surfaces (such as a towing basin) and tends to bias BT velocities low (Steve Maier, TRDI, private communication, 2006). BT measurements in natural streams where the bed roughness is greater and sound scattering is less uniform result in lower terrain bias than BT measurements in a smooth tank like DTMB. Two tests were conducted with the Rio Grande ADCP in which the tow carriage was not moved, while both tow cart and ADCP velocities were recorded. Mean measured BT velocities were 0.62 cm/s, mean measured WT velocities and tow-cart velocities were zero; another indication of less accurate BT measurements in towing basins with a smooth bed. Shih et al. (2000) observed the same result for BT measurements at DTMB.

Field Validation

One of the most common uses of ADCPs is the measurement of streamflow. Laboratory validations, similar to those discussed earlier, provide information about WT and BT velocities measured using an ADCP but the limitations and problems discussed earlier imply that these types of measurements are not necessarily representative of the field environment. Therefore it is necessary to validate ADCP measurements in the field while using all the ADCP sensors (heading, tilt, and water temperature) and measurements (boat velocity, water velocity, and depth) required to make an ADCP streamflow measurement in a natural backscatter environment. Further, it is also necessary to determine whether any discernible bias is present between ADCP discharge measurements and those made using conventional discharge measurement methods (Rantz et al. 1982; ISO 1979) commonly used by organizations engaged in hydrometric measurements.

Table 2. Locations of ADCP Field Validations

Site ID	Station No.	Station name	Latitude	Longitude	Drainage area (km^2)	Year of validation	No. of transects
Älgån	—	Älgån River near Arvika, Sweden	60.150	12.500	—	2003	11
Algon	05550000	Fox River at Algonquin, Ill.	42.166	−88.290	3,630	2004	97
Alley	07065495	Jacks Fork at Alley Spring, Mo.	37.148	−91.443	772	2004	24
Burl	07182510	Neosho River at Burlington, Kan.	38.195	−95.735	7,880	2003	80
Chest	07020500	Mississippi River at Chester, Ill.	37.904	−89.836	1,840,000	2001–2002	50
Cov	03336000	Wabash River at Covington, Ind.	40.140	−87.407	21,300	2004	16
Driel	NR890625	Lower Rhine River at Driel, The Netherlands	51.969	5.819	185,000	2004	42
Dunns	05517500	Kankakee River at Dunns Bridge, Ind.	41.219	−86.969	3,500	2001	12
Emin	07066000	Jacks Fork at Eminence, Mo.	37.154	−91.358	1,030	2004	84
Fisk	07040000	St. Francis River at Fisk, Mo.	36.781	−90.202	3,550	2004	24
Frank	03289500	Elkhorn Creek near Frankfort, Ky.	38.269	−84.815	1,230	2002	82
Benton	06090800	Missouri River at Fort Benton, Mont.	47.817	−110.667	64,100	2003	48
Mars	05543500	Illinois River at Marseilles, Ill.	41.327	−88.718	21,400	2001	28
Mont	05551540	Fox River at Montgomery, Ill.	41.734	−88.333	4,490	2004	163
Sauble	02FA001	Sauble River at Sauble Falls, Ont.	44.511	−81.256	927	2003	4
Shelby	05518000	Kankakee River at Shelby, Ind.	41.183	−87.340	4,610	2001	12
Sidney	06329500	Yellowstone River near Sidney, Mont.	47.678	−104.157	179,000	2003	16
TerHte	03341500	Wabash River at Terre Haute, Ind.	39.476	−87.419	31,800	2004	17
Virg	06109500	Missouri River at Virgelle, Mont.	48.005	−110.258	89,000	2003	22
Well	—	Welland Supply Canal near Port Colborne, Ont.	42.894	−78.750	—	2004	147
Willet	—	Willet Bridge near Intake, Mont.	47.310	−104.491	—	2003	28
Wolf	06177000	Missouri River near Wolf Point, Mont.	48.067	−105.532	213,000	2003	25

Note: — = data not available.

Instruments Tested

Field validation of ADCP discharge measurements was conducted with ADCPs manufactured by TRDI and SonTek/YSI at 22 sites. Validation data were collected with TRDI 600- and 1,200-kHz Workhorse Rio Grande ADCPs, using water modes 1, 5, 11, and 12. Although data were collected using SonTek/YSI ADCPs, these data are not included in the present analysis because improvements in SonTek/YSI firmware were not reflected in the available data. Additional field validation measurements with SonTek/YSI ADCPs are planned and these data will be analyzed with the results reported later.

Description of Sites

Sites for field validation measurements were selected to provide a variety of measuring conditions and to facilitate comparison of simultaneous measurement of discharge using ADCPs and mechanical current meters. Sites chosen for this study (Table 2) included 18 sites in the United States, 2 sites in Canada, and 1 site each in Sweden and The Netherlands. The streams selected were upland rivers near continuous-record streamflow-gauging stations where flow was steady and not subject to tidal or backwater effects. Some sites were located near control structures (Burl, Mars, Virg, Well, and Wolf) that are used to regulate flow in the stream. For some of these sites, flow was not steady during validations, requiring concurrent comparison measurements.

The drainage areas for the sites used for validations ranged from 772 to 1,840,000 km^2. Measured stream widths ranged from 7.2 to 499 m; mean depths ranged from 0.48 to 9.00 m. Although stream slope and roughness data were not available for most of the sites, the streams used for validation measurements ranged from channelized low-slope streams, such as Dunns Bridge, to natural higher-sloped streams, such as Älgån.

Data Collection and Processing Methods

ADCP validation measurements were made for four water modes available in TRDI ADCPs (modes 1, 5, 11, and 12). Mode 1 is the default water mode and is available in all TRDI ADCPs and can be used in a wide range of flow conditions. Modes 5 and 11 are used in shallow (<4 m for a 1,200-kHz ADCP and <8 m for a 600-kHz ADCP) and slow flows (typically <1 m/s). Mode 12 makes use of the same measurement technique as Mode 1, but the data are processed differently and allow for more accurate velocity measurements than Mode 1. More detailed information regarding each water mode is provided in subsequent sections.

A detailed procedure for collecting data was followed at each site, based on procedures outlined by Oberg et al. (2005, pp. 12–19), but adapted for the comparison measurements being conducted. This procedure included making an independent water-temperature measurement, calibrating the compass of each ADCP, carefully measuring the immersion depth of the ADCP, and recording the results of ADCP diagnostic tests. Both manned boats and tethered boats (Rehmel et al. 2003) were used for data collection. Moving-bed tests were conducted at each site to determine whether the ADCP measurements would be affected by moving bed (Oberg et al. 2005, p. 15). Start and end locations were identified and marked at a distance measured from the shore that permitted at least two depth cells to be recorded by the ADCPs tested. Buoys were used to mark start and end locations for measurements made with manned boats. Approximately 10 s of data were collected from a nearly stationary position at the beginning and end of each transect, in order to obtain more accurate estimates of the near-shore velocity for estimating the edge discharge. The stream was traversed at a boat speed less than or equal to the downstream speed of the water. Where possible, 12 or more transects were collected with each ADCP and configuration. However, at some sites only 4 transects were collected for a specific configuration. This procedure was repeated until data were collected with each of the available instruments and water modes appropriate for the site.

A current meter was used to make one or two streamflow measurements simultaneously with the ADCPs at each site and the resulting discharge used for comparison with ADCP-measured discharges. Price AA current meters were used for comparison measurements made in the United States and Canada. The performance of each current meter was evaluated in a USGS or Environment Canada towing basin. All the current meters were within specifications with the exception of one meter that was biased 1 to 2% high. Salt dilution measurements using the finite mass dilution method (Okunishi et al. 1992) were made at Älgån using standard procedures used by the Norwegian Water Resources and Energy Directorate (NVE). Data collected at Driel were compared with streamflow computed from a four-path travel-time acoustic velocity meter located at this site.

At some sites, many different validation measurements were made using different water modes and configurations. For many of the validation measurements, concurrent current meter or dilution streamflow measurements were not available for all of the ADCP validation measurements. For these situations, the current-meter measurement was compared to the rating for that site. If the current meter measurement agreed within approximately 2% of the rated discharge, the rated discharge was used for comparison with ADCP measurements. If the current meter did not agree within 2% of the rated discharge, the ADCP data that were not collected concurrent with the current-meter measurement were not included in this analysis.

All ADCP data were analyzed and reviewed using TRDI's WinRiver software version 10.06 in order to identify any data quality issues or to correct any mistakes in data entry in the field. Procedures for data review suggested by Oberg et al. (2005, pp. 21–23) were followed. The extrapolation techniques for the top and bottom discharges were reviewed by means of the WinRiver software and an appropriate extrapolation method was chosen for each measuring section or site. The 1/6th power law (TRDI 2003; Chen 1991) was used for the top and bottom discharge extrapolations for all data sets, except at two sites. The constant method (TRDI 2003) was used to estimate the top discharge and the 1/6th power law was used to extrapolate the bottom discharge for data collected at Burlington and Montgomery, for the upstream measuring section (Table 2). The velocity data at the beginning and end of each transect were reviewed. Where necessary, the starting and ending points of the transects were adjusted to obtain a proper edge estimate.

Test Results

The percent difference between discharges measured with an ADCP and the reference discharge were computed assuming that the reference discharge was the "true" value.

Mode 1

Water mode 1 (WM1) is a general purpose water mode for TRDI ADCPs (TRDI 2000). WM1 is typically used in streams with a mean depth deeper than 1 m and/or with velocities exceeding 1 m/s. WM1 measures the Doppler shift using two phase-coded broadband pulses separated by a lag that is dependent on the user-specified ambiguity velocity. The lag is inversely proportional to the radial ambiguity velocity, the maximum relative radial velocity (including boat speed and water speed) that can be accurately measured with the ADCP. The recommended radial ambiguity velocity range is from 175 to 700 cm/s (the minimum recommended value during some of the testing was 170 cm/s). The bin size and lag between the pulses, and, thus, the ambiguity velocity, are key variables in determining the standard deviation of the random instrument noise present in velocity measurements. The recommended and commonly used bin sizes for 600- and 1,200-kHz instruments are 50 and 25 cm, respectively. Standard deviations of instrument noise for these bin sizes range between 13 and 22 cm/s, depending on the radial ambiguity velocity value. The standard deviations will increase dramatically for smaller bin sizes.

The evaluation data set for WM1 contains 28 measurements made at 11 different sites using different field crews and instruments (Table 3). These measurements represent mean depths, mean velocities, and channel widths ranging from 1.2 to 9.0 m, from 0.5 to 1.5 m/s, and from 20 to 500 m, respectively. Streamflows ranging from 20 to over 5,000 m^3/s were obtained from averaging between 4 and 16 transects. The reference measurements consist of 14 current meter measurements, 11 discharges determined from rating curves, and 3 discharges measured by an AVM. The mean and median percent difference between the ADCP and reference discharges is 0.5% with a maximum difference of 5.63%. Graphical analysis of, and a single sample t-test on, the percent differences [Fig. 2(a) showed that the WM1 data were not biased relative to the reference measurements.

The WM1 data were analyzed for relations between the percent differences between the ADCP and reference discharges and selected site and measurement characteristics (Fig. 3). No strong correlations between the percent difference and the selected characteristics were observed. Although some weak correlations appear to be present, they are likely the result of the four largest streamflow measurements all being from the same site. Therefore, streamflow measured using an ADCP with WM1 compare well with reference discharges determined by current-meter methods with no statistical bias evident in the data presented here.

Modes 5/11

Water modes 5 and 11 are pulse-to-pulse coherent modes. Like WM1, two pulses are transmitted, but unlike WM1, the lag between the pulses for WM5 and WM11 is long and variable. The lag is equal to the time for the first pulse to travel to the bottom and back. After the signal from the first pulse is received at the transducer face, the ADCP transmits the second pulse. This approach creates a very long lag with extremely low instrument noise, typically less than 2 cm/s with bin sizes of 5 and 10 cm for 1,200- and 600-kHz instruments, respectively. Because of the long lag, the ambiguity velocity is very low and could render the modes nearly useless, but an ambiguity resolving bin is used to help resolve the ambiguity and allow a lower ambiguity velocity than the actual water velocity (TRDI 2000). The time dilation technique used to determine the velocity in the ambiguity resolving bin and the bin-to-bin tracking algorithm used to apply the ambiguity velocity to consecutive bins limits the use of WM5 and

Table 3. Summary of ADCP Validation Measurements Made with Water Mode 1

Site ID	No. of transects	Instrument configuration Frq (kHz)	WS (cm)	WV (cm/s)	ADCP Q (m^3/s)	Ref Q (m^3/s)	Ref type	Difference (%)	ADCP Q COV (%)	Width (m)	Mean depth (m)	Max. depth (m)	Mean vel (m/s)	Max vel (m/s)	Dur (min)
Burl	8	1,200	25	170	144	144	R	−0.29	1.79	37.4	2.56	4.36	1.50	3.27	3.27
Burl	8	1,200	10	170	145	144	R	0.46	2.61	37.2	2.61	4.40	1.49	4.08	4.08
Burl	8	1,200	25	170	142	144	R	−1.33	1.98	36.7	2.58	4.35	1.50	3.05	3.05
Chest	12	600	50	170	5,420	5,580	AA	−2.82	0.94	499	9.00	14.77	1.26	4.27	4.27
Chest	4	600	50	170	5,360	5,580	AA	−4.00	0.83	494	8.92	14.64	1.27	2.81	2.81
Chest	12	600	50	188	3,140	3,120	AA	0.68	0.72	488	6.19	12.28	1.08	2.32	2.32
Chest	12	600	50	188	3,110	3,120	AA	−0.15	1.13	486	6.17	12.33	1.08	2.76	2.76
Driel	10	600	50	350	201	200	AVM	0.79	4.90	113	4.63	5.83	0.39	1.23	1.23
Driel	22	600	50	350	197	196	AVM	0.55	7.41	111	4.54	6.61	0.39	1.56	1.56
Driel	10	600	50	350	200	199	AVM	0.46	4.50	110	4.76	5.92	0.38	1.25	1.25
Dunns	12	1,200	25	170	23.0	22.6	AA	1.54	1.78	29.4	1.61	2.18	0.49	1.58	1.58
Benton	4	1,200	25	170	135	128	R	5.15	1.37	140	1.57	2.44	0.61	1.86	1.86
Benton	4	1,200	25	170	126	122	R	2.98	0.52	141	1.55	2.35	0.58	1.73	1.73
Benton	4	1,200	25	170	94.2	91.5	R	2.99	2.93	135	1.46	2.27	0.48	2.14	2.14
Benton	4	1,200	25	170	93.6	91.5	R	2.37	2.27	134	1.45	2.24	0.48	1.79	1.79
Mars	12	1,200	25	170	223	219	R	1.58	6.06	120	1.94	3.13	0.96	2.26	2.26
Mars	16	1,200	25	170	226	220	R	2.79	3.65	120	1.95	2.96	0.97	2.74	2.74
Shelby	12	1,200	25	170	29.6	29.8	AA	−0.52	2.37	40.4	1.40	1.78	0.52	1.81	1.81
Sidney	4	1,200	25	170	117	116	R	0.62	1.20	170	1.47	2.76	0.47	1.50	1.50
Virg	4	1,200	25	170	121	125	R	−3.32	3.40	155	1.16	1.94	0.67	2.01	2.01
Well	22	1,200	25	205	158	150	AA	5.63	2.26	37.9	5.48	5.81	0.76	2.14	2.14
Well	22	1,200	25	170	194	195	AA	−0.65	2.04	36.4	5.46	5.83	0.98	2.75	2.75
Well	22	1,200	25	170	204	207	AA	−1.25	2.33	36.3	5.50	5.84	1.02	3.06	3.06
Well	8	1,200	25	170	156	150	AA	3.46	2.05	39.7	5.41	5.86	0.72	2.43	2.43
Well	20	1,200	25	170	187	187	AA	−0.01	1.48	39.5	5.35	5.87	0.88	2.59	2.59
Well	16	1,200	25	170	218	220	AA	−1.05	2.95	36.7	5.42	7.18	1.10	3.03	3.03
Well	13	1,200	25	170	257	267	AA	−3.52	4.95	36.6	5.41	5.82	1.30	3.00	3.00
Willet	4	1,200	25	170	20.5	20.5	AA	−0.16	0.99	19.7	1.90	2.87	0.55	1.63	1.63

Note: ID=identification; No.=number; Frq.=frequency; WS=bin size; WV=ambiguity velocity; Q=discharge; Ref=reference; R=stage-discharge rating curve; AA=Price AA current meter; AVM=acoustic velocity meter index rating; Diff=difference; COV=coefficient of variation; Max=maximum; vel=velocity; and Dur=duration.

WM11 to conditions with low turbulence and low shear. Shear caused by coarse bed material or other conditions will often cause these modes to fail. Because of the short pulses and long lag, WM5 and WM11 are limited to shallow depths (<4 m for 1,200 kHz and 8 m for 600 kHz) and slow velocities (typically <1 m/s).

The evaluation data set for WM5 and WM11 contains 11 measurements made at 6 different sites using different field crews and instruments (Table 4). These measurements represent mean depths, mean velocities, and channel widths ranging from 0.6 to 2.4 m, from 0.1 to 0.5 m/s, and from 7 to 105 m, respectively. Measured streamflow ranged from 1.93 to 44.3 m^3/s and were computed as the average of between 6 and 12 transects. The reference measurements for comparison purposes consist of five current-meter measurements, one salt-dilution measurement, and five discharges determined from rating curves. The mean and median percent difference between the ADCP and reference discharges were 0.33 and −0.77, respectively; but both were less than 1%. Although the maximum percent difference was 7.09%, only one other measurement (5.08%) exceeded a difference of 4%. Graphical analysis of, and a single sample t-test on, the percent differences [Fig. 2(b)] showed that the WM5 and WM11 data were not biased relative to the reference measurements.

The WM5 and WM11 data were analyzed for relations between the percent differences between the ADCP and reference discharges and selected site and measurement characteristics (Fig. 3). There was no evidence of strong correlations between the percent difference and the selected characteristics. Therefore, discharges measured using an ADCP with WM5 and WM11 compare well with reference discharges determined by current-meter methods with no statistical bias evident in the data presented here.

Mode 12

WM12 is essentially a high ping rate WM1. WM12 is designed so that the heading, pitch, and roll sensors are only read at the beginning of the averaging period, the individual pings are averaged in phase space, and only the average is transformed into water velocities. This design eliminates some of the processing overhead and potential for averaging ambiguity velocity errors associated with WM1. The ping rate for WM1 is approximately 2 to 3 Hz whereas the ping rate for WM12 is 10–20 Hz (depending on number of bins). However, because the heading pitch and roll sensors are sampled only at the beginning of the averaging period, changes in heading, speed, pitch, or roll will lead to errors in the measured velocity. Thus, it is important that the sampling period be short, generally 1 s or less. WM12 can be used anywhere

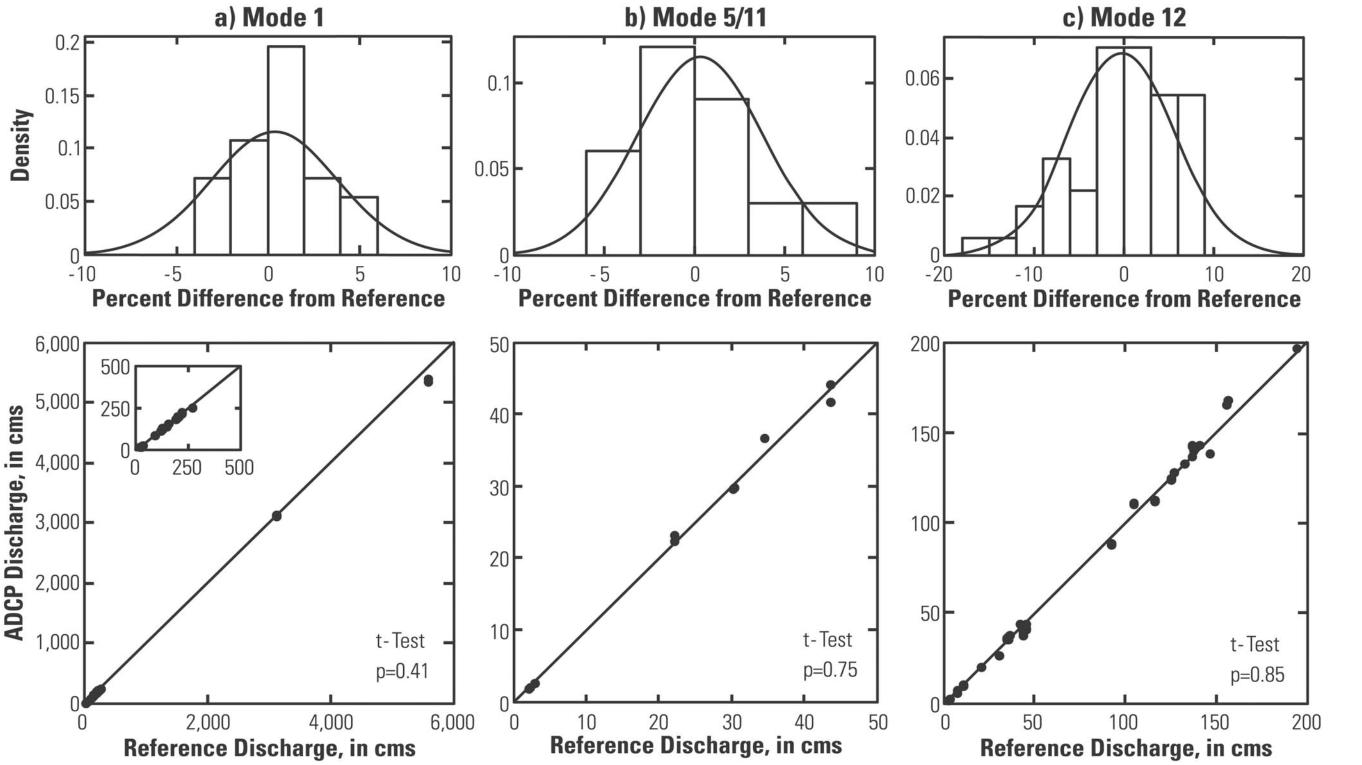

Fig. 2. Probability density plots of the percent difference between ADCP and reference discharges with normal distributions overlayed and scatter plots showing the relation between ADCP and reference discharges with lines of perfect agreement

WM1 can be used, provided the ambiguity velocity is set properly as in WM1. The velocity standard deviation for WM12 cannot be stated as broadly as for the other water modes because WM12 is more configurable and the velocity standard deviation is dependent on the sampling period, the bin size, the number of pings fit into the sampling period, and the ambiguity velocity.

The evaluation data set for WM12 contains 61 measurements made at 16 different sites using different field crews and instruments (Table 5). These measurements represent mean depths, mean velocities, and channel widths ranging from 0.5 to 5.3 m, 0.1 to 1.5 m/s, and 15.4 to 184 m, respectively. Measured streamflow ranged from 1.84 to 198 m^3/s and were computed as the average of between 4 and 33 transects across the stream. The reference measurements consist of 23 current-meter measurements and 38 discharges determined from rating curves. The mean and median percent difference between the ADCP and reference discharges were different, −0.14 and 0.50%, respectively; but both were less than 1%. The difference between the ADCP discharge and the reference discharge ranged from −15.9 to 8.7%, and the standard deviation was 5.8%. Graphical analysis of, and a

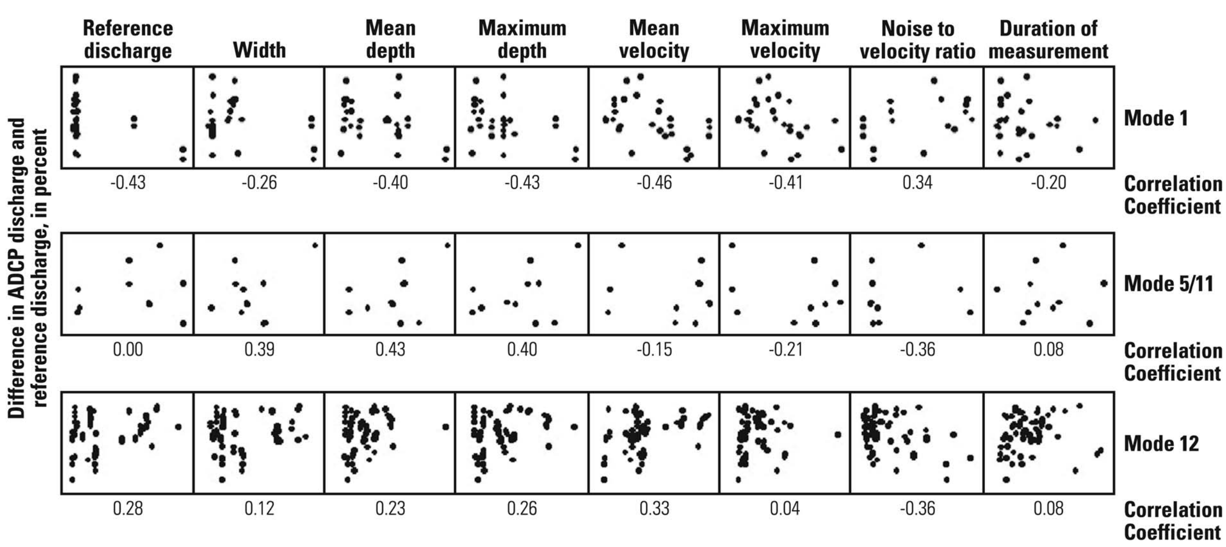

Fig. 3. Scatter plots and correlation coefficients for selected variables compared with the percent difference between ADCP and reference discharges for water modes 1, 5/11, and 12

Table 4. Summary of ADCP Validation Measurements Made with Water Modes 5 and 11

Site ID	No. of transects	Instrument configuration Frq. (kHz)	WM	WS (cm)	ADCP Q (m^3/s)	Ref Q (m^3/s)	Ref type	Diff (%)	ADCP Q COV (%)	Width (m)	Mean depth (m)	Max depth (m)	Mean vel (m/s)	Max vel (m/s)	Dur (min)
Älgån	11	1,200	5	5	2.69	2.74	SD	−1.65	5.87	7.20	0.97	1.29	0.38	1.12	48.77
Frank	12	1,200	11	5	1.93	1.97	AA	−2.20	1.72	35.2	0.64	1.10	0.09	0.46	31.18
Frank	6	1,200	11	5	2.21	2.19	AA	1.00	0.90	37.2	0.64	1.11	0.09	0.42	10.05
Mont	12	600	11	10	44.3	43.5	R	1.87	3.14	56.2	1.63	2.41	0.48	1.35	84.07
Mont	10	600	11	10	41.9	43.5	R	−3.69	2.30	58.0	1.91	2.73	0.38	0.98	27.40
Mont	10	600	5	10	41.8	43.4	R	−3.74	2.30	56.5	1.58	2.35	0.47	1.17	74.40
Algon	12	600	11	10	36.7	34.3	R	7.09	2.42	105	2.42	3.19	0.14	0.41	55.65
Dunns	12	1,200	5	5	23.3	22.1	AA	5.08	2.27	29.5	1.59	2.25	0.50	1.16	36.30
Dunns	12	600	5	10	22.5	22.1	R	1.72	1.69	29.9	1.61	2.19	0.49	1.35	32.60
Shelby	12	1,200	5	5	29.8	30.0	AA	−0.77	2.25	40.4	1.40	1.79	0.53	1.40	52.90
Shelby	12	600	5	10	30.0	30.3	AA	−1.02	1.66	41.2	1.43	1.95	0.53	1.26	37.88

Note: ID=identification; No.=number; Frq=frequency; WM=water mode; WS=bin size; Q=discharge; Ref=reference; SD=salt dilution; R=stage-discharge rating curve; AA=Price AA current meter; Diff=difference; COV=coefficient of variation; Max=maximum; vel=velocity; Dur=duration.

single sample t-test on, the percent differences [Fig. 2(c)] showed that the WM12 data were not biased relative to the reference measurements.

The WM12 data were analyzed for trends among percent differences between the ADCP and reference discharges and selected site and measurement characteristics (Fig. 3). No strong correlations between the percent difference and the selected characteristics were evident. Therefore, discharges measured using an ADCP with WM12 across a range of channel and measurement characteristics compare well with reference discharges determined by current-meter methods with no statistical bias evident in the data presented here.

Measurement Duration Analysis

The uncertainty of a discharge measurement is affected by the duration of the measurement, random instrument noise, and temporal changes in streamflow characteristics caused by turbulence and unsteady flow. Natural streams exhibit temporal changes in discharge at any cross section on multiple time scales ranging from many times per second for turbulence to hours or days for the passage of a flood. Flow in a natural stream is seldom, if ever steady; it frequently has oscillations with time scales of seconds to minutes about a mean value that may change with time scales of hours to days. The goal of many discharge measurements is to measure this mean value. Therefore, the discharge measurement should be of sufficient duration to average the random instrument noise and the shorter temporal fluctuations to obtain a mean discharge. The duration of current-meter discharge measurements in the United States and Canada are grossly determined by the requirements to make one or two velocity measurements at a vertical, that each velocity measurement last at least 40 s, and that no more than 5% of the discharge be computed for any vertical. Therefore, in a typical streamflow measurement, the meter is exposed to the flow field from approximately 15 to 30 min depending on depth of the flow and the resulting measurement lasts 1 h or longer. ADCPs, however, can complete a transect (single pass across the stream) and, thus, a measurement of streamflow in less than 2 min. The USGS currently (2007) requires that at least four transects be averaged for a complete discharge measurement, except in rapidly changing flow (Oberg et al. 2005). Therefore, it is possible to complete a streamflow measurement with an ADCP using standard procedures and yet not sample the flow for more than 8 min total. Although use of four transects is also common practice in countries other than the United States, there is no published research suggesting that four transects is the optimal approach for making streamflow measurements with ADCPs.

The random uncertainty of ADCP streamflow measurements associated with measurement duration is assessed using data sets having at least 12 transects. The primary obstacle in determining the uncertainty of a discharge measurement is that the “true” value of discharge is not known. Thus, the bias portion of uncertainty cannot be easily determined. The comparison of different water modes to traditional measurement techniques (Rantz et al. 1982; ISO 1979) assumes the traditional technique to be the true value despite known uncertainty associated with traditional techniques (Pelletier 1988; Carter and Anderson 1963). ADCP streamflow measurement data used in this analysis showed no statistically significant bias when compared with traditional techniques. The mean discharge from data sets with 12 transects is therefore assumed to be the true discharge for the purpose of assessing the uncertainty associated with the duration of discharge measurements.

Variation in measured discharge can occur because of random error in the instrument, turbulence, and unsteadiness of the flow. Stationarity of the discharges in the data sets was evaluated by linear regression of discharge with time and visually screening plots of discharge and time. Traditionally, regression coefficients with a p value less than 0.05 are considered statistically significant (Helsel and Hirsch 1992, p.106). To ensure that all samples were collected at approximately the same discharge, only data sets that passed the visual screening and had a slope coefficient with a p value greater than 0.4 were used for this analysis.

Uncertainties associated with 1, 2, 4, 6, and 8 transect means were computed as the percent deviation from the mean of 12 transects. Running means were computed using sequential data because multiple transects would be measured sequentially. The deviations from the mean for different numbers of transects are shown in Fig. 4. As expected, the deviation from the mean discharge decreases as the number of transects in the mean increases. Because the mean of all 12 transects and the n-transect means are correlated, the uncertainty values computed earlier were corrected by multiplying the computed uncertainties by the square root of

Table 5. Summary of ADCP Validation Measurements Made with Water Mode 12

Site ID	No. of transects	Instrument configuration Frq. (kHz)	WS (cm)	WV (cm/s)	WO	ADCP Q (m^3/s)	Ref Q (m^3/s)	Ref type	Diff (%)	ADCP Q COV (%)	Width (m)	Mean depth (m)	Max depth (m)	Mean vel (m/s)	Max vel (m/s)	Dur (min)
Algon	13	1,200	10	340	12	37.9	36.2	R	4.7	2.6	39.4	0.83	1.38	1.16	2.34	35.4
Algon	8	600	10	480	12	37.4	35.1	AA	6.6	4.7	59.6	1.08	1.67	0.58	2.56	49.3
Algon	12	1,200	5	175	12	37.7	35.1	AA	7.3	2.5	39.9	0.82	1.38	1.15	2.08	25.6
Algon	12	1,200	2	480	12	36.3	35.1	AA	3.4	4.2	39.6	0.81	1.37	1.13	3.75	55.5
Algon	8	600	5	480	12	37.2	35.1	AA	5.9	5.8	61.5	1.06	1.69	0.57	3.05	61.8
Algon	8	1,200	2	480	6	35.9	35.1	AA	2.2	3.2	39.2	0.81	1.39	1.13	5.46	29.7
Algon	12	600	2	480	12	35.4	34.3	R	3.3	4.8	38.8	0.85	1.35	1.07	4.94	43.1
Algon	12	600	10	175	12	36.7	34.1	R	7.8	4.8	106	2.45	3.20	0.14	0.90	50.2
Alley	12	1,200	10	340	12	2.93	2.97	R	−1.5	6.0	23.1	0.82	1.22	0.16	1.21	72.6
Alley	12	1,200	5	278	12	2.97	2.97	R	0.2	3.4	23.3	0.80	1.22	0.16	1.33	50.8
Burl	8	1,200	10	340	12	139	146	R	−4.8	2.2	36.1	2.83	4.57	1.36	3.04	16.5
Burl	16	1,200	10	170	12	143	137	AA	4.2	2.7	36.8	2.74	4.57	1.42	2.62	55.6
Burl	8	1,200	10	340	12	141	137	AA	2.7	3.2	37.6	2.69	4.46	1.39	2.80	24.1
Burl	8	1,200	10	480	8	138	136	AA	1.7	1.5	36.4	2.73	4.48	1.39	3.05	21.5
Burl	8	1,200	25	170	12	143	136	AA	5.2	2.0	37.2	2.63	4.54	1.46	2.61	15.6
Burl	8	1,200	25	170	8	144	136	AA	5.9	1.5	37.4	2.55	4.35	1.51	2.70	13.2
Cov	8	1,200	10	340	12	112	104	R	7.3	3.8	125	1.84	3.62	0.49	1.31	27.1
Cov	8	1,200	10	340	12	111	104	R	6.7	2.8	125	1.83	3.56	0.49	1.30	29.3
Frank	12	1,200	10	340	12	2.48	2.52	R	−1.4	8.7	34.3	0.70	1.17	0.10	1.07	40.9
Frank	12	1,200	10	340	12	2.54	2.61	R	−2.5	8.7	34.3	0.70	1.17	0.10	1.07	41.6
Frank	12	1,200	10	340	12	1.93	1.97	R	−2.1	8.7	34.3	0.70	1.17	0.10	1.07	33.7
Frank	12	1,200	10	340	12	1.84	2.05	AA	−10.5	17.6	36.6	0.63	1.10	0.08	1.03	32.5
Frank	8	1,200	5	340	12	2.00	2.19	AA	−8.4	9.5	36.1	0.64	1.10	0.09	1.45	14.7
Frank	8	1,200	10	340	12	1.84	2.19	AA	−15.9	18.4	36.6	0.64	1.10	0.08	0.83	14.5
Emin	13	1,200	10	340	12	7.07	6.71	R	5.3	14.1	26.2	0.50	0.92	0.53	1.65	20.2
Emin	12	1,200	5	195	12	7.08	6.85	AA	3.3	6.0	26.0	0.51	0.89	0.53	1.16	30.1
Emin	12	1,200	2	481	12	7.16	6.71	R	6.6	6.4	26.1	0.54	0.89	0.51	2.93	32.7
Emin	12	1,200	2	481	6	7.24	6.68	R	8.4	10.0	25.8	0.54	0.89	0.52	4.22	25.5
Emin	12	1,200	1	481	12	6.75	6.71	R	0.6	6.4	26.1	0.55	0.89	0.47	4.33	36.1
Emin	12	1,200	1	481	6	6.68	6.74	R	−0.8	6.7	26.2	0.56	0.90	0.46	9.67	41.0
Emin	11	1,200	2	688	12	6.26	6.81	R	−8.1	7.0	22.8	0.48	0.97	0.58	4.93	30.5
Fisk	12	1,200	10	340	12	10.5	10.1	R	3.2	3.2	15.4	1.27	2.04	0.54	1.70	45.3
Fisk	12	1,200	10	340	12	10.3	10.1	R	1.9	1.5	15.4	1.28	2.01	0.53	1.48	22.2
Benton	8	1,200	10	340	12	126	125	R	0.5	2.1	136	1.57	2.47	0.59	1.63	34.5
Benton	8	1,200	10	340	12	89.4	91.5	R	−2.2	1.2	134	1.43	2.25	0.47	1.44	42.2
Benton	8	1,200	5	480	12	88.8	91.5	R	−2.9	1.0	134	1.42	2.25	0.46	2.57	42.4
Benton	8	1,200	2	480	12	88.7	91.5	R	−3.1	1.4	138	1.39	2.14	0.46	3.11	50.9
Mont	33	1,200	10	340	12	44.3	41.3	AA	7.1	2.9	58.3	2.01	2.51	0.38	1.33	80.6
Mont	12	1,200	5	175	10	44.5	44.7	R	−0.4	2.1	58.6	2.03	2.52	0.37	1.11	25.8
Mont	12	1,200	2	480	12	42.4	45.1	R	−6.0	2.5	70.3	0.98	1.37	0.61	3.41	121
Mont	4	1,200	10	340	12	41.5	44.7	R	−7.2	2.1	73.0	0.91	1.36	0.62	1.48	8.8
Mont	8	1,200	10	340	12	38.5	43.0	AA	−10.6	2.2	73.1	0.89	1.34	0.59	1.47	21.1
Mont	12	1,200	5	175	12	39.5	43.0	AA	−8.3	2.5	73.5	0.89	1.33	0.60	1.36	43.9
Mont	8	1,200	1	480	12	39.9	43.0	AA	−7.3	11.5	74.3	0.94	1.32	0.57	5.01	117
Mont	10	600	25	340	12	40.6	43.5	R	−6.6	2.0	57.1	1.93	2.43	0.37	0.85	22.8
Mont	18	600	5	480	12	38.0	43.5	R	−12.7	4.4	71.3	0.97	1.41	0.55	4.28	91.8
Mont	4	600	25	340	12	41.4	43.5	R	−4.8	3.1	56.3	1.59	2.37	0.46	1.00	9.6
Sauble	4	1,200	10	340	12	27.2	29.9	AA	−9.1	1.0	36.7	1.69	2.81	0.44	1.20	8.0
Sidney	8	1,200	10	340	12	114	116	R	−1.5	1.0	184	1.44	2.76	0.43	1.43	52.7
Sidney	8	1,200	25	170	12	113	116	R	−2.4	1.7	170	1.48	2.75	0.45	1.01	46.2
TerHte	9	1,200	10	340	12	169	156	R	8.7	1.4	172	1.92	2.68	0.51	1.43	96.9
TerHte	8	1,200	10	340	12	167	155	R	7.9	1.7	171	1.92	2.64	0.51	1.45	67.8
Virg	9	1,200	10	340	12	134	132	R	1.2	2.3	159	1.25	1.99	0.68	1.65	48.0

Table 5. (*Continued.*)

Site ID	No. of transects	Instrument configuration Frq. (kHz)	WS (cm)	WV (cm/s)	WO	ADCP Q (m^3/s)	Ref Q (m^3/s)	Ref type	Diff (%)	ADCP Q COV (%)	Width (m)	Mean depth (m)	Max depth (m)	Mean vel (m/s)	Max vel (m/s)	Dur (min)
Virg	9	1,200	5	480	12	144	140	R	3.5	2.5	160	1.34	2.05	0.67	2.48	48.0
Well	24	1,200	25	170	12	198	194	AA	1.7	1.7	40	5.33	5.82	0.92	2.54	62.2
Willet	8	1,200	10	340	12	20.1	20.5	AA	−2.2	1.2	19.7	1.98	2.87	0.52	1.43	19.5
Willet	8	1,200	25	170	12	20.1	20.5	AA	−2.1	2.9	19.9	1.87	2.87	0.54	0.92	12.5
Willet	8	1,200	5	170	12	20.4	20.5	AA	−0.8	2.6	19.6	1.95	2.86	0.53	1.26	14.4
Wolf	8	1,200	10	340	12	126	125	R	0.5	0.6	131	1.54	2.13	0.62	1.55	36.1
Wolf	8	1,200	25	170	12	125	125	R	−0.3	0.9	130	1.51	2.11	0.64	1.16	33.9
Wolf	9	1,200	5	170	12	129	126	R	2.2	0.5	134	1.53	2.14	0.63	1.59	54.7

Note: ID=identification; No=number; Frq=frequency; WS=bin size; WV=ambiguity velocity; WO=number of subpings; Q=discharge; Ref =reference; R=stage-discharge rating curve; AA=Price AA current meter; Diff=difference; COV=coefficient of variation; Max=maximum; vel =velocity; Dur=duration.

the quantity $[12/(12\text{-}n)]$. The range of uncertainty at 2 SD associated with 1, 2, 4, 6, and 8 transect means are ±12.5, 7.6, 5.4, 4.4, and 4.2%, respectively. Thus, the 4-transect average compares well with the commonly stated accuracy of ±5% for discharge measurements.

Analysis of these data shows that the uncertainty is more dependent on the duration of the measurement, which would be analogous to the sampling time for a current-meter measurement, than on the number of transects collected. The duration for each mean was computed by summing the durations of the transects used in the mean. Uncertainty associated with means comprised of fewer transects with longer total durations is often less than the uncertainty associated with means comprised of more transects with a shorter total duration (Fig. 5). Channel width initially appeared to be correlated with depth and duration (correlation coefficients of 0.85 and 0.74, respectively). This correlation could indicate that duration was simply serving as a surrogate for one of the other variables. Removing Mississippi River data, which is much wider and deeper than other rivers represented in the analysis, reduced the correlation coefficients between width and depth

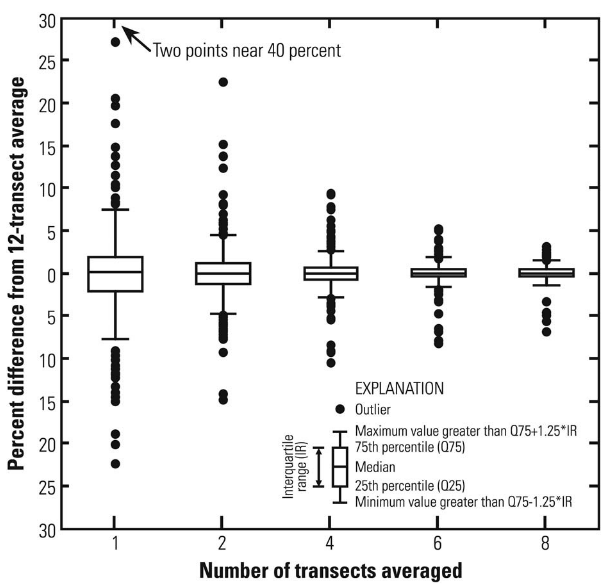

Fig. 4. Boxplot of the deviations from the mean of discharge measurements based on varying numbers of transects

and width and duration to 0.30 and 0.37, respectively. The results displayed in Fig. 5 remained unchanged. Therefore, the uncertainty associated with a discharge measurement is better described by the duration of the measurement than the number of transects included in the measurement.

Additional scatter along the upper and lower fringes of the trend shown in Fig. 5 may be realized if the instrument noise is high relative to the mean velocity of the flow. For instrument noise to velocity ratios greater than one, a measurement of a specified duration would have greater uncertainty. Measurements with these characteristics would not be made during routine operation, except for very low-flow conditions. However, some of the field validation measurements were specifically configured to test the limits of the instrument and resulted in instrument noise to mean velocity ratios exceeding one. These measurements have not been included in Fig. 5.

Traditional current-meter measurements with 40-s sample times and approximately 25 verticals result in measurement durations from 920 to 1,840 s and based on published uncertainty analyses have an uncertainty at 2 SD of about 5.5% (Pelletier 1988; Carter and Anderson 1963). The uncertainty associated with ADCP measurements based on the data and analysis presented here for measurement durations from 500 to 1,000 s, from 1,000 to 1,500 s, and from 1,500 to 2,000 s are ±2.4, 1.8, and 1.2%, respectively. These values are for 2 SD with data having instrument noise ratios to mean velocity less than 1. If all data including those with high instrument noise to mean velocity ratios are included, the uncertainty increases to ±4.4, 3.2, and 3.0% for measurement durations from 500 to 1,000 s, from 1,000 to 1,500 s, and from 1,500 to 2,000 s, respectively.

The results of the above-presented analyses indicate that reductions in uncertainty of ADCP streamflow measurements are more dependent on the duration of the measurement than the number of transects made per ADCP streamflow measurement. On the basis of statistical analysis of the data presented herein (which are not necessarily representative of all flow conditions where ADCPs may be used) an uncertainty of ±5% in the measured discharge should be achieved by ADCP measurements with a duration of at least 720 s, regardless of the number of transects made. A minimum of two transects should be made (with measurement duration for all transects >720 s) in order to minimize the possibility of directional bias in ADCP measured streamflow. The writers plan to explore this issue in more detail with addi-

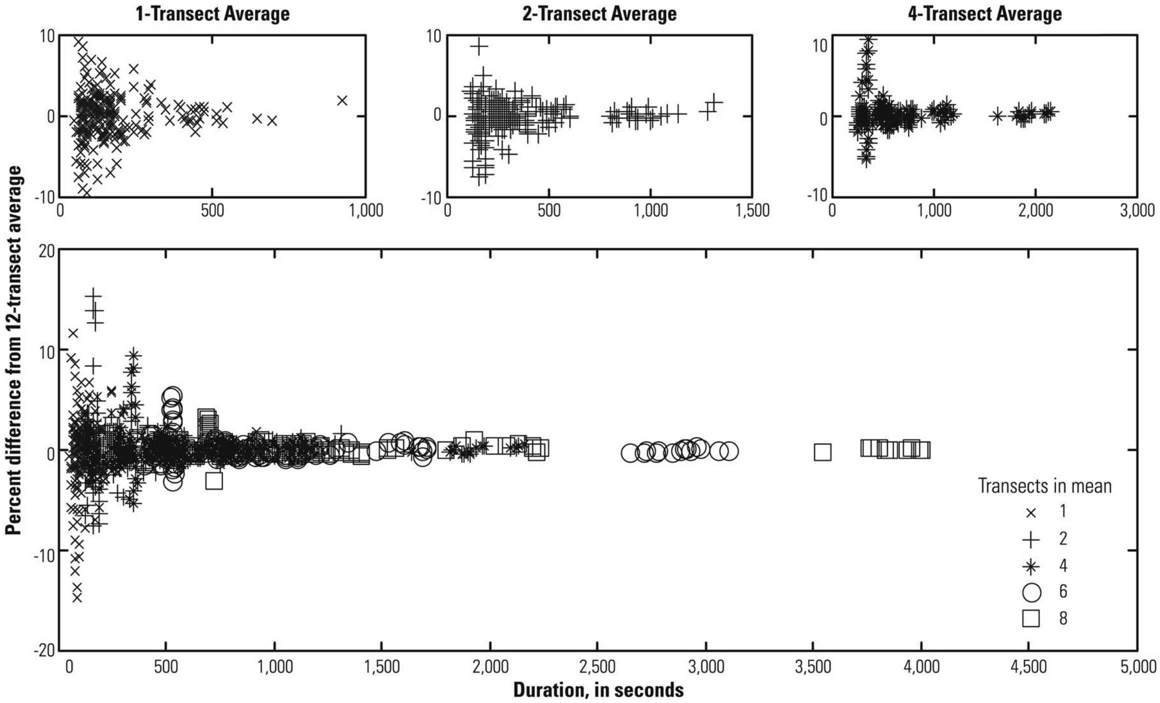

Fig. 5. Relation between measured discharge uncertainty and duration of measurement

tional field validation measurements for a variety of ADCPs with a view to developing protocols for future measurements.

Conclusions

Laboratory validations made in a large towing basin show that for ADCPs used for streamflow measurements the mean differences between tow-cart velocity and ADCP BT and WT velocities were −0.51 and −1.10%, respectively. Laboratory validations are subject to limitations caused by inadequate and changing backscatter conditions, acoustically bright surfaces that can result in contamination of velocity measurements, and compass and pitch-roll sensors that must be fixed to constant values.

Field validations of commercially available ADCPs were also conducted by comparing streamflow measurements made with ADCPs to reference streamflow measurements obtained from concurrent mechanical current-meter measurements, stable rating curves, salt-dilution measurements, or AVMs. Data were collected at 22 sites in the United States, Canada, Sweden, and The Netherlands, with drainage areas ranging from 772 to 1,840,000 km^2, stream widths ranging from 7.2 to 499 m, and mean depths from 0.48 to 9.00 m. One-hundred field validation measurements analyzed for ADCPs manufactured by TRDI show that ADCP streamflow measurements are unbiased when compared to the reference discharges regardless of the mode used for making the measurement.

Measurement duration is more important than the number of transects for reducing the uncertainty of the ADCP streamflow measurement. The present work suggests that ADCP streamflow measurements consisting of at least 2 transects and having a duration for all transects of 720 s or greater, will result in acceptable levels of uncertainty. The use of ADCPs for measuring streamflow produced reliable measurements over a wide range of conditions and compare well to existing methods for streamflow measurement.

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