Field Assessment of Acoustic-Doppler Based Discharge Measurements

David S. Mueller[1], M.ASCE

Abstract

The use of equipment based on the Doppler principle for measuring water velocity and computing discharge is common within the U.S. Geological Survey (USGS). The instruments and software have changed appreciably during the last 5 years; therefore, the USGS has begun a field validation of the instruments currently (2002) available for making discharge measurements from a moving boat in streams of various sizes. Instruments manufactured by SonTek/YSI[2] and RD Instruments, Inc. were used to collect discharge data at five different sites. One or more traditional discharge measurements were made by the use of a Price AA current meter and standard USGS procedures with the acoustic instruments at each site during data collection. The discharges measured with the acoustic instruments were compared with the discharges measured with Price AA meters and the current USGS stage-discharge rating for each site. The mean discharges measured by each acoustic instrument were within 5 percent of the Price AA-based measurement and (or) discharge from the stage-discharge rating. Additional analysis of the data collected indicates that the coefficient of variation of the discharge measurements consistently was less for the RD Instruments, Inc. Rio Grandes than it was for the SonTek/YSI RiverSurveyors. The bottom-tracking referenced measurement had a lower coefficient of variation than the differentially corrected global positioning system referenced measurements. It was observed that the higher frequency RiverSurveyors measured a moving bed more often than the lower frequency Rio Grandes. The detection of a moving bed caused RiverSurveyors to be consistently biased low when referenced to bottom tracking. Differentially corrected global positioning system data may be used to remove the bias observed in the bottom-tracking referenced measurements.

Introduction

The U.S. Geological Survey (USGS) has used acoustic Doppler instruments since the early 1990's to measure discharge in our nation's inland waterways (Oberg and Mueller, 1994). Initially, the instrument most commonly used was a broadband acoustic Doppler

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[1]U.S. Geological Survey, 9818 Bluegrass Parkway, Louisville, KY 40299 (dmueller@usgs.gov).

[2] The use of trade, product, or firm names in this paper is for descriptive purposes only and does not imply endorsement by the U.S. Government.

profiler manufactured by RD Instruments, Inc. (RDI).[2] Morlock (1996) evaluated 1,200- and 600-kilohertz (kHz) versions of this instrument at 12 geographically diverse sites and found the results compared favorably with discharge measurements made by the use of mechanical current meters and standard USGS techniques. Since Morlock (1996), RDI has revised the recommended water mode and configuration settings for operation, introduced new water and bottom modes, and introduced a new instrument—the Rio Grande. In addition, SonTek/YSI introduced the RiverSurveyor line of instruments and software for making discharge measurements using narrowband technology. The use of equipment based on the Doppler principle for measuring water velocity and computing discharge has become common in the USGS; therefore, it was necessary for the USGS to begin a testing program to evaluate new and modified equipment and to ensure consistency of results with standard USGS techniques. The purpose of this paper is to provide a summary of the most recent evaluations of selected acoustic Doppler instruments that can be used from a moving boat to make discharge measurements in streams and rivers.

Instruments Tested

Instruments manufactured by SonTek/YSI and RDI were used to collect discharge data at five different sites. Instruments manufactured by SonTek/YSI used in this assessment were a 1.5 megahertz (MHz) RiverSurveyor acoustic Doppler profiler (ADP) and a 3 MHz RiverSurveyor mini-ADP. Instruments manufactured by RDI used in this assessment were 1,200 and 600 kHz WorkHorse Rio Grande acoustic Doppler current profilers (ADCP). The instruments were configured according to manufacturer recommendations (table 1).

Table 1. Configuration parameters
[kHz, kilohertz; cm, centimeters; N/A, not applicable]

Parameter	**Rio Grande**				**RiverSurveyor**	
Frequency (kHz)	1,200		600		1,500	3,000
Water Mode	1	5	1	5	N/A	N/A
Bin Size (cm)	25	5	50	10	50	25
Blank (cm)	25		25		40	20
Bottom Mode	5		5		N/A	N/A
Averaging	1 ping per profile		1 ping per profile		5-second profiles	5-second profiles

Site Descriptions

Evaluation sites were chosen to provide conditions that would allow testing instrument operation in both small and large streams and the use of bottom-tracking and differentially corrected global positioning system (DGPS) data for navigation corrections. Five sites with a wide range of characteristics were selected for this evaluation (table 2). All water modes and frequency of instruments that were appropriate for the site conditions were evaluated at each site (table 3).

Table 2. Location and characteristics of test sites
[R., river; m, meter; s, second]

Station number	River name	Nearest town	Average		
			Depth (m)	**Width** (m)	**Velocity** (m/s)
05543500	Illinois R.	Marseilles, Ill.	1.6	128.9	1.0
05517500	Kankakee R.	Dunns Bridge, Ind.	1.1	32.9	0.6
05518000	Kankakee R.	Shelby, Ind.	1.2	57.6	0.4
07020500	Mississippi R.	Chester, Ill.	8.0	527.3	1.3
06934500	Missouri R.	Hermann, Mo.	3.8	410.0	1.0

Table 3. Summary of instruments and water modes used at each site
[kHz, kilohertz; MHz, megahertz; R., river]

Station number	River name	Nearest town	Rio Grande				RiverSurveyor	
			1,200 kHz		600 kHz			
			Water Mode					
			1	5	1	5	1.5 MHz	3 MHz
05543500	Illinois R.	Marseilles, Ill.	X					X
05517500	Kankakee R.	Dunns Bridge, Ind.	X	X		X		X
05518000	Kankakee R.	Shelby, Ind.	X	X		X		X
07020500	Mississippi R.	Chester, Ill.	X		X		X	
06934500	Missouri R.	Hermann, Mo.	X		X		X	

Data-Collection and Processing Methods

A detailed procedure for collecting data was documented and followed at each site. This procedure included making an independent water-temperature measurement, calibrating the compass of each instrument according to manufacturer recommendations, carefully measuring the instrument draft, and recording the results of instrument self-test programs, if available. The boat was setup to allow two instruments to be tested simultaneously (fig. 1). The two-paired instruments were chosen to be far enough apart in frequency for interference to be eliminated (Rio Grande 1,200 or 600 kHz with a RiverSurveyor 3 MHz; a Rio Grande 600 kHz with a RiverSurveyor 1.5 MHz or Rio Grande 1,200 kHz). The vendors were contacted about this procedure and additional data also were collected to verify that no interference occurred. A single

Figure 1. USGS employees collecting data on the Kankakee River near Shelby, Indiana.

DGPS receiver was used at each site, and the output split so that both instruments tested received the same DPGS input. Buoys were set at a distance measured from the shore that permitted at least two depth cells to be recorded on the instruments tested. Approximately 10 seconds of data were collected from a nearly stationary position at both edges of the stream during each transect. The stream was traversed at a speed at or below the downstream speed of the water. Typically, at least 12 transects were collected with each instrument. The instrument location (front or back mount) was then reversed to ensure that the mounting location did not introduce a bias into the data. An additional 12 transects were collected with the instruments in their new positions. This procedure was repeated until data were collected with all of the instruments and water modes appropriate for the site. The Price AA current meter was used to make one or more discharge measurements (Rantz and others, 1982) simultaneously with the acoustic instruments at each site.

All data were replayed in the office, and the quality of the data was reviewed. Data from Rio Grandes were collected and processed by use of RDI WinRiver 10.03 software; data from the RiverSurveyors were collected and processed by use of RiverSurveyor 2.5 software. The extrapolation techniques for the top and bottom discharges were reviewed by use of WinRiver. A 1/6th-power law extrapolation was used for the top and bottom discharge extrapolations for all data collected with both RDI and SonTek/YSI instruments. 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. Because DGPS data were collected, a discharge referenced to bottom tracking and a discharge referenced to DGPS were computed for each transect.

The author detected two problems with the RiverSurveyor 2.5 software after completion of data processing and just prior to submission of this paper. RiverSurveyor 2.5 did not compute discharges referenced to DGPS properly. This has been changed in RiverSurveyor 3.33 (Matthew Hull, SonTek/YSI, personal commun., 2002), but the author has not verified the changes to date (July 2002). Therefore, no discharges referenced to DGPS are reported for the RiverSurveyor in this paper. The second problem is of wider scope. RiverSurveyor 2.5 and 3.33 do not account for the draft of the transducer when computing the edge discharge estimates; therefore, the depth of flow used to compute the edge discharges is too shallow and the discharge is biased low. This negative bias in the discharge is likely small (<1 percent) for most measurements but could be significant on long shallow edges. All data reported in this paper contain the effects of this bias. The manufacturer was notified and intends to make changes in the next version of RiverSurveyor.

Discussion of Results

Except for the Missouri River site, the discharges measured by the acoustic Doppler instruments compared closely with the discharges measured by the use of Price AA cup meters and the existing stage-discharge rating at each site. The Price AA current-meter measurement on the Missouri River at Hermann, Missouri, was 13 to 15 percent higher than the acoustically measured discharge and about 11 percent higher than the stage-discharge rating. During their annual records analysis, USGS Missouri District employees evaluated the measurements for the last water year and acknowledged that the Price AA current-meter measurement made during this evaluation was not consistent with their other measurements. They did not adjust their rating to that measurement; therefore, the comparisons for the Missouri River at Hermann, Mo., should be based on the discharge from the stage-discharge rating.

On average, all the Rio Grandes and water modes measured the discharge within 5 percent of either the cup-meter measurement or the stage-discharge rating (table 4). Because the 1,200-kHz unit detected a moving bed on the Missouri and Mississippi Rivers, only the DGPS referenced discharges are valid for comparison for those sites. Although a single four-transect measurement on the Mississippi River at Chester was 6.6 percent below the rated discharge, the remaining measurements were within 5 percent of the Price AA current-meter measurements or the stage-discharge rating. On average, the 1,200-kHz Rio Grande operating in water mode 1 was within 3 percent of the discharges determined from Price AA current-meter measurements and current stage-discharge rating.

The Rio Grande 1,200-kHz unit running water mode 5 could only be compared against two Price AA cup-meter measurements. The mode 5 measurements displayed a deviation from the Price AA current-meter measurements of 5.1 percent at Dunns Bridge, Indiana, and -0.8 percent at Shelby, Ind. These numbers indicate that the instrument can measure within 5 percent of the Price AA current-meter measurements and the current stage-discharge ratings.

The 600-kHz Rio Grande requires 50-centimeter (cm) bins in water mode 1 for acceptable accuracy for discharge measurements; therefore, it is only applicable in deeper rivers with depths greater than 2 to 3 meter (m). The lower frequency of this instrument allowed it to accurately bottom track in the flow conditions on the Missouri and Mississippi Rivers, which was not accomplished by any of the other instruments. The discharges measured by this instrument compared closely with the Price AA current-meter measurements on the Mississippi River. The comparisons for the Missouri River are not reliable. The consistent negative bias in the comparison with the stage-discharge ratings (table 4) is of some concern and more testing would be helpful to ensure that this is not a long-term consistent bias.

The 600-kHz Rio Grande can be operated with 10-cm bins when using mode 5. This water mode makes the instrument useable in streams less than 8-m deep with low velocities (<1 meter per second (m/s)) and smooth bottoms. The discharges measured by this instrument were within 1 percent of discharges measured with the Price AA current meter on the Kankakee River at Shelby, Ind., and within 5 percent of the discharges from stage-discharge ratings on the Kankakee River at Shelby and Dunns Bridge, Ind.

Table 4. Summary of RD Instruments, Inc.* Rio Grande measurements processed with WinRiver 10.03 software
[m^3/s, cubic meter per second; COV, coefficient of variation; DGPS, differential global positioning system; RDI, RD Instruments, Inc.; WM, water mode, --, no data; MB, moving bed; GPS, problems with global positioning system data]

						Bottom tracking			DGPS		
							Percent deviation from			Percent deviation from	
Instrument	**River**	**Nearest city**	**Price AA discharge (m^3/s)**	**Rated discharge (m^3/s)**	**No. Meas.**	**Discharge COV**	**Meter**	**Rating**	**Discharge COV**	**Meter**	**Rating**
RDI 1,200 WM1	Mississippi	Chester,Ill.	--	5,681	4	MB	--	MB	0.028	--	-6.6
RDI 1,200 WM1	Mississippi	Chester,Ill.	--	3,228	12	MB	--	MB	.014	--	-4.9
RDI 1,200 WM1	Kankakee	Dunn Bridge, Ind.	22.62	22.45	9	0.018	1.2	2.0	GPS	GPS	GPS
RDI 1,200 WM1	Missouri	Hermann, Mo.	--	1,501	8	MB	--	MB	.011	--	-3.3
RDI 1,200 WM1	Missouri	Hermann, Mo.	--	1,529	4	MB	--	MB	.007	--	-2.9
RDI 1,200 WM1	Kankakee	Shelby, Ind.	29.79	28.32	12	.024	-.5	4.7	GPS	GPS	GPS
RDI 1,200 WM1	Illinois	Marseilles, Ill.	211.2	219.2	12	**.061	5.4	1.6	**.072	4.8	1.0
RDI 1,200 WM1	Illinois	Marseilles, Ill.	221.4	220.0	16	**.036	2.1	2.7	**.046	- .3	0.3
Average						**.021**	**2.0**	**2.7**	**.015**	**2.2**	**-2.7**
RDI 1,200 WM5	Kankakee	Dunn Bridge, Ind.	22.14	22.34	12	.023	5.1	4.1	GPS	GPS	GPS
RDI 1,200 WM5	Kankakee	Shelby, Ind.	30.04	28.60	12	.022	-.8	4.2	GPS	GPS	GPS
Average						**.023**	**2.2**	**4.2**			
RDI 600 WM1	Mississippi	Chester,Ill.	5,578	5,720	12	.009	-2.8	-5.2	.045	-3.9	-6.2
RDI 600 WM1	Mississippi	Chester,Ill.	--	5,692	4	.008		-5.9	.043	--	-6.8
RDI 600 WM1	Mississippi	Chester,Ill.	3,115	3,228	12	.007	.7	-2.8	.014	-.9	-4.3
RDI 600 WM1	Mississippi	Chester,Ill.	--	3,228	12	.011	--	-3.6	.020	--	-4.9
RDI 600 WM1	Missouri	Hermann, Mo.	1,586	1,430	4	.003	**-15.3	-6.1	.015	**-15.2	-6.0
RDI 600 WM1	Missouri	Hermann, Mo.	1,586	1,447	8	.007	**-13.0	-4.6	.022	**-12.9	-4.5
RDI 600 WM1	Missouri	Hermann, Mo.	--	1,501	8	.012	--	-3.4	.023	--	-3.3
RDI 600 WM1	Missouri	Hermann, Mo.	--	1,529	4	.006	--	-2.8	.010	--	-2.3
Average						**.008**	**-1.0**	**-4.3**	**.024**	**-2.4**	**-4.8**
RDI 600 WM5	Kankakee	Dunn Bridge, Ind.	--	22.11	12	.017	--	1.8	GPS	--	GPS
RDI 600 WM5	Kankakee	Shelby, Ind.	--	29.73	12	.010	--	5.0	GPS	GPS	GPS
RDI 600 WM5	Kankakee	Shelby, Ind.	30.30	29.17	12	.017	-1.0	2.8	GPS	GPS	GPS
Average						**.015**	**-1.0**	**3.2**			

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**Not included in average due to unsteady flow or erroneous Price AA current meter measurements.

On average, the 3-MHz RiverSurveyor provided measurements of discharge within 5 percent of either the Price AA current-meter measurement or the stage-discharge rating (table 5). The 1.5-MHz RiverSurveyor requires 50-cm bins and is only appropriate for deeper rivers. No good comparisons were obtained for the 1.5-MHz system. The 1.5-MHz system did not detect the streambed at depths greater than about 13.7 m on the Mississippi River, so accurate discharge could not be computed. This problem was reported to the manufacturer and a new firmware that would improve the bottom detection in deep water was to be developed (John Sloat, SonTek/YSI, personal commun., 2001). The 1.5-MHz system detected the bottom on the Missouri River but required DGPS to account for the moving bottom detected by the bottom-tracking algorithms.

The 3-MHz RiverSurveyor was evaluated at three sites. With the exception of one comparison on the Kankakee River at Shelby, Ind., all comparisons were within 5 percent of the discharges from standard USGS stream-gaging techniques; however, the consistent negative bias in the bottom-tracking referenced discharges from all three sites was of some concern. Careful review of the moving bottom tests indicated a moving bottom of 0.026 m/s on the Kankakee River at Shelby, Ind. Although this may seem like a negligible amount, it represents about a 5-percent negative bias in the discharge at that location in the river. A moving bottom of 0.007 m/s was observed on the Kankakee River at Dunns Bridge, Ind., which represents about a 1-percent negative bias in the discharge at that location in the river. Thus, at least some of the negative bias is explained by the fact that a higher frequency instrument is more likely to detect a moving bed than a lower frequency instrument. In addition, the error in the software (discussed previously) contributed to the negative bias.

Variation in discharge measurements can be caused by the instrument or by the stream that is being measured. Variation in discharge from the instruments can be caused by noise in measurements of either the water or boat velocity. The measurement of the Doppler shift is inherently noisy and RDI and SonTek/YSI have taken different approaches to averaging this noise. In any discharge measurement there is variation in the instantaneous flow in the stream. This variation can be caused by turbulence and unsteady flow conditions. To evaluate variation in the discharge measurements, the coefficient of variation was computed for each set of discharge measurements (tables 4 and 5). The flow on the Illinois River was unsteady because of gate changes and lockage at the nearby lock and dam. Stream conditions dominated the coefficient of variation for the data collected on the Illinois River (tables 4 and 5). At the other sites, the flow was reasonably uniform and the variations are more typical of turbulence and instrument noise. The Rio Grandes computed more consistent discharges resulting in coefficients of variation for bottom-tracking referenced measurements that are about one-half of the coefficients of variation from comparable RiverSurveyors measurements. The coefficient of variation for DGPS-referenced measurements was slightly higher than comparable bottom-tracking referenced measurements. This indicates that DGPS-referenced corrections are noisier than bottom-tracking referenced corrections.

Table 5. Summary of SonTek/YSI* RiverSurveyor measurements processed with RiverSurveyor 2.5 software [m^3/s, cubic meter per second; COV, coefficient of variation; DGPS, differential global positioning system; MB, moving bed; BTP, bottom tracking problems; RP, data must be reprocessed with RiverSurveyor 3.33; GPS, problems with global positioning system data; --, no data]

Instrument	River	Nearest city	Price AA discharge (m^3/s)	Rated discharge (m^3/s)	No. Meas.	Bottom tracking			DGPS		
						Discharge COV	Percent deviation from		Discharge COV	Percent deviation from	
							Meter	Rating		Meter	Rating
SonTek 1,500	Mississippi	Chester,Ill.	5,578	5,720	12	MB	MB	MB	BTP	BTP	BTP
SonTek 1,500	Mississippi	Chester,Ill.	3,115	3,228	12	MB	MB	MB	BTP	BTP	BTP
SonTek 1,500	Missouri	Hermann, Mo.	1,586	1,430	4	MB	MB	MB	RP	RP	RP
SonTek 1,500	Missouri	Hermann, Mo.	1,586	1,447	10	MB	MB	MB	RP	RP	RP
Average											
SonTek 3,000	Kankakee	Dunn Bridge, Ind.	22.62	22.46	9	0.048	-2.3	-1.5	GPS	GPS	GPS
SonTek 3,000	Kankakee	Dunn Bridge, Ind.	22.14	22.34	15	.038	-1.6	-2.4	GPS	GPS	GPS
SonTek 3,000	Kankakee	Dunn Bridge, Ind.	--	22.12	12	.045	--	-4.7	GPS	GPS	GPS
SonTek 3,000	Illinois	Marseilles, Ill.	211.2	219.2	12	**.053	-1.2	-4.8	RP	RP	RP
SonTek 3,000	Illinois	Marseilles, Ill.	221.4	220.0	16	**.051	-1.8	-1.2	RP	RP	RP
SonTek 3,000	Kankakee	Shelby, Ind.	--	29.73	12	.032	--	-1.3	GPS	GPS	GPS
SonTek 3,000	Kankakee	Shelby, Ind.	30.30	29.17	12	.052	-4.0	-.3	GPS	GPS	GPS
SonTek 3,000	Kankakee	Shelby, Ind.	30.04	28.60	12	.050	-6.5	-1.8	GPS	GPS	GPS
SonTek 3,000	Kankakee	Shelby, Ind.	29.79	28.32	12	.057	-4.7	.2	GPS	GPS	GPS
Average						**.046**	**-3.2**	**-2.0**			

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** Not included in average due to unsteady flow or erroneous Price AA current meter measurements..

Summary and Conclusions

The U.S. Geological Survey (USGS) has conducted field evaluations of selected acoustic Doppler instruments capable of measuring discharge from a moving boat. The selected instruments were tested at five sites with widely varying conditions. All instruments and water modes that were appropriate for a given test site were used at that site. On average, all instruments evaluated yielded discharges that were within 5 percent of discharges determined from standard USGS stream-gaging techniques. The 3-megahertz (MHz) RiverSurveyor detected moving-bed conditions more frequently than the other lower frequency units. Where a moving bed is detected, the discharge will be biased low unless differentially corrected global positioning system (DGPS) is used as the reference. The coefficient of variation for the various sets of discharge measurements was the lowest for Rio Grandes utilizing bottom tracking as the reference. The DGPS-referenced discharge measurements had higher coefficients of variation than comparable bottom-tracking referenced measurements. The acoustic Doppler instruments evaluated in this paper are capable of measuring discharge within 5 percent of the discharges determined by standard USGS stream-gaging techniques, provided the instruments are configured and used properly.

References

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