Field Evaluation Of Boat-Mounted Acoustic Doppler Instruments Used To Measure Streamflow

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Abstract— The use of instruments 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 field validation of the instruments used to make discharge measurements from a moving boat. Instruments manufactured by SonTek/YSI and RD Instruments, Inc. were used to collect discharge data at five different sites. One or more traditional discharge measurements were made using a Price AA current meter and standard USGS procedures concurrent with the acoustic instruments at each site. Discharges measured with the acoustic instruments were compared with discharges measured with Price AA current meters and the 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.

I. 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 [1]. The USGS previously evaluated 1,200- and 600-kilohertz (kHz) versions of instrument manufactured by RD Instruments (RDI) 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 [2]. Since that evaluation, acoustic Doppler instruments have continued to evolve and new instruments have been introduced; 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. Preliminary results of this work found some problems with the Sontek/YSI[1] RiverSurveyor software [3]. The Sontek/YSI RiverSurveyor software was subsequently modified to correct the identified errors [3] and to adjust the top and bottom cutoff limits for the profiles. Subsequently all Sontek/YSI data have been reprocessed using RiverSurveyor version 3.4. The purpose of this paper is to provide an update to the previous analysis [3].

A. Instruments Tested

Instruments manufactured by SonTek/YSI and RDI were used to collect discharge data at five sites. Instruments manufactured by SonTek/YSI and 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 and 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 I).

TABLE I
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

B. 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 II). All water modes and frequency of instruments that were appropriate for the site conditions were evaluated at each site (Table III).

[1] 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.

TABLE II

LOCATION AND CHARACTERISTICS OF TEST SITES

[R., river; m, meter; s, second]

Station number	River name	Nearest town	Average Depth (m)	Average Width (m)	Average 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 III

SUMMARY OF INSTRUMENTS AND WATER MODES USED AT EACH SITE

[kHz, kilohertz; MHz, megahertz; R., river]

River name	Nearest town	Rio Grande 1,200 kHz Water Mode 1	Rio Grande 1,200 kHz Water Mode 5	Rio Grande 600 kHz Water Mode 1	Rio Grande 600 kHz Water Mode 5	River-Surveyor 1.5 MHz	River-Surveyor 3 MHz
Illinois R.	Marseilles, Ill.	X					X
Kankakee R.	Dunns Bridge, Ind.	X	X		X		X
Kankakee R.	Shelby, Ind.	X	X		X		X
Mississippi R.	Chester, Ill.	X		X		X	
Missouri R.	Hermann, Mo.	X		X		X	

II. DATA –COLLECTION 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

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

available. The boat was setup to allow two instruments to be tested simultaneously (Fig. 1). The frequencies of the two-paired instruments were selected to eliminate interference between the instruments (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 were collected to verify that no interference occurred. A single DGPS receiver was used during each measurement, and the output from the DGPS was 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 the beginning and end of each transect. The stream was traversed at a speed at or below the downstream speed of the water. 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. A Price AA current meter was used to make one or more discharge measurements [4] simultaneously with the acoustic instruments at each site. Each current meter has been checked in the laboratory and with the exception of one meter that read 1-2 percent high all were within USGS specifications.

III. DATA PROCESSING PROCEDURES

All data were analyzed and reviewed in the office using the vendor's software in order to identify any data quality issues or to correct any mistakes in data entry in the field. Data from Rio Grandes were collected and processed by use of RDI WinRiver 10.03 software. Data from the RiverSurveyors were collected and originally processed by use of RiverSurveyor version 2.5, but have been reprocessed using RiverSurveyor version 3.4. Two problems with version 2.5 of the software were identified. RiverSurveyor version 2.5 did not compute discharges referenced to DGPS properly. This was changed in RiverSurveyor versions 3.1 and later (Matthew Hull, SonTek/YSI, personal commun., 2002). The second problem is of wider scope. RiverSurveyor versions prior to version 3.4 did 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 was too shallow and the discharge was biased low. This was fixed in version 3.4, which also includes some changes to the cutoff limits for the measured portion of each profile (Matthew Hull, SonTek/YSI, personal commun., 2002).

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 for both instruments. 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.

IV. 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 Price AA current meters and the existing stage-discharge rating at each site. The Price AA current-meter measurement on the Missouri River at Hermann, Mo., 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 staff 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 not on the concurrent Price AA current-meter measurement.

A. RD Instruments Systems

On average, all the Rio Grandes and water modes measured the discharge within 5 percent of either the Price AA current meter measurement or the stage-discharge rating (Table IV). 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 made with a 1,200 kHz Rio Grande 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

TABLE IV

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; WM, water mode; --, no data; MB, moving bed; GPS, problems with global positioning system data]

Frequency and Water Mode	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
1,200 WM1	Mississippi	Chester,Ill.	--	5,681	4	MB	--	MB	0.028	--	-6.6
1,200 WM1	Mississippi	Chester,Ill.	--	3,228	12	MB	--	MB	.014	--	-4.9
1,200 WM1	Kankakee	Dunn Bridge, Ind.	22.62	22.45	9	0.018	1.2	2.0	GPS	GPS	GPS
1,200 WM1	Missouri	Hermann, Mo.	--	1,501	8	MB	--	MB	.011	--	-3.3
1,200 WM1	Missouri	Hermann, Mo.	--	1,529	4	MB	--	MB	.007	--	-2.9
1,200 WM1	Kankakee	Shelby, Ind.	29.79	28.32	12	.024	-.5	4.7	GPS	GPS	GPS
1,200 WM1	Illinois	Marseilles, Ill.	211.2	219.2	12	**.061	5.4	1.6	**.072	4.8	1.0
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**
1,200 WM5	Kankakee	Dunn Bridge, Ind.	22.14	22.34	12	.023	5.1	4.1	GPS	GPS	GPS
1,200 WM5	Kankakee	Shelby, Ind.	30.04	28.60	12	.022	-.8	4.2	GPS	GPS	GPS
Average						**.023**	**2.2**	**4.2**			
600 WM1	Mississippi	Chester,Ill.	5,578	5,720	12	.009	-2.8	-5.2	.045	-3.9	-6.2
600 WM1	Mississippi	Chester,Ill.	--	5,692	4	.008		-5.9	.043	--	-6.8
600 WM1	Mississippi	Chester,Ill.	3,115	3,228	12	.007	.7	-2.8	.014	-.9	-4.3
600 WM1	Mississippi	Chester,Ill.	--	3,228	12	.011	--	-3.6	.020	--	-4.9
600 WM1	Missouri	Hermann, Mo.	1,586	1,430	4	.003	**-15.3	-6.1	.015	**-15.2	-6.0
600 WM1	Missouri	Hermann, Mo.	1,586	1,447	8	.007	**-13.0	-4.6	.022	**-12.9	-4.5
600 WM1	Missouri	Hermann, Mo.	--	1,501	8	.012	--	-3.4	.023	--	-3.3
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**
600 WM5	Kankakee	Dunn Bridge, Ind.	--	22.11	12	.017	--	1.8	GPS	--	GPS
600 WM5	Kankakee	Shelby, Ind.	--	29.73	12	.010	--	5.0	GPS	GPS	GPS
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 questionable Price AA current-meter measurements.

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 current-meter measurements. The mode 5 measurements displayed a deviation from the Price AA current-meter measurements of 5.1 percent at Dunns Bridge, Ind., 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 meters (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 with the Price AA current meter for the Missouri River are not reliable. The consistent negative bias in the comparison with the rated discharge (Table IV) is of some concern and additional investigation is necessary to determine whether this indicates a problem with measuring using acoustic methods or is a long-term bias in the rating.

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 a smooth bed. 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.

B. Sontek/YSI Systems

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 V). The 1.5-MHz RiverSurveyor requires 50-cm bins and is only appropriate for deeper rivers. No reliable 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 they are investigating an improved bottom detection algorithm (John Sloat, SonTek/YSI, personal commun., 2002). The 1.5-MHz system detected the bottom on the Missouri River but required DGPS to account for the moving bed detected by the bottom-tracking algorithms.

TABLE V

SUMMARY OF SONTEK/YSI* RIVERSURVEYOR MEASUREMENTS PROCESSED WITH RIVERSURVEYOR VERSION 3.4 SOFTWARE

[m3/s, cubic meter per second; COV, coefficient of variation; DGPS, differential global positioning system; MB, moving bed; BTP, bottom tracking problems; GPS, problems with global positioning system data; --, no data]

						Bottom tracking			**DGPS**		
							Percent deviation from			**Percent deviation from**	
Frequency (kHz)	**River**	**Nearest city**	**Price AA discharge (m^3/s)**	**Rated discharge (m^3/s)**	**No. Meas.**	**Discharge COV**	**Meter**	**Rating**	**Discharge COV**	**Meter**	**Rating**
1,500	Mississippi	Chester,Ill.	5,578	5,720	12	MB	MB	MB	BTP	BTP	BTP
1,500	Mississippi	Chester,Ill.	3,115	3,228	12	MB	MB	MB	BTP	BTP	BTP
1,500	Missouri	Hermann, Mo.	1,586	1,430	4	MB	MB	MB	0.005	**-15.9	-6.8
1,500	Missouri	Hermann, Mo.	1,586	1,447	10	MB	MB	MB	0.013	**-13.3	-5.0
Average									**.009**	**--**	**-5.9**
3,000	Kankakee	Dunn Bridge, Ind.	22.62	22.46	9	0.041	-0.8	0.0	GPS	GPS	GPS
3,000	Kankakee	Dunn Bridge, Ind.	22.14	22.34	15	.039	-0.3	-1.2	GPS	GPS	GPS
3,000	Kankakee	Dunn Bridge, Ind.	--	22.12	12	.038	--	-3.5	GPS	GPS	GPS
3,000	Illinois	Marseilles, Ill.	211.2	219.2	12	**.054	0.7	-3.0	0.064	2.7	-1.0
3,000	Illinois	Marseilles, Ill.	221.4	220.0	16	**.052	0.2	0.8	0.066	0.3	1.0
3,000	Kankakee	Shelby, Ind.	--	29.73	12	.037	--	-0.7	GPS	GPS	GPS
3,000	Kankakee	Shelby, Ind.	30.30	29.17	12	.056	-3.2	0.6	GPS	GPS	GPS
3,000	Kankakee	Shelby, Ind.	30.04	28.60	12	.050	-6.1	-1.4	GPS	GPS	GPS
3,000	Kankakee	Shelby, Ind.	29.79	28.32	12	.054	-4.6	0.2	GPS	GPS	GPS
Average						**.045**	**-2.0**	**-0.9**	**0.065**	**1.5**	**0.0**

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

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 [4]. Table V shows that the SonTek/YSI profiler measurements had a consistent negative bias in the bottom-tracking-referenced discharges for the two Kankakee River sites. It appears that this bias can be at least partially explained by a small moving-bed condition. Careful review of the moving-bed tests indicated a moving bed of 0.03 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 bed 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.

C. Coefficient of Variation

Variation in discharge measurements can be caused by the instrument or by the stream that is being measured. 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. The variation in the measured discharges was evaluated using the coefficient of variation (standard deviation divide by the mean) computed for each set of discharge measurements (Tables IV and V). 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 IV and V). At the other sites, the flow was reasonably constant over time 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 more inconsistent than corresponding bottom-tracking-referenced measurements. This indicates that DGPS-referenced corrections depend on the quality of the DGPS-derived positions.

D. Use of DGPS

Either bottom tracking or DGPS can be used as the boat navigation reference to correct the measured water velocities for the movement of the boat. When there is sufficient sediment movement that the bottom tracking algorithms detect the sediment movement the measured water velocities and discharges are biased low. This happens more frequently with higher frequency systems. DGPS is typically used in these situations to make an accurate measurement. However, the site conditions must permit a good and consistent GPS signal to be received during each of the transects. The Kanakakee River sites were not suitable sites for DGPS-based measurements because of the significant tree canopy on the banks and hanging over the river. DGPS-based discharges were extremely variable and unreliable at these two sites. DGPS data quality indicators available in WinRiver 10.03 and soon to be available in RiverSurveyor were successful at identifying the potential problems with DGPS at the Kankakee sites and indicating acceptable quality DGPS at the other sites.

V. 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, which could be limited by site conditions. The coefficient of variation for the various sets of discharge measurements was the lowest for Rio Grandes utilizing bottom tracking as the reference, but the average deviation from the Price AA and USGS discharge ratings were very similar among all of the instruments tested. 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.

VI. REFERENCES

1. Oberg, K.A., and Mueller, D.S., 1994, Recent applications of acoustic Doppler current profilers, *in* Fundamentals and Advancements in Hydraulic Measurements and Experimentation: New York, ASCE, p. 341-350.

2. Morlock, S.E., 1996, Evaluation of acoustic Doppler current profiler measurements of river discharge: U.S. Geological Survey Water-Resources Investigations Report 95-4218, 37 p.

3. Mueller, D.S., 2002, Field assessment of acoustic-Doppler based discharge measurements in Hydraulic Measurements and Experimental Methods 2002, T.L. Wahl, C.A. Pugh, K.A. Oberg, and T.B. Vermeyen, eds., ASCE, Reston, VA.

4. Rantz, S.E., and others, 1982, Measurement and computation of streamflow: U.S. Geological Survey Water-Supply Paper 2175, 2 v., 631 p.