Correcting Acoustic Doppler Current Profiler Discharge Measurements Biased by Sediment Transport

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Abstract: A negative bias in discharge measurements made with an acoustic Doppler current profiler (ADCP) is attributed to the movement of sediment on or near the streambed, and is an issue widely acknowledged by the scientific community. The integration of a differentially corrected global positioning system (DGPS) to track the movement of the ADCP can be used to avoid the systematic bias associated with a moving bed. DGPS, however, cannot provide consistently accurate positions because of multipath errors and satellite signal reception problems on waterways with dense tree canopy along the banks, in deep valleys or canyons, and near bridges. An alternative method of correcting for the moving-bed bias, based on the closure error resulting from a two-way crossing of the river, is presented. The uncertainty in the mean moving-bed velocity measured by the loop method is shown to be approximately 0.6 cm/s. For the 13 field measurements presented, the loop method resulted in corrected discharges that were within 5% of discharges measured utilizing DGPS to compensate for moving-bed conditions.

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Introduction

The use of vessel-mounted acoustic Doppler current profilers (ADCPs) for measuring streamflow has expanded rapidly. Discharges measured using vessel-mounted ADCPs may be biased by bed-load transport, which is referred to herein as a moving-bed error. ADCPs mounted on moving vessels measure the velocity of the water relative to the velocity of the instrument. To obtain the true water velocity, the velocity of the instrument must be measured and removed from the measured relative water velocity. The ADCP can determine its velocity relative to the streambed using the Doppler shift in bottom-tracking acoustic pulses reflected off the streambed, assuming that the streambed is motionless. Bottom tracking, however, can be biased by sediment transport along and near the streambed. If an ADCP is held stationary in a stream and the streambed is moving, the ADCP will interpret this condition as upstream movement of the ADCP. The underestimation of measured velocity and discharge by ADCP discharge measurements attributed to the movement of sediment near the streambed is an issue widely acknowledged by the scientific community (Oberg and Mueller 1994; Callede et al. 2000; Mueller 2002).

The integration of a differentially corrected global positioning system (DGPS) to measure the velocity of the ADCP has been shown to alleviate the errors associated with a moving bed (Mueller 2002). However, DGPS systems will not work in all conditions. For example, a DGPS will have trouble providing consistently accurate positions (and thus, ADCP measured velocities) on waterways with dense tree canopy along the banks, in deep valleys or canyons, and near bridges because of multipath and satellite signal reception problems. An alternative method (referred to herein as the loop method) of correcting for the moving-bed error is developed based on initial research by Brazilian federal hydrologists on the Amazon River (Callede et al. 2000).

Method Description

The loop method is based on the fact that as an ADCP moves across the stream, a moving bed will cause the bottom-track based ship track to be distorted in the upstream direction. Therefore, if an ADCP makes a two-way crossing of a stream (loop) with a moving bed and returns to the exact starting position, the bottom-track based ship track will show that the ADCP will have returned to a position upstream from the original starting position (Fig. 1). Because the ADCP appears to have moved upstream, the water velocity measured by the ADCP will be biased low, and consequently the discharge will be biased low. If the moving-bed velocity can be determined, the discharge missing from the measurement caused by the moving bed could be computed and added to the measured discharge to yield a corrected discharge

$$Q_{\mathrm{TC}} = Q_{\mathrm{TM}} + Q_{\mathrm{mb}} \tag{1}$$

where Q_{TC}=discharge corrected for the moving-bed bias; Q_{TM}=measured discharge; and Q_{mb}=discharge missed caused by the moving bed.

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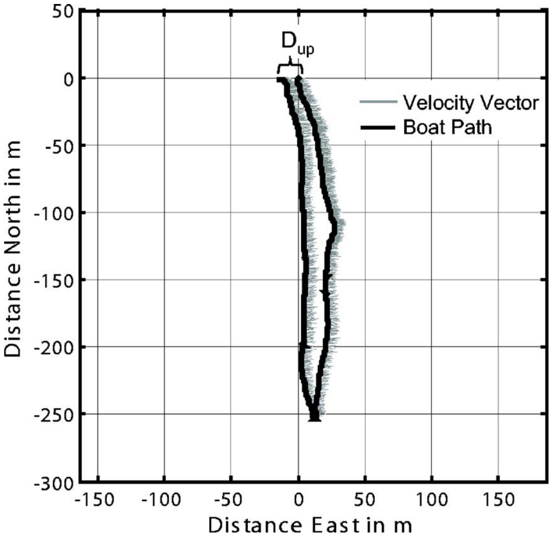


Fig. 1. Example of the distorted ship track in a loop caused by a moving bed

Mean Correction

The simplest method for computing the discharge missed because of the moving bed is to compute the mean moving-bed velocity and multiply it by the cross-sectional area measured perpendicular to the flow

$$Q_{\mathrm{mb}} = \bar{V}_{\mathrm{mb}} A_{\mathrm{pf}} \tag{2}$$

where $\bar{V}_{\mathrm{mb}}$=mean velocity of the moving bed; and A_{pf}=cross-sectional area perpendicular to the mean flow direction.

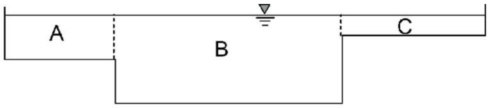
The mean moving-bed velocity can be estimated from the distance the ADCP appeared to have moved upstream from the starting position (loop-closure error) and the time required to complete the loop

$$\bar{V}_{\mathrm{mb}} = \frac{D_{\mathrm{up}}}{T} \tag{3}$$

where D_{up}=loop-closure error (distance made good, straight-line distance from starting point to ending point); and T=measurement time required to complete the loop. These data are readily available from most commercial software used to measure discharge with ADCPs.

It is important that the cross-sectional area is computed perpendicular to the mean flow direction. If the cross-sectional area is computed parallel to the ship track measured by the ADCP, then the cross-sectional area will be computed based on a ship track that is distorted in the upstream direction by the moving bed. The distortion of the ship track by a moving bed will result in a cross-sectional area that is too large.

Although the mean correction is simple to compute by hand and provides reasonable corrections for many streams (as will be shown later in this paper), if the cross-sectional area, discharge, and moving-bed velocities are not reasonably uniform, the mean correction method will improperly weight the discharge throughout the cross section. This potential problem can be illustrated by a simple compound channel (Fig. 2).



Hydraulic Properties	Subsections		
	A	B	C
Width (m)	40	100	60
Depth (m)	2	4	1
Actual Velocity (m/s)	1	2	0.5
Moving-Bed Velocity (m/s)	0.05	0.15	0
Measured Velocity (m/s)	0.95	1.85	0.5

Fig. 2. Simple example to illustrate effects of nonuniformly distributed moving-bed velocities and cross-sectional properties

The total discharge is equal to the product of the cross-sectional area of each subsection of the channel and the mean velocity in that subsection (910 m^3/s). Due to the moving bed in subsections A and B, the measured discharge will only be 846 m^3/s. If the ADCP were to make a loop through this cross section with a boat speed of 1 m/s, the ship track would show the ADCP moved upstream 34 m, and the duration of the loop would have been 400 s. Applying Eq. (3) results in a mean moving-bed velocity of 0.085 m/s. The discharge missed because of the moving bed is computed from Eq. (2) as 45.9 m^3/s, which when added to the measured discharge [Eq. (1)], yields a total corrected discharge of 891.9 m^3/s. The corrected discharge is more accurate than the measured discharge but is still 2% less than the actual discharge. This 2% error is caused by using a uniform representation of the moving-bed velocity and cross-sectional area to estimate the effects of nonuniformly distributed moving-bed velocities and cross-sectional area.

Distributed Correction

The actual moving-bed velocity at any point in the stream is unknown, but it is reasonable to assume that the moving-bed velocity is proportional to the near-bed water velocity (Callede et al. 2000). However, Callede et al. (2000) did not specify how to determine the near-bed velocity nor how to apply their correction technique called the "flow method" in which the discharge was recomputed. In this paper, a distributed correction method is proposed, which uses a one-sixth power curve to provide a consistent estimate of the near-bed velocity at any point in the cross section. To determine the distributed loop method correction, the measured mean moving-bed velocity from the loop is distributed to each ADCP profile by a ratio of near-bed velocity for each profile and the mean near-bed velocity for the cross section. The distributed moving-bed velocities are then applied to the water and boat velocities for all bins in each of the corresponding profiles in the measured portion of the cross section to determine the corrected measured discharge (Q_{mc}). The total discharge measured (Q_{TM}) by an ADCP consists of a measured portion (Q_m) and estimates of discharge in the unmeasured top (Q_t), bottom (Q_b), left (Q_l), and right (Q_r) edges. Therefore, the final corrected measured discharge is computed using the ratio of the corrected (Q_{mc}) and uncorrected (Q_m) measured portion of the discharge to correct the sum of the measured (Q_m) and top (Q_t) and bottom (Q_b) estimated discharges. It is assumed that water velocities near the bank will be sufficiently low as to not cause a moving bed and therefore, no correction is applied to the left (Q_l) and right (Q_r) edge discharges.

Distribution of the mean moving-bed velocity based on near-bed velocities requires a consistent method of determining near-bed velocities at each measured vertical. Because of side-lobe interference, the approximate lower 6–10% of each velocity profile is unmeasured. In addition, bad velocity measurements are common in the lower portions of a profile. Therefore, simply using the last valid velocity in each measured velocity profile would result in near-bed velocities at various distances from the streambed. The one-sixth power law has been shown to be consistent with a logarithmic velocity profile and is commonly used to estimate the unmeasured top and bottom discharges for ADCP measurements (Chen 1989; Simpson and Oltmann 1993). The near-bed velocity is computed by fitting the one-sixth power curve through zero at the bed and through the mean velocity of the last two good velocity measurements in the profile. Velocity is a vector, so both the east and north components of the near-bed velocity must be determined

$$V_{\mathrm{Enb}_i} = \bar{v}_{\mathrm{Enb}_i}\left(\frac{z_c}{\bar{z}_{\mathrm{nb}_i}}\right)^{1/6} \tag{4}$$

$$V_{\mathrm{Nnb}_i} = \bar{v}_{\mathrm{Nnb}_i}\left(\frac{z_c}{\bar{z}_{\mathrm{nb}_i}}\right)^{1/6} \tag{5}$$

where V_{Enb_i}=east component of the computed near-bed velocity for each profile i; $\bar{v}_{\mathrm{Enb}_i}$=east component of the mean velocity of the two velocity measurements nearest the streambed for each profile i; z_c=distance above the bed of the computed near-bed velocity, arbitrarily assigned a value of 0.3 m; $\bar{z}_{\mathrm{nb}_i}$=mean distance from the streambed of the two velocity measurements nearest the streambed for each profile i; V_{Nnb_i}=north component of the computed near-bed velocity for each profile i; $\bar{v}_{\mathrm{Nnb}_i}$=north component of the mean velocity of the two velocity measurements nearest the streambed for each profile i; and i=index for each measured velocity profile.

The amount of moving-bed correction applied to each profile is computed from the near-bed velocities and the mean moving-bed velocity using Eqs. (6) and (7). A linear relation between the near-bed velocity and the moving-bed velocity is perhaps not as accurate as applying a sediment transport equation to compute the distributed moving-bed velocity from the near-bed velocity. However, the use of a complex equation would require additional data (i.e., bed material) that are not practical to collect during every discharge measurement; therefore, the simplified linear approach shown in Eqs. (6) and (7) was applied

$$V_{\mathrm{mbE}_i} = \bar{V}_{\mathrm{mb}}\left(\frac{V_{\mathrm{Enb}_i}}{\bar{V}_{\mathrm{nb}}}\right) \tag{6}$$

$$V_{\mathrm{mbN}_i} = \bar{V}_{\mathrm{mb}}\left(\frac{V_{\mathrm{Nnb}_i}}{\bar{V}_{\mathrm{nb}}}\right) \tag{7}$$

where V_{mbE_i}=east component of the moving-bed velocity in profile i; V_{mbN_i}=north component of the moving-bed velocity in profile i; *and* $\bar{V}_{\mathrm{nb}}$=mean near-bed velocity defined as

$$\bar{V}_{\mathrm{nb}} = \sqrt{\left(\frac{\sum_{i=1}^{n} V_{\mathrm{Enb}_i}}{n}\right)^2 + \left(\frac{\sum_{i=1}^{n} V_{\mathrm{Nnb}_i}}{n}\right)^2} \tag{8}$$

and n=number of velocity profiles.

The mean moving-bed speed has been converted to a distributed moving-bed velocity that can be used to compute a corrected measured discharge Q_{mc}. The measured discharge from an ADCP is computed using the cross product of the water velocity and boat velocity

$$Q_m = \sum_{i=1}^{n}\sum_{j=1}^{m}(V_{E_{i,j}}V_{\mathrm{BN}_i} - V_{N_{i,j}}V_{\mathrm{BE}_i})bt_i \tag{9}$$

where j=index for bins containing a velocity measurement; m=maximum number of bins in each profile i; $V_{E_{i,j}}$=east component of the water velocity in velocity profile i; bin j; V_{BN_i}=north component of the boat velocity in velocity profile i; $V_{N_{i,j}}$=north component of the water velocity in velocity profile i, bin j; V_{BE_i}=east component of the boat velocity in velocity profile i; b=bin size; and t_i=time between profiles for profile i.

To compute the corrected measured discharge, the moving-bed velocities must be applied to the water and boat velocities

$$V_{E_{i,j}}^{c} = V_{E_{i,j}} + V_{\mathrm{mbE}_i} \tag{10}$$

$$V_{N_{i,j}}^{c} = V_{N_{i,j}} + V_{\mathrm{mbN}_i} \tag{11}$$

$$V_{\mathrm{BE}_i}^{c} = V_{\mathrm{BE}_i} + V_{\mathrm{mbE}_i} \tag{12}$$

$$V_{\mathrm{BN}_i}^{c} = V_{\mathrm{BN}_i} + V_{\mathrm{mbN}_i} \tag{13}$$

$$Q_{\mathrm{mc}} = \sum_{i=1}^{n}\sum_{j=1}^{m}(V_{E_{i,j}}^{c}V_{\mathrm{BN}_i}^{c} - V_{N_{i,j}}^{c}V_{\mathrm{BE}_i}^{c})bt_i \tag{14}$$

The superscript "c" designates velocities that have been corrected for the moving bed.

Finally, the corrected discharge is computed using the ratio of the corrected (Q_{mc}) and uncorrected (Q_m) measured portion of the discharge to correct the sum of the measured (Q_m) and estimated top (Q_t) and bottom (Q_b) discharges. It is assumed that water velocities near the bank will be sufficiently low as to not cause a moving bed and, therefore, no correction is applied to the left (Q_l) and right (Q_r) edge discharges

$$Q_{\mathrm{TM}}^{c} = Q_l + Q_r + (Q_m + Q_t + Q_b)\left(\frac{Q_{\mathrm{mc}}}{Q_m}\right) \tag{15}$$

The computations associated with the distributed correction are best performed using a computer program. A computer program was developed to apply this method. The program reads ASCII files that are readily output by standard vendor-supplied ADCP software. This allows all the utilities of the data collection and processing software to be used to validate the measured discharge before applying any corrections.

The distributed correction can be demonstrated using the previous example (Fig. 2). The boat velocity from bottom track will be assumed to be 1 m/s in the east (cross-channel direction) and equal to the moving-bed speed in the south direction. If we assume that the mean velocity for each subsection occurs at 0.6 depth, the one-sixth power law can be applied to compute the near-bed velocities 0.3 m from the bed. Making these assumptions and working through Eqs. (4)–(15) yields a corrected discharge of 901.3 m^3/s, an error of 1% from the actual discharge. In this example, the distributed correction improved the corrected discharge from low 2% based on the mean correction method to low 1%, based on the distributed correction method. Note, there is no difference in field procedures required between the two methods, only a difference in how the correction obtained from the loop is applied.

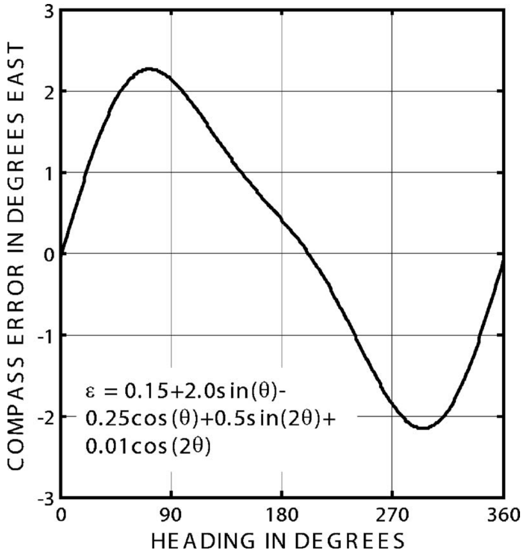


Fig. 3. Hypothetical compass error curve

Assessment of Errors and Uncertainty

The loop method is valid only if the moving bed is the dominant cause of the loop-closure error and the ADCP can maintain constant bottom track. The following are common sources of errors associated with the loop method, which will be addressed in detail:

- Compass errors;
- Bottom-tracking uncertainty;
- Failure to return to the initial starting point; and
- Irregular or insufficient sampling of the cross section because of loss of bottom track, nonuniform boat speed, and (or) loitering at the banks.

The magnitude and direction of these errors must be evaluated to determine the expected uncertainty in applying the loop method for field measurements. These potential errors and the resulting uncertainty of the method are assessed analytically and practically through assessment of field measurements collected by different personnel with different instruments in widely varying conditions.

Compass Errors

The most common mistake made in applying the loop method is to ignore the effect of the ADCP's compass on the resulting loop-closure error. An error in the compass reading can be caused by distortion in the earth's magnetic field because of local objects on the boat, and displacement of the compass out of the horizontal position. Many fluxgate compasses are gimbaled to reduce the effects of pitch and roll, but horizontal accelerations and pitch and roll may still cause the compass to be displaced out of the horizontal position. The amount of distortion of the magnetic field by objects near a compass depends on the shape, material content, and proximity of the object to the compass. Objects that distort the magnetic field are commonly classified as hard iron and soft iron. Hard iron can be permanent magnets, magnetized iron or steel, or current-carrying conductors. Soft iron is material that, when placed in a magnetic field, will become magnetized, but unlike hard iron, when removed from the magnetic field will lose its magnetism (National Geospatial-Intelligence Agency 2004). For ADCPs, hard iron and soft iron consist of the boat, instrument mount, objects on the boat, or structures near the measurement section (such as bridges). The result of the distortion of the magnetic field on compass heading is typically not constant and varies with heading. The errors caused by hard iron and soft iron are accounted for by in situ calibration of the compass. Internal compasses in commercially available bottom-tracking ADCPs have a built-in compass calibration routine.

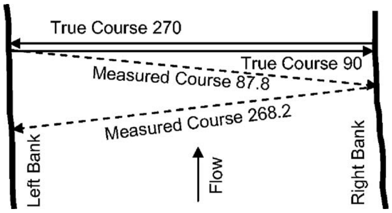


Fig. 4. Illustration of the difference between the true course traversed by the boat (solid line) and the measured course (dashed line) for straight-line east-west transects with the compass error described in Fig. 3

Compass errors caused by hard iron and soft iron vary with heading and can be modeled as sine and cosine curves. The general equation for compass error for a compass mounted on a boat is (National Geospatial-Intelligence Agency 2004)

$$\varepsilon = A + B\sin(\theta) + C\cos(\theta) + D\sin(2\theta) + E\cos(2\theta) \qquad (16)$$

where ε=compass error; θ=compass heading; A=coefficient that accounts for compass alignment; B=coefficient that accounts for the fore-aft permanent magnetic field across the compass and a resultant asymmetrical vertical induced effect; C=coefficient that accounts for the port-starboard permanent magnetic field across the compass, and a resultant asymmetrical vertical induced effect; D=coefficient that accounts for symmetrical arrangements of horizontal soft iron; and E=coefficient that accounts for asymmetrical arrangements of horizontal soft iron. A hypothetical compass error curve, shown in Fig. 3, will be used to show the effect of compass errors on the loop method.

Assume a 200 m wide channel with flow to the north, a mean velocity of 1.7 m/s, a moving-bed velocity of 0.085 m/s, a cross-sectional area of 540 m^2, total loop time of 400 s, and a loop made by east-west transects. If the errors shown in Fig. 3 were not corrected by calibration of the compass, the closure error caused by these errors would be 14 m in the upstream direction (Fig. 4). Thus, rather than measuring a moving-bed velocity of 0.085 m/s, a moving-bed velocity of 0.120 m/s would have been measured, an error of 41%. This 41% error in moving-bed velocity would translate to a 2% difference in the final corrected discharge.

A properly calibrated compass is critical to application of the loop method. This method cannot be used with profilers that do not have a compass or cannot be referenced to an external compass. Only those compass errors that change with heading are important. A constant error, such as not entering the correct magnetic variation, will not affect the loop method. The error caused by an improperly or uncalibrated compass can be in either direction, resulting in either more or less moving bed than is actually present.

Assessment of Errors

For the loop method to have practical application in the field, the loop-closure error caused by instrument and procedural errors must be insignificant relative to the loop-closure error caused by a

Table 1. Summary of Field Data Used to Evaluate the Uncertainty in the Loop Method Caused by Instrument and Procedural Errors

Site name	Measurement time (sec)	Stream width (m)	Loop-closure error (m)	Average course (degrees)	Measured mean moving bed velocity (m/s)	Average water velocity (m/s)	Bed velocity/ water velocity (%)	Compass calibration error (degrees)
Cape Fear River at Lock 3, North Carolina	599	57.9	−0.50	245	−0.0008	0.12	−0.7	0.2
Cape Fear River at Lock 3, North Carolina	362	57.9	0.79	244	0.0022	0.12	1.9	0.2
Big Swamp near Tar Heel, North Carolina	161	11.0	−0.21	230	−0.0013	0.03	−4.2	0.3
Big Swamp near Tar Heel, North Carolina	175	11.6	−0.56	230	−0.0032	0.03	−10.4	0.3
Kentucky River at Lock 2, Kentucky	295	83.8	1.12	322	0.0038	0.82	0.5	0.4
Kentucky River at Lock 5, Kentucky	342	87.5	−1.48	297	−0.0043	1.13	−0.4	1
Kentucky River at Lock 7, Kentucky	260	84.7	−1.82	287	−0.0070	0.70	−1.0	2
Kentucky River at Lock 8, Kentucky	214	68.6	−1.04	283	−0.0048	0.94	−0.5	0.7
Kentucky River at Lock 8, Kentucky	192	63.4	2.23	306	0.0116	0.98	1.2	0.7
Hay River near Hay River, Canada	369	82.3	−1.04	86	−0.0028	0.88	−0.3	1.1
Hay River near Hay River, Canada	212	79.2	−0.40	75	−0.0019	0.91	−0.2	0.3
Hay River near Hay River, Canada	232	81.4	1.30	73	0.0056	0.98	0.6	0.3
St. Lawrence River at 1000 Islands, Canada	769	269.1	1.92	120	0.0025	0.41	0.6	0.2
St. Lawrence River at 1000 Islands, Canada	818	271.3	3.57	120	0.0044	0.41	1.1	0.2
St. Lawrence River at 1000 Islands, Canada	783	271.6	−4.57	121	−0.0058	0.42	−1.4	0.2
St. Lawrence River near 1000 Islands, Canada	359	134.1	−1.74	163	−0.0048	0.42	−1.2	0.2
Pee Dee River at Rockingham, North Carolina	421	110.3	−1.14	259	−0.0027	0.28	−1.0	0.6
Pee Dee River at Rockingham, North Carolina	550	113.7	−2.27	247	−0.0041	0.27	−1.6	0.6
Pee Dee River at Rockingham, North Carolina	348	110.3	2.37	255	0.0068	0.28	2.5	0.5
Connecticut River at Hartford, Connecticut	1,005	326.1	−7.41	105	−0.0074	0.76	−1.0	<1.0
Sacramento River at Sacramento, California	762	161.5	1.25	25	0.0016	0.60	0.3	0.2
Kissimmee River, Florida (site KQ001)	865	38.1	−0.55	292	−0.0006	0.48	−0.1	—
Kissimmee River, Florida (site KQ001)	871	37.8	−0.34	292	−0.0004	0.47	−0.1	—
Kissimmee River, Florida (site KQ011)	744	30.2	−1.43	44	−0.0019	0.59	−0.3	—
Kissimmee River, Florida (site KQ011)	663	29.9	−1.04	44	−0.0016	0.58	−0.3	—
Kissimmee River, Florida (site KQ013)	484	21.3	−0.55	261	−0.0011	0.65	−0.2	—
Kissimmee River, Florida (site KQ013)	500	21.3	0.27	261	0.0005	0.63	0.1	—
Androscoggin River near Gorham, New Hampshire	784	35.1	0.43	225	0.0006	0.52	0.1	0.3

Note: m=meters; —=no data; −=closure error in upstream direction; m/s=meters per second; <=less than.

moving bed. Sources of error include, but are not limited to, failure to return the ADCP to the exact starting location, ADCP compass errors, and bottom-tracking errors. Loop-closure errors measured where there is no moving bed provide an estimate of magnitude of these errors. Twenty-eight individual loop measurements were made during low-flow conditions at 17 sites across the United States and Canada by different field personnel using different deployment techniques and ADCPs. An important aspect of the loop-closure error data was the direction of the closure error (upstream or downstream). In order to qualify the closure error, upstream errors were established as negative values and downstream errors were positive values. The loop-closure error and other pertinent information regarding site conditions are summarized in Table 1. The measured mean moving-bed velocity defined as the loop-closure error divided by measurement time ranged from 0.0116 m/s in the downstream direction to 0.0074 m/s in the upstream direction. The moving-bed velocities had no statistically significant bias based on a mean of −0.0006 and a two-tailed *t*-test level of significance of 0.468. Since there was no moving bed at these sites, the measured mean moving-bed velocities are caused by instrument and procedural uncertainty.

The assessment of uncertainty was conducted on the measured mean moving-bed velocities rather than the actual loop-closure errors because determining the mean moving-bed velocity is the objective of the loop method. A bootstrap analysis (Davidson and Hinkley 1998) was conducted on the measured mean moving-bed velocity data presented in Table 1 to determine the summary statistics that could be used to quantify the uncertainty in application of the loop method. The standard deviation of the measured mean moving-bed velocity was the statistic chosen to summarize uncertainty in the data. For the bootstrap, 1,000 new samples, each of the same population size as the observed data, were created from the observed data. In this analysis, the standard deviation was calculated for each new set of data. The observed standard deviation of all the fields mean moving-bed velocity data is 0.0043 m/s. The mean standard deviation of the mean moving-bed velocities from the bootstrap distribution is 0.0042 m/s, with a standard error of 0.00066 m/s. The 95% and 99% confidence levels for the standard deviation from the bootstrap distribution are 0.0057 m/s and 0.0060 m/s, respectively. Therefore, at a 99% confidence level, the bootstrap statistics indicate that the measured mean moving-bed velocity would have an uncertainty of 0.0060 m/s due to random errors. Users applying the loop method should ensure that this uncertainty is small, when compared to the mean water velocity for the discharge measurement.

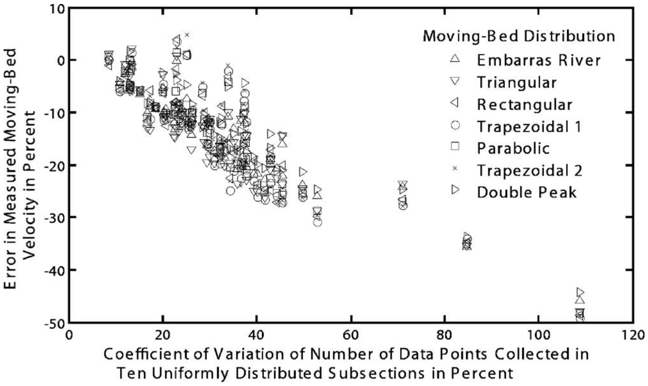


Fig. 5. Plot showing error in measured mean moving-bed velocity as a function of nonuniformity in boat speed measured as the coefficient of variation in the number of data points collected in ten uniformly distributed subsections of the cross section

Effect of Irregular or Insufficient Sampling

The principle underlying the loop method is that during the loop, the effect of the spatially varying moving bed is averaged. Rennie and Millar (2002) demonstrated that the bottom-tracking technique in an ADCP can be used to detect the spatial and temporal variability of sediment transport. The effect of the mean and variability in boat speed on the measured mean moving-bed velocity was evaluated using seven different spatial distributions of moving-bed velocities, an actual distribution from the Embarras River in Illinois, and various distributions based on rectangular, trapezoidal, parabolic, and double peak shapes. A theoretical simulation of different uniform boat speeds (that did not include simulated instrument and procedural errors) showed little effect of uniform boat speed on the measured mean moving-bed velocity. When instrument and procedural errors are considered, effect of boat speed plays a role in determining the magnitude of the upstream movement measured during the loop. The faster the loop, the shorter the distance moved upstream, and the greater the effect of random instrument and procedural errors.

Nonuniformity of boat speed during the loop will result in the moving bed in portions of the cross section being unequally weighted in the computation of the mean moving-bed velocity, and will result in an error in the measured mean moving-bed velocity. Purely theoretical simulations of nonuniform boat speed were determined to be unreliable, because randomly generated variations in boat speed may not be representative of actual boat operation in the field. Therefore, field data from 59 loop tests conducted at 39 different sites by different boat operators were used with seven constructed moving-bed velocity distributions, for which the true moving-bed velocities were known, to assess the effect of nonuniform boat speed, represented by the coefficient of variation of the boat speed during each transect, on the measured mean moving-bed velocity. The magnitude of the error between the measured mean moving-bed velocity and the true mean moving-bed velocity increases as the nonuniformity in boat speed increases (Fig. 5).

The accuracy of the mean moving-bed velocity measured by the loop method will depend on the speed at which the ADCP is transported through the cross section and the spatial distribution of the moving-bed velocity. To obtain an accurate measure of the mean moving-bed velocity, the operator should maintain a uniform boat speed. Based on the limits of the field data used in this analysis, the recommended maximum boat speed should be the lesser of a boat speed that requires no less than 3 min to complete the loop or a boat speed that is less than 1.5 times the mean water speed.

Application to Field Discharge Measurements

The evaluation of the loop method ultimately requires analyzing field data biased by a moving bed that represent a wide range of hydraulic conditions and river characteristics. The U.S. Geological Survey loop-method analysis utilized field data collected at sites throughout the United States and Canada. The field evaluation of the loop method consisted of comparing loop-method-corrected discharges to DGPS-based discharges for sites with moving beds and analyzing the effects of instrument and procedural errors.

Correction Method Comparisons

The mean correction for the loop method is relatively simple to apply; however, as previously discussed in the Method Description section, if the cross-sectional area, discharge, and moving-bed velocities are not reasonably uniform, the mean-correction method will improperly weight the discharge throughout the cross section. A distributed correction applied to each ensemble is a more sophisticated process to apply but alleviates much of the bias associated with nonuniform cross sections. In order to make the distributed loop-method correction practical, a computer program was developed to automate the process.

A comparison of discharge data adjusted with both the mean and distributed loop-method corrections is presented in Table 2 for 13 field sites affected by a moving-bed bias greater than 1% of the arithmetic mean of all water velocities. The maximum difference between the two correction methods is less than 0.4% for all but one observation (Battle River). All 13 measurement sites included in the comparison had relatively uniform rectangular or trapezoidal channel cross sections; therefore, the lack of difference displayed between the mean and distributed correction methods in Table 2 is largely explained by the uniform cross-sectional characteristics of the sites.

Comparison of Loop Method to DGPS-Based Discharges

In order to compare the absolute accuracy of both loop methods (mean and distributed), a DGPS was integrated with an ADCP, and river discharge measurements and loop tests were collected at nine sites with moving beds. The final discharges were adjusted by both loop methods and compared to discharges measured using the DGPS (Table 2). The comparison shown in Table 2 reveals that for the nine sites, discharge corrected using the averaged loop method is within −5.0 to 1.3% (standard deviation =1.9%) of the discharge measured using a DGPS as the bottom reference. Discharge corrected using the distributed loop-method correction is within −5.4 to 0.96% (standard deviation=2.0%) of the discharge measured using a DGPS as the bottom reference. A discharge measurement using DGPS to determine the boat movement is affected by the quality of the DGPS signal. Multipath, limited satellite reception and changes in visible satellites can greatly impact the quality of the measured discharge. An assessment of the DGPS signal quality is provided in Table 2 to qualify the level of reliability for the DGPS-referenced discharge data. The quality of the DGPS signal in

Table 2. Comparison of Discharge Collected with DGPS and Adjusted by Mean and Distributed Loop-Method Corrections at Sites Affected by a Moving-Bed Bias Greater Than 1% of the Arithmetic Mean of All Water Velocities

Site name	Number of transects	Bottom track discharge (m^3/s)		DGPS discharge (m^3/s)		Mean corrected discharge (m^3/s)		Distributed corrected discharge (m^3/s)		GPS quality
		Mean	COV	Mean	COV	Mean	COV	Mean	COV	
Flat River near the Mouth, Canada	4	311	0.024	313	0.011	317	0.024	316	0.023	Good
South Nahanni River above Virginia Falls, Canada	4	850	0.004	890	0.005	891	0.004	893	0.005	Excellent
Rocky River near Stanfield, North Carolina	8	450	0.076	486	0.044	462	0.076	460	0.077	Fair
Yadkin River near Yadkin College, North Carolina	4	685	0.022	698	0.034	697	0.022	696	0.022	Good
Moose River above Moose River, Canada	4	1,785	0.009	1,865	0.018	1,868	0.009	1,874	0.008	Poor
Missouri River at Nebraska City, Nebraska	4	1,028	0.025	1,123	0.014	1,093	0.025	1,096	0.022	Good
Missouri River at Nebraska City, Nebraska	4	819	0.009	866	0.017	863	0.009	863	0.008	Good
Missouri River at Decatur, Nebraska	4	744	0.013	777	0.008	776	0.013	777	0.015	Fair
Missouri River at Hermann, Missouri	4	1,078	0.013	1,101	0.006	1,103	0.013	1,102	0.013	Good
Battle River near the Saskatchewan Boundary, Canada	4	55	0.049	—	—	64	0.049	66	0.047	—
Beaver River below Matson Creek, Canada	4	280	0.016	—	—	286	0.016	285	0.017	—
Porcupine River near International Boundary, Canada	6	1,665	0.034	—	—	1,743	0.034	1,740	0.029	—
Moose River above Moose River, Canada	1	2,764	—	—	—	2,849	—	2,853	—	—

Note: (m^3/s)=cubic meters per second; COV=coefficient of variation; GPS=global positioning system.

Table 2 was established using GPS parameters and limits reported by standard data collection software (RD Instruments 2003):

- Excellent—No GPS parameters were outside recommended limits;
- Good—One GPS parameter was outside the recommended limits, but no velocity spikes or losses can be attributed to GPS signal problem;
- Fair—Multiple GPS parameters were outside the recommended limits, but no major velocity spikes or losses are attributed to GPS signal problem;
- Poor—Multiple GPS parameters were outside the recommended limits and major velocity spikes and/or losses correspond to GPS signal problems.

The DGPS signal quality in Table 2 represents the worse-case scenario for the individual transects that comprise each of the discharge measurements.

Effect of Instrument and Procedural Errors on Discharge

The analysis of errors, presented herein, was based on data collected where there was no moving bed. The errors characterized by that analysis, however, are also relevant to loops collected in channels with a moving bed. For example, suppose a loop test was conducted on a stream with a mean water velocity of 1.5 m/s and a moving-bed bias of 0.020 m/s (the bias is 1.3% of the water velocity). According to the uncertainty analysis, errors of 0.0060 m/s at the 99% confidence level could be present in the measured mean moving-bed velocity. The uncertainty could be in either direction. Therefore, if the true moving-bed velocity were 0.02 m/s, the measured mean moving-bed velocity could range from 0.014 to 0.026 m/s, which is 0.93 to 1.7% of the mean water velocity. Applying the uncertainty of the measured mean moving-bed velocity (0.0060 m/s) to 13 field data sets (Table 2) having a moving-bed bias greater that 1% of the arithmetic mean of all water velocities results in an uncertainty in final discharge of less than +/− 1.0%.

Summary and Conclusions

A systematic bias in discharge measurements made with an acoustic Doppler current profiler (ADCP) attributed to the movement of sediment near the streambed leads to an underestimation of measured velocity and discharge. Although the use of differentially corrected global positioning systems (DGPS) to measure the movement of the ADCP is the common and preferred solution to this bias, DGPS cannot provide consistently accurate positions because of multipath errors and satellite signal reception problems on waterways with dense tree canopy along the banks, in deep valleys or canyons, and near bridges. The loop method is shown to be an alternative method to the use of DGPS. The loop method is based on analysis of the error between the actual position of the boat and position computed by the ADCP when the boat returns to its starting point after a two-way crossing of the river. The results of the loop method are valid only if the compass in the ADCP has been properly calibrated to compensate for hard and soft iron errors and bottom track is maintained throughout the loop. The uncertainty associated with instrument and procedural errors is approximately 0.0060 m/s at the 99% confidence level. The accuracy with which the mean moving-bed velocity can be measured also depends on the uniformity of the boat speed as the loop is made. Nonuniformity of boat speed during the loop will result in the moving bed in portions of the cross section being unequally weighted in the computation of the mean moving-bed velocity, which will result in an error in the measured mean moving-bed velocity. Two methods, the mean correction method and the distributed correction method, to correct the measured discharge using measured mean moving-bed velocity were evaluated. The mean correction method is simple to apply but does not account for the cross section shape and spatial distribution of the sediment transport. The distributed method uses a near-bed water velocity computed from the ADCP data to distribute the mean moving-bed velocity through the cross section. Application of both methods to 13 field measurements showed little variation between the methods, due to the uniformity of the cross sections and flow distributions represented in the data. Both methods provided discharges that were within 5% of the measured value using DGPS. Therefore, when properly applied, the loop method represents a valid alternative to the use of DGPS for measuring discharge with an ADCP in streams with sufficient sediment to cause moving-bed conditions.

Notation

The following symbols are used in this paper:

A = coefficient that accounts for compass alignment;
A_{pf} = cross-sectional area perpendicular to the mean flow direction;
B = coefficient that accounts for the fore-aft permanent magnetic field across the compass and a resultant asymmetrical vertical induce effect;
b = bin size;
C = coefficient that accounts for the port-starboard permanent magnetic field across the compass, and a resultant asymmetrical vertical induced effect;
D = coefficient that accounts for symmetrical arrangements of horizontal soft iron;
D_{up} = loop-closure error (distance made good, straight-line distance from starting point to ending point);
E = coefficient that accounts for asymmetrical arrangements of horizontal soft iron;
i = index for each measured velocity profile;
j = index for bins containing a velocity measurement;
m = maximum number of bins in each profile i;
n = number of velocity profiles;
Q_b = discharge estimated in the bottom unmeasured portion of the cross section;
Q_l = discharge estimated in the left unmeasured portion of the cross section;
Q_m = portion of the discharge measured directly by the ADCP;
Q_{mb} = bias in the discharge caused by the moving bed;
Q_{mc} = portion of the discharge measured directly by the ADCP, corrected for the moving bed;
Q_r = discharge estimated in the right unmeasured portion of the cross section;
Q_t = discharge estimated in the top unmeasured portion of the cross section;
Q_{TC} = discharge corrected for the moving-bed bias;
Q_{TM} = total measured discharge;
Q^c_{TM} = total measured discharge corrected for the moving bed;
T = measurement time required to complete the loop;
t_i = time between profiles for profile i;
V_{BE_i} = east component of the boat velocity in profile i;
$V^c_{\mathrm{BE}_i}$ = east component of the boat velocity corrected for the moving-bed velocity in profile i;
V_{BN_i} = north component of the boat velocity in profile i;
$V^c_{\mathrm{BN}_i}$ = north component of the boat velocity corrected for the moving-bed velocity in profile i;
$V_{E_{i,j}}$ = east component of the water velocity in profile i, bin j;
$V^c_{E_{i,j}}$ = east component of the water velocity corrected for the moving bed in profile i, bin j;
V_{Enb_i} = east component of the computed near-bed velocity for each profile i;
$\bar{V}_{\mathrm{mb}}$ = mean velocity of the moving bed;
V_{mbE_i} = east component of the moving-bed velocity in profile i;
V_{mbN_i} = north component of the moving-bed velocity in profile i;
$V_{N_{i,j}}$ = north component of the water velocity in velocity profile i, bin j;
$V^c_{N_{i,j}}$ = north component of the water velocity corrected for the moving bed in profile i, bin j;
$\bar{V}_{\mathrm{nb}}$ = mean near-bed velocity;
V_{Nnb_i} = north component of the computed near-bed velocity for each profile i;
$\bar{v}_{\mathrm{Enb}_i}$ = east component of the mean velocity of the two velocity measurements nearest the streambed for each profile i;
$\bar{v}_{\mathrm{Nnb}_i}$ = north component of the mean velocity of the two velocity measurements nearest the streambed for each profile i;
z_c = distance above the bed of the computed near-bed velocity, arbitrarily assigned a value of 0.3 m;
$\bar{z}_{\mathrm{nb}_i}$ = mean distance from the streambed of the two velocity measurements nearest the streambed for each profile i;
ε = compass error; and
θ = compass heading.

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