Use of Acoustic Doppler Instruments for Measuring Discharge in Streams with Appreciable Sediment Transport

David S. Mueller[1], M.ASCE

Abstract

Acoustic Doppler instruments measure the velocity of water relative to the instrument (relative water velocity). To obtain the true water velocity in a stream when the instrument is mounted onto a boat, the instrument must accurately measure the speed and direction of the boat and correct the relative water velocity for the boat motion.
Boat speed and direction usually are measured by means of bottom tracking. Bottom tracking uses acoustic pulses to measure the boat velocity relative to the streambed, similar to those used to measure the water velocity. This technique can be accurate and is resistant to errors in the internal compass of the instrument; however, streams often transport fine sediments and sand as suspended load near the streambed or as bed load. During flood flows streams may transport appreciable volumes of larger sediments. The acoustic Doppler instrument measures a “moving bed” when the transported sediment causes a Doppler shift in the bottom-tracking pulses. This moving-bed condition will cause the instrument to measure an upstream boat velocity greater than the true boat velocity. When this boat velocity is used to correct the relative water velocity, it results in water-velocity measurements that are biased low. This moving-bed condition is commonly encountered in the Mississippi and Missouri Rivers when using acoustic instruments with frequencies greater than 600 kilohertz and can occur in most streams during higher flows. The best method of compensating for boat velocity on streams where a moving-bed condition occurs is to use a differentially corrected global positioning system (DGPS). When using DGPS to measure the boat velocity any errors in the acoustic instrument’s internal compass become important sources of error in the resulting velocity and discharge measurements. Data collected by use of instruments and software manufactured by RD Instruments, Inc.[2] indicate that with proper calibration and data-collection techniques, accurate discharges can be measured with DGPS as the boat-velocity reference. Conversely, these data indicate that appreciable errors will result if the compass is not properly calibrated and (or) proper data-collection techniques are not followed. Although proper data-collection technique is always important, measurements

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

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made using DGPS as the boat-velocity reference are particularly sensitive to errors introduced by improper data-collection techniques.

Introduction

Acoustic Doppler current profilers (ADCP's) deployed from moving boats are an efficient method for measuring discharge and mapping velocity patterns in rivers. The velocity measured by use of the ADCP is the relative velocity between the water and the instrument (relative water velocity). Because the instrument is mounted on a moving boat, the velocity of the boat must be measured and used to compute the true water speed. ADCP's can measure the boat speed with a technique called bottom tracking; bottom tracking computes the Doppler shift of acoustic pulses reflected from the streambed. Assuming the streambed is not moving, the velocity measured by bottom tracking is the velocity of the boat; however, sediment transport on or near the streambed can affect the Doppler shift of the bottom-tracking pulses. If bottom tracking is affected by sediment transport, the bottom-tracking velocity (boat velocity) will be biased in the opposite direction of the sediment movement. A stationary boat in the stream would appear to be moving upstream (fig. 1). This bias in the boat velocity will result in measured water velocities and discharges that are biased low (less than the true discharge). It is required that every ADCP measurement made by the U.S. Geological Survey includes documentation of whether or not a moving bed was present. Differentially corrected global positioning systems (DGPS) can be used to measure the velocity of a boat and correct the velocity measured by the ADCP to compute water velocities and discharge. Use of DGPS can cause complexities and potential errors in the water-velocity and discharge measurements.

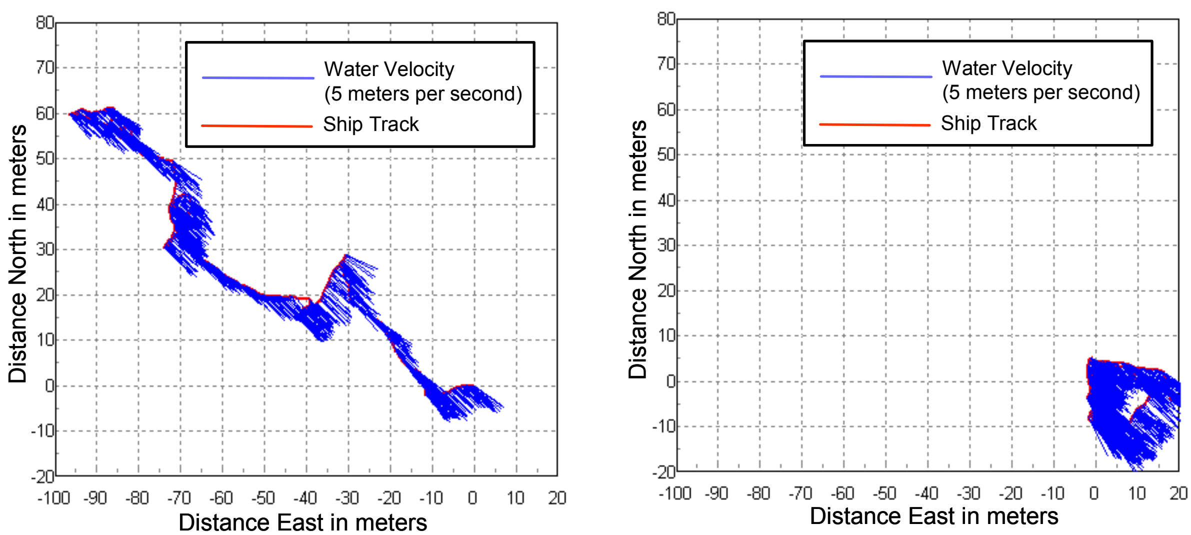

Figure 1. Example of a moving bottom measured with a 1,200-kilohertz acoustic Doppler current profiler on the Mississippi River at Chester, Illinois.

Considerations When Using DGPS with ADCP's

The computation of water velocity from an ADCP mounted onto a moving boat is a vector-algebra problem. The ADCP measures the water velocity relative to the moving boat (relative water velocity), so the velocity of the boat must be accounted for to obtain the true water velocity (WV) (fig. 2). The true water velocity is computed by subtracting the bottom-tracking velocity (BT) vector from the water-tracking velocity (WT) vector. When bottom tracking is used, the direction of the boat velocity vector (θ_{BT}) and water-tracking velocity vector (θ_{WT}) are referenced to the instrument. The ADCP has an internal fluxgate compass to measure the orientation of the instrument (θ_{Inst}) relative to the local ambient magnetic field (magnetic north). The water-tracking ping and the bottom-tracking ping occur separately but both occur within a fraction of a second; a single reading of the compass is used to determine the orientation of the instrument for both pings. The water-velocity vector can be easily referenced to magnetic north by rotating the vector based on the measured θ_{Inst}. The magnitude of the water velocity is unaffected by any errors in the measurement of θ_{Inst}.

The basic equation presented in Simpson and Oltmann (1993) for computing measured discharge (exclusive of unmeasured areas) by use of an ADCP mounted onto a moving boat is

$$Q = \int_0^T \int_0^D \left|\vec{V}_f\right|\left|\vec{V}_b\right| \mathrm{Sin}\theta \, dz \, dt ,$$

where

- Q is the total discharge;
- T is the total time for which data were collected;
- D is the total depth;
- $\vec{V}_f$ is the mean water-velocity vector;
- $\vec{V}_b$ is the mean boat-velocity vector;
- θ is the angle between the water-velocity vector and a vector normal to the boat-velocity vector (fig. 3);
- dz is the vertical differential depth; and
- dt is differential time.

To compute the discharge, only the angle between the water-velocity and the boat-velocity vectors is needed. When bottom tracking is used, the direction of the relative water-velocity (WT) vector and the boat-velocity (BT) vector are referenced to the instrument (fig. 3a). When DGPS is used to determine the boat-velocity vector, this vector is

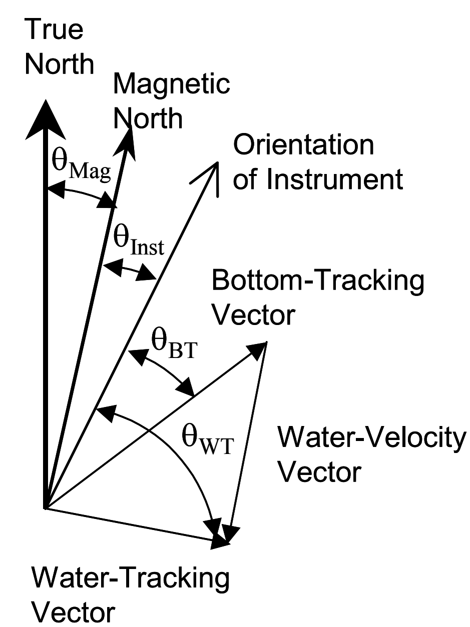

Figure 2. Vectors for computing the water-velocity vector.

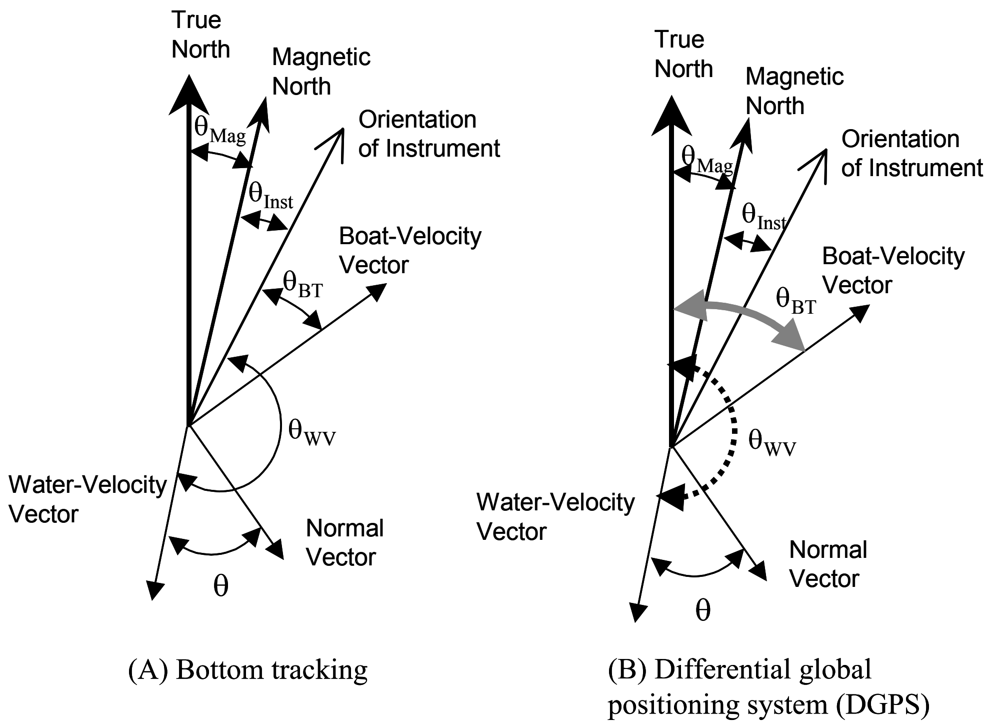

Figure 3. Vectors illustrating the difference between bottom-tracking and differential global positioning system (DGPS)-referenced boat-velocity vectors.

referenced to true north by use of the DGPS coordinates (fig. 3b). The orientation of the instrument relative to true north must be determined to put the boat-velocity vector and the relative water-velocity vector in the same coordinate system and allow the computation of the water-velocity vector (WV) and θ . The discharge is affected by errors in measuring θ_{Inst} and in the determination of the magnetic variation (θ_{Mag}) when DGPS is used as the boat reference. The errors associated with measuring θ_{Inst} can cause errors in the measured discharge that are proportional to the speed of the boat. Proper setup and calibration of the ADCP's internal compass, determination of the local magnetic variation, and a slow boat speed are critical to discharge measurements made using DGPS as the boat-velocity reference.

Errors associated with fluxgate-compass measurements can result from horizontal accelerations of the instrument and (or) environmental conditions near the instrument. Most fluxgate compasses are gimbal-mounted, which allows them to measure the Earth's horizontal magnetic field. When the instrument is subject to horizontal accelerations, such as when a boat accelerates or turns, the force generated by the acceleration causes the compass to swing out of the vertical position and measure something other than the horizontal magnetic field. Most of the significant errors associated with horizontal accelerations can be eliminated by slow, smooth boat operation.

Errors associated with fluxgate-compass measurements caused by environmental conditions can be classified as one- and two-cycle errors. One-cycle errors are caused by permanent magnets and current-carrying conductors; two-cycle errors are caused by iron and magnetically permeable material. ADCP's manufactured by RD Instruments, Inc.[3] and SonTek/YSI for making discharge measurements from a moving boat have firmware routines to allow the calibration of the compasses in place to compensate for environmental conditions.

The local magnetic variation (or declination) can be either estimated or measured, depending upon site conditions. Estimates of the local magnetic variation can be obtained from USGS 7.5-minute quadrangles, magnetic field charts, and geomagnetic field models. Although these estimated values are often accurate, some areas have appreciable magnetic anomalies that are not accurately predicted by models or general charts. RD Instruments, Inc. (2001) documents a procedure for measuring the magnetic variation on site by use of an ADCP and a DGPS. This same procedure can be used with RiverSurveyor instruments and RiverSurveyor software from SonTek/YSI. The limitation of this procedure is that there can be no moving-bottom conditions because both the bottom tracking and DGPS are used in the computations.

The DGPS receivers typically used for ADCP discharge measurements made from a moving boat are accurate within less than a meter. Although the differential correction accounts for errors induced by the troposphere and selective availability, the user must be aware of and take action to minimize uncorrectable errors, which can be caused by the user, the satellite configuration, or the characteristics of the site. It is important to locate the DGPS antenna as near to the center of the ADCP as possible so that the direction of travel are the same for both the antenna and the ADCP during all boat maneuvers. The antenna should be located above the boat cabin or other accessories on the boat to eliminate multi-path errors. Occasionally, the configuration of the satellites does not allow an accurate determination of the horizontal position. This can be monitored using the horizontal dilution of precision (HDOP). If the HDOP parameter is greater than 2 or the HDOP changes by more than 1 during a transect, the quality of the DGPS positions is suspect. Local site characteristics such as canyon walls, bluffs, tall buildings, and tree cover can result in poor DGPS positions because of multi-path errors and loss of satellite visibility. Poor satellite visibility often results in numerous changes in the number and configuration of satellites used to determine a position. Numerous changes in satellites are another indication that the quality of the DGPS positions may be poor. In addition to horizontal-position coordinates, the DGPS also computes elevation. This elevation is 2 to 4 times less accurate than the horizontal position. The elevation of the boat should be reasonably constant. Changes greater than 3.5 meters (m) in the DGPS-determined elevation indicate that the quality of the DGPS positions may be poor (RD Instruments, Inc., WinRiver 10.03 Help File, written commun., 2002).

Comparison of DGPS and Bottom-Tracking Referenced Boat Velocities

Boat velocities should be similar for bottom tracking and DGPS at sites where no moving bottom is detected. Two sites with good DGPS data are used to illustrate that DGPS-referenced boat velocities compare favorably with bottom-tracking-referenced boat

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velocities. Data collected on the Missouri River at Hermann, Mo., and on the Ohio River near Louisville, Ky., provide typical examples of the consistency between DGPS and bottom tracking that can be expected from properly calibrated instruments and good quality DGPS data (figs. 4 and 5). The data collected on the Missouri River at Hermann, Mo., (fig. 4) have only one satellite change, the change in altitude is less than 0.8 m, and the HDOP was less than 1.5—all indications of good quality DGPS data. The only obvious difference between DGPS and bottom-tracking referenced boat velocities occurs at the beginning of the measurement and is concurrent with changes in the DGPS-measured altitude. The data collected on the Ohio River near Louisville, Ky., (fig. 5) have only one satellite change, the change in altitude is less than 2.5 m, and the HDOP was less than 1.2. The percent difference in boat speed measured by bottom tracking and DGPS for both examples was less than 1.5 percent.

The Kankakee River at Dunns Bridge, Ind., is about 30-m wide with tree cover extending out over the river from both banks. The DGPS data-quality indicators (fig. 6) show the DGPS data could be suspect. There are numerous satellite changes, which are reflected in the HDOP. Because of the poor quality DGPS data, the DGPS-referenced velocities do not compare favorably with the bottom-tracking-referenced velocities. There is a difference of about 20 percent between the DGPS and bottom-tracking-referenced boat velocities for this measurement.

Comparison of DGPS and Bottom-Tracking Referenced Discharges

Discharges measured by the use of an ADCP should be similar for bottom tracking and DGPS at sites where no moving bottom is detected. Three sites from Mueller (in press) were selected for comparison (table 1). The instruments were calibrated according to the manufacturer's recommended procedures, and the quality of the DGPS data were within the criteria presented in this paper. The discharges measured by use of DGPS were within 1.5 percent of the discharges measured using bottom tracking (table 1). On average, the discharges measured by use of DGPS were within 5 percent of the discharges measured by use of Price AA current meters and determined from USGS stage-discharge ratings.

A higher frequency ADCP is more likely to detect a moving bottom than a lower frequency instrument. The 1,200-kilohertz (kHz) ADCP detected a moving bottom on the Mississippi River at Chester, Ill. and on the Missouri River at Hermann, Mo., but the 600-kHz ADCP did not detect a moving bottom at either site (table 1). Oberg and Mueller (1994) reported that measurements made with a 1,200-kHz ADCP during the 1993 flood on the Mississippi River near St. Louis, Mo., indicated a moving bed of 0.6 meters per second (m/s) but a 300-kHz ADCP used at the same location did not indicate a moving bed. Therefore, the higher the acoustic frequency of the ADCP the more likely a moving bed will be detected, and measured discharges will be less than the true discharge unless DGPS data are used for the boat-velocity reference.

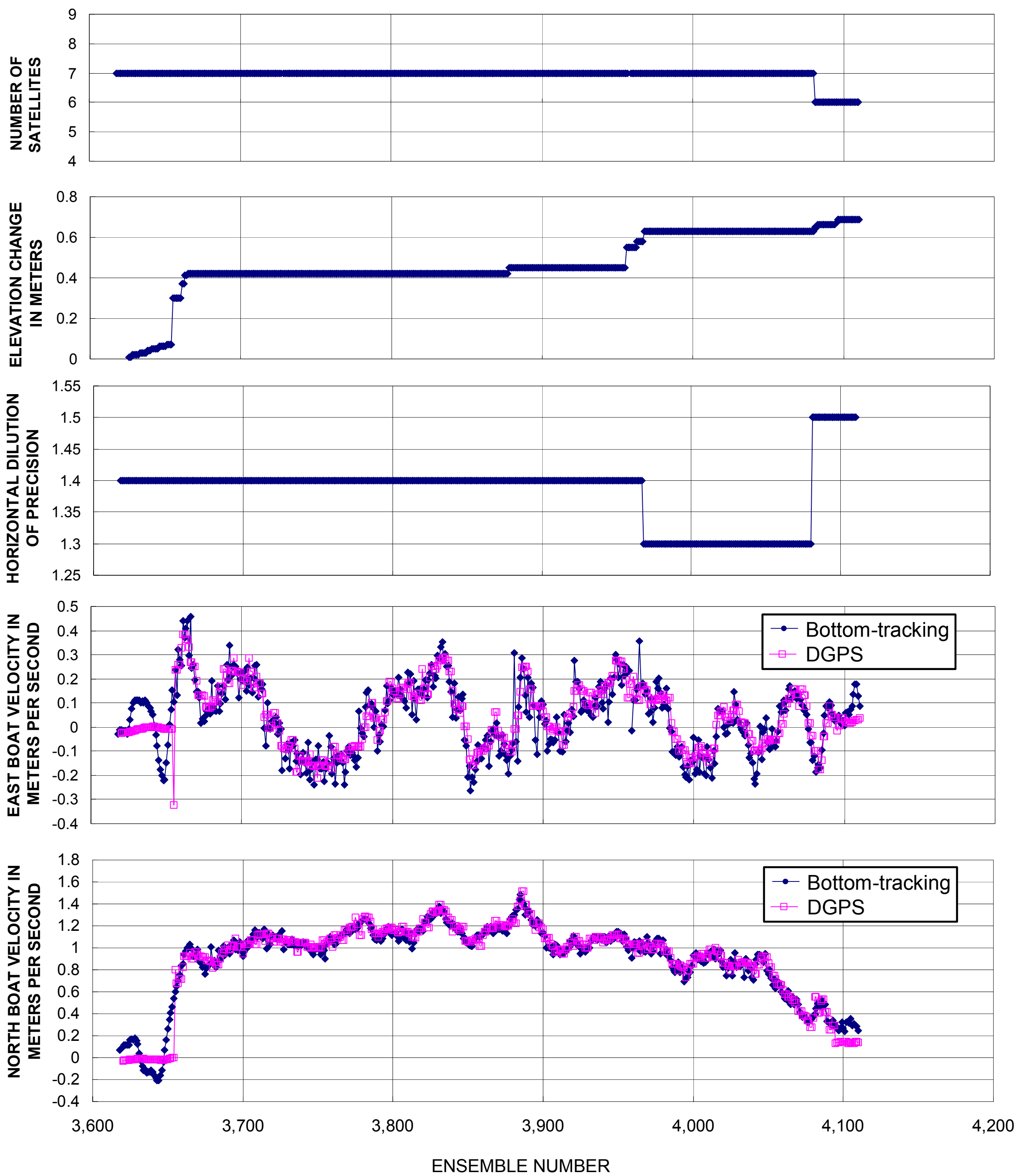

Figure 4. Comparison of differential global positioning system- and bottom-tracking-referenced boat velocities with differential global position system data-quality indicators for data collected on the Missouri River at Hermann, Missouri.

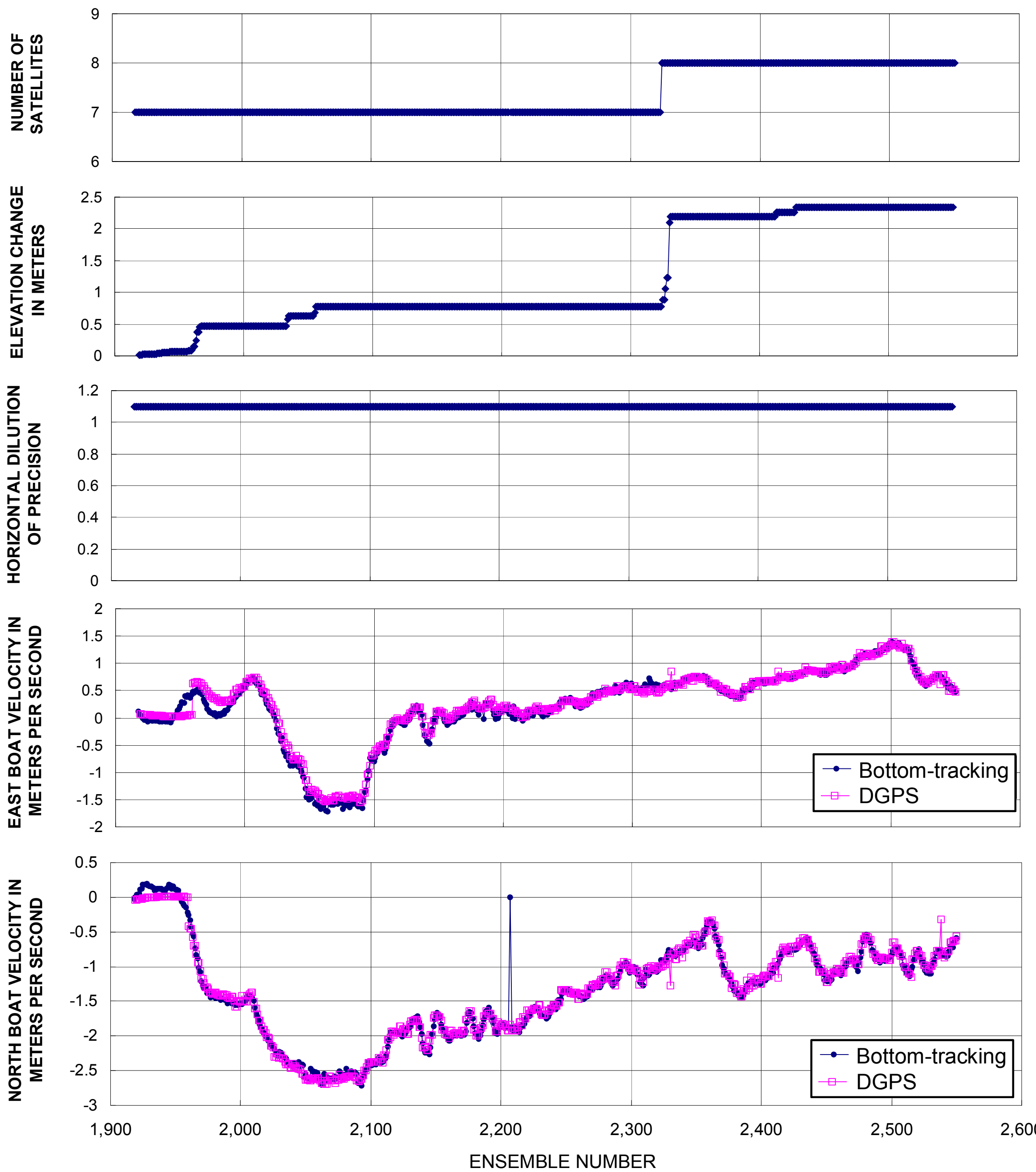

Figure 5. Comparison of differential global positioning system- and bottom-tracking-referenced boat velocities with differential global position system data-quality indicators for data collected on the Ohio River near Louisville, Kentucky.

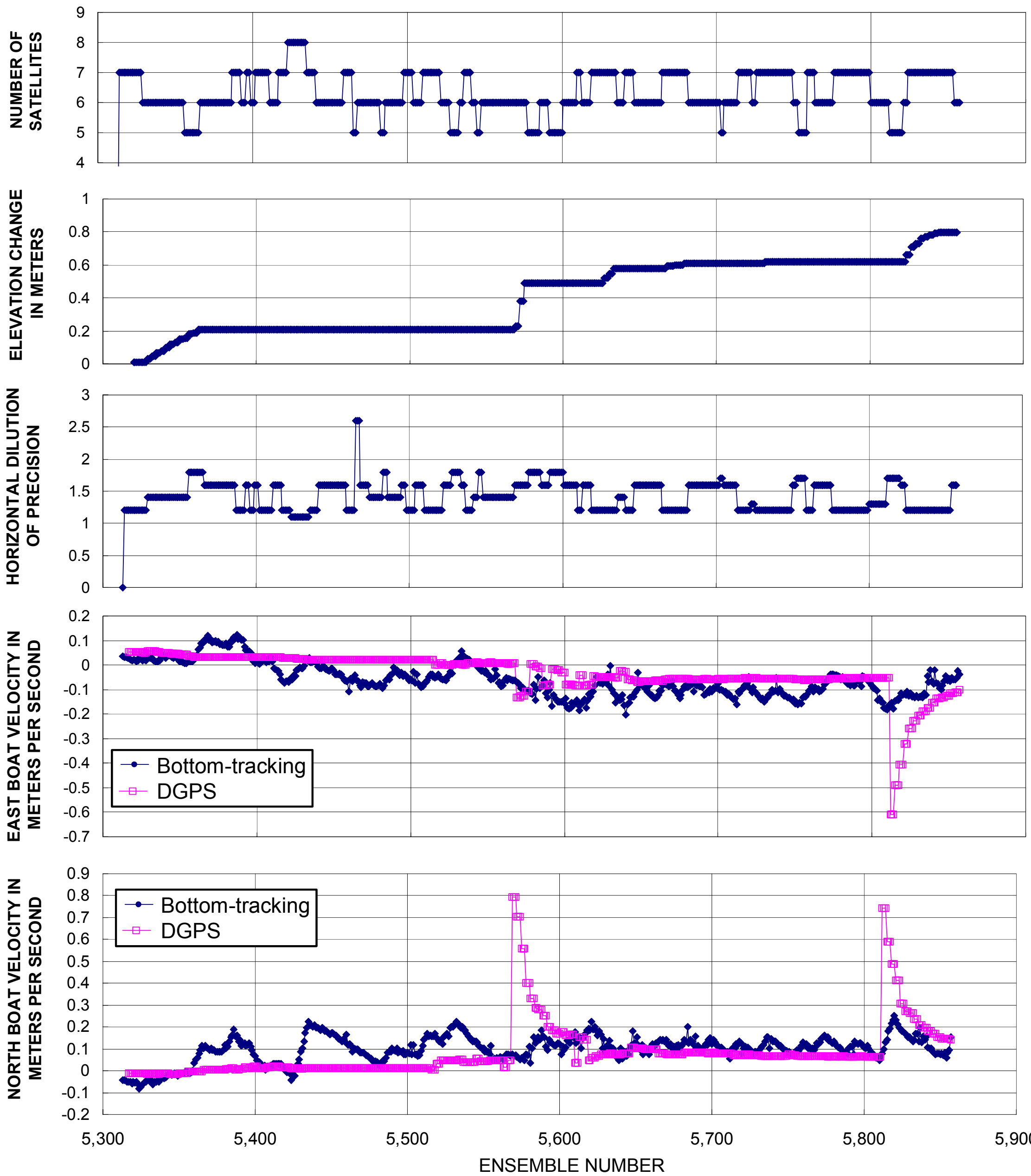

Figure 6. Comparison of differential global positioning system- and bottom-tracking-referenced boat velocities with differential global position system data-quality indicators for data collected on the Kankakee River at Dunns Bridge, Indiana.

Table 1. 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, GPS, global positioning system; BT, bottom tracking; RDI, RD Instruments, Inc.; WM, water mode; --, no data; MB, moving bed]

Instrument	River	Nearest city	Price AA measured discharge (m^3/s)	Rated discharge (m^3/s)	No. Meas.	Bottom tracking: Discharge COV	Bottom tracking: Percent deviation from Meter	Bottom tracking: Percent deviation from Rating	Differential GPS: Discharge COV	Differential GPS: Percent deviation from Meter	Differential GPS: Percent deviation from Rating	Differential GPS: Percent deviation from BT
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	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	Illinois	Marseilles, Ill.	211.2	219.2	12	**0.061	5.4	1.6	**.072	4.8	1.0	-0.6
RDI 1,200 WM1	Illinois	Marseilles, Ill.	221.4	220.0	16	**.036	2.1	2.7	**.046	-.3	.3	-2.4
Average						**--**	**3.8**	**2.2**	**.015**	**2.2**	**-2.7**	**-1.5**
RDI 600 WM1	Mississippi	Chester,Ill.	5,578	5,720	12	.009	-2.8	-5.2	.045	-3.9	-6.2	-1.0
RDI 600 WM1	Mississippi	Chester,Ill.	--	5,692	4	.008		-5.9	.043	--	-6.8	-.9
RDI 600 WM1	Mississippi	Chester,Ill.	3,115	3,228	12	.007	.7	-2.8	.014	-.9	-4.3	-1.5
RDI 600 WM1	Mississippi	Chester,Ill.	--	3,228	12	.011	--	-3.6	.020	--	-4.9	-1.3
RDI 600 WM1	Missouri	Hermann, Mo.	1,586	1,430	4	.003	**-15.3	-6.1	.015	**-15.2	-6.0	.1
RDI 600 WM1	Missouri	Hermann, Mo.	1,586	1,447	8	.007	**-13.0	-4.6	.022	**-12.9	-4.5	.1
RDI 600 WM1	Missouri	Hermann, Mo.	--	1,501	8	.012	--	-3.4	.023	--	-3.3	.1
RDI 600 WM1	Missouri	Hermann, Mo.	--	1,529	4	.006	--	-2.8	.010	--	-2.3	.5
Average						**.008**	**-1.0**	**-4.3**	**.024**	**-2.4**	**-4.8**	**-.5**

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**Not included in average because of unsteady flow or erroneous Price AA current-meter measurements.

Summary and Conclusions

The combination of the acoustic frequency of an acoustic Doppler current profiler (ADCP) and the sediment-transport characteristics in a river can cause the ADCP bottom-tracking algorithms to detect a moving bottom. A moving bottom will cause bottom-tracking-referenced water velocities and discharges to be biased low. Differential global positioning system (DGPS) data can be used for the boat-velocity reference to allow accurate measurement of water velocities and discharges by use of the ADCP where bottom tracking detects a moving bottom. The use of DGPS for the boat-velocity reference can cause errors in the ADCP measurements. When using DGPS as the boat-velocity reference it is important that the ADCP compass is properly calibrated, the magnetic variation is accurately determined, and that the DGPS data are of high quality. When properly used, DGPS-referenced boat velocities compare favorably with bottom-tracking-referenced velocities at sites with no moving bottom. Conversely, when DGPS is not properly used, large differences between DGPS and bottom-tracking-referenced boat velocities can be observed. Discharges measured by use of DGPS were within 2.5 percent of the discharges measured by use of bottom tracking at three measurement sites. On average, the discharges measured by the use of an ADCP with DGPS for the boat-velocity reference were within 5 percent of the discharges measured by use of Price AA current meters and determined from USGS stage-discharge ratings.

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