Prepared in cooperation with Environment Canada

Application of the Loop Method for Correcting Acoustic Doppler Current Profiler Discharge Measurements Biased by Sediment Transport

Scientific Investigations Report 2006–5079

U.S. Department of the Interior
U.S. Geological Survey

Cover. **U.S. Geological Survey hydrologists measuring discharge along the heavily canopied Kankakee River in Indiana using a vessel-mounted acoustic Doppler current profiler (ADCP) and applying the loop method** *(photograph by Mike Rehmel, U.S. Geological Survey)***.**

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
	Area	
square centimeter (cm^2)	0.001076	square foot (ft^2)
square meter (m^2)	10.76	square foot (ft^2)
square centimeter (cm^2)	0.1550	square inch (in^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
	Flow rate	
meter per second (m/s)	3.281	foot per second (ft/s)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)

Abbreviations and Acronyms used in this report:

ADCP	acoustic Doppler current profiler
DGPS	differentially corrected Global Positioning System
DMG	distance made good
USGS	U.S. Geological Survey

Application of the Loop Method for Correcting Acoustic Doppler Current Profiler Discharge Measurements Biased by Sediment Transport

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Abstract

A systematic bias in discharge measurements made with an acoustic Doppler current profiler (ADCP) is attributed to the movement of sediment near the streambed—an issue widely acknowledged by the scientific community. This systematic bias leads to an underestimation of measured velocity and discharge. 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 systems, 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, was investigated by the U.S. Geological Survey. The uncertainty in the measured mean moving-bed velocity caused by nonuniformly distributed sediment transport, failure to return to the starting location, variable boat speed, and compass errors were evaluated using both theoretical and field-based analyses. The uncertainty in the mean moving-bed velocity measured by the loop method is approximately 0.6 centimeters per second. Use of this alternative method to correct the measured discharge was evaluated using both mean and distributed correction techniques. Application of both correction methods to 13 field measurements resulted in corrected discharges that were typically within 5 percent of discharges measured using DGPS.

Introduction

The use of vessel-mounted, acoustic Doppler current profilers (ADCPs) in the field of water resources is rapidly expanding. The rapid growth in the use of ADCPs by scientists and engineers has resulted in a greater need to measure discharge in conditions not conducive to unbiased measurements by standard ADCP procedures. Discharges measured using vessel-mounted ADCPs during high-flow conditions are often biased by bed-load transport, which is referred to herein as 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 velocity. The ADCP can determine its velocity relative to the streambed using the Doppler shift of 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. A systematic error in ADCP measurements attributed to the movement of sediment near the streambed is an issue widely acknowledged by the scientific community (Oberg and Mueller, 1994; Callede and others, 2000; Mueller, 2002). This systematic error (moving-bed error) leads to an underestimation of measured velocity and discharge.

The integration of a differentially corrected Global Positioning System (DGPS) to measure the velocity of the ADCP has been shown to alleviate the systematic errors associated with a moving bottom (Mueller, 2002). DGPS systems, however, will not work in all conditions. For example, a DGPS will have trouble providing consistently accurate positions and velocities on waterways with dense tree canopy along the banks, in deep valleys or canyons, and near bridges because of multipath errors and satellite signal reception problems.

An alternative method (referred to herein as the loop method) of correcting for the moving-bottom error was applied in the late 1990s by Brazilian Federal hydrologists on the Amazon River (Callede and others, 2000). Although the Brazilian research presented the basic method and its application to a measurement on the Amazon River, it was not exhaustive and ADCP technology has evolved a great deal since the mid 1990s. This report describes research conducted by the U.S. Geological Survey (USGS) to evaluate potential errors and uncertainty associated with application of the loop method that were not addressed in the original research and compares and evaluates the applicability of the method to a variety of field measurements.

Method Description

The loop method is based on the fact that as an ADCP is moved 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, then the discharge missing from the measurement caused by the moving bed can be computed and added to the measured discharge to yield a corrected discharge.

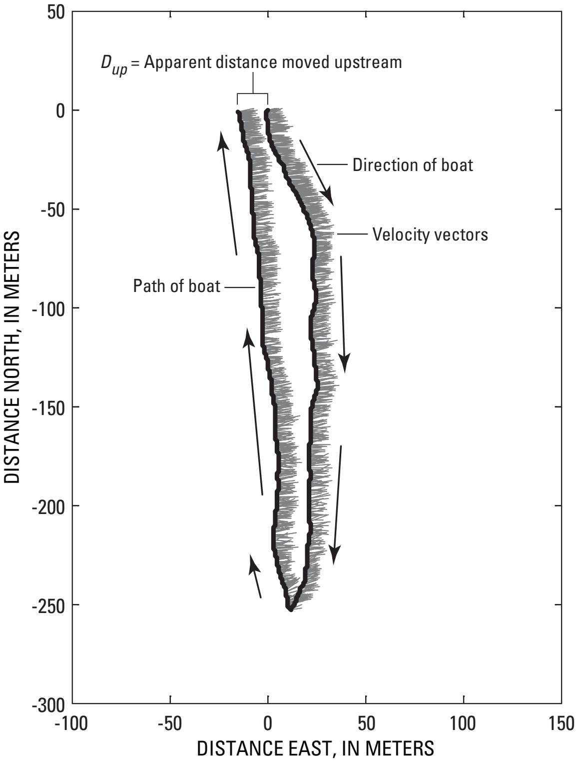


Figure 1. Example of the distorted ship track in a loop caused by a moving bed.

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

where

Q_{TC} is the discharge corrected for the moving-bed bias,

Q_{TM} is the measured discharge, and

Q_{mb} is the discharge missed caused by the 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.

$$Q_{mb} = \bar{V}_{mb} A, \tag{2}$$

where

$\bar{V}_{mb}$ is the mean velocity of the moving bed, and

A is the 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.

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

where

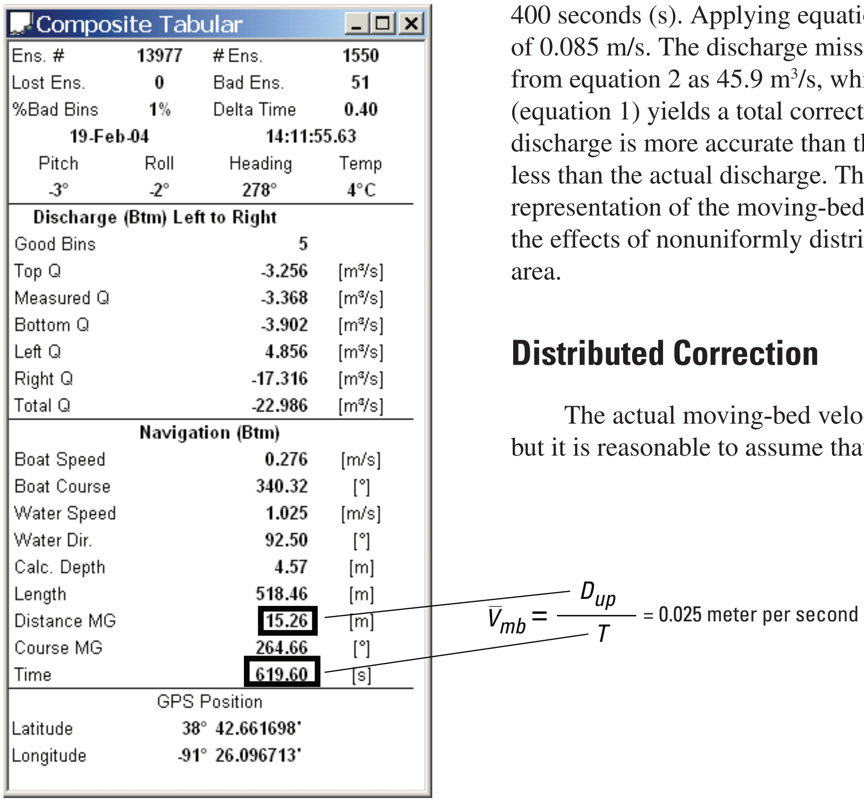
D_{up} is the loop-closure error (distance made good, straight-line distance from starting point to ending point), and

T is the measurement time required to complete the loop.

These data are readily available from most commercial software used to measure discharge with ADCPs (fig. 2).

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 report), if the cross-sectional



```
Ens. #        13977   # Ens.       1550
Lost Ens.         0   Bad Ens.       51
%Bad Bins        1%   Delta Time   0.40
     19-Feb-04           14:11:55.63
  Pitch     Roll     Heading     Temp
   -3°       -2°       278°       4°C
  Discharge (Btm) Left to Right
Good Bins                 5
Top Q                -3.256   [m³/s]
Measured Q           -3.368   [m³/s]
Bottom Q             -3.902   [m³/s]
Left Q                4.856   [m³/s]
Right Q             -17.316   [m³/s]
Total Q             -22.986   [m³/s]
        Navigation (Btm)
Boat Speed            0.276   [m/s]
Boat Course          340.32   [°]
Water Speed           1.025   [m/s]
Water Dir.            92.50   [°]
Calc. Depth            4.57   [m]
Length               518.46   [m]
Distance MG           15.26   [m]
Course MG            264.66   [°]
Time                 619.60   [s]
          GPS Position
Latitude      38° 42.661698'
Longitude    -91° 26.096713'
```

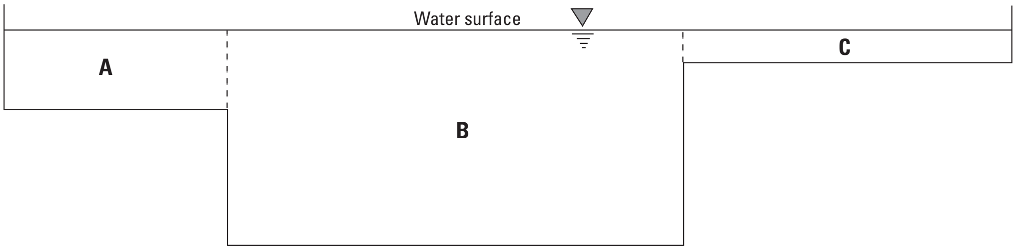
$$\bar{V}_{mb} = \frac{D_{up}}{T} = 0.025 \text{ meter per second}$$

Figure 2. Example of parameters used to compute the mean correction for data collected with an acoustic Doppler current profiler (ADCP) and displayed with conventional software.

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 using a simple compound channel. In figure 3, 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 cubic meters per second (m^3/s)); however, because of 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 meter per second (m/s), the ship track would show the ADCP moved upstream 34 meters (m) and the duration of the loop would have been 400 seconds (s). Applying equation 3 results in a mean moving-bed velocity of 0.085 m/s. The discharge missed because of the moving bed is computed from equation 2 as 45.9 m^3/s, which when added to the measured discharge (equation 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 percent less than the actual discharge. This 2-percent 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 and others, 2000). Callede and others (2000) do not specify how to determine the near-bed velocity. In addition, they applied the correction using a technique called the "flow method" in which the discharge was recomputed. In this report, a distributed correction method is proposed, which uses a 1/6th power curve to provide a consistent estimate of the near-bed velocity at each profile 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



Hydraulic properties	Subsections		
	A	B	C
Width (meter)	40	100	60
Depth (meter)	2	4	1
Actual velocity (meter per second)	1	2	0.5
Moving-bed velocity (meter per second)	0.05	0.15	0
Measured velocity (meter per second)	0.95	1.85	0.5

Figure 3. Example of a simple compound channel illustrating the effects of nonuniformly distributed moving-bed velocities and cross-sectional properties.

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, approximately the lower 6–10 percent of each velocity profile is unmeasured. In addition, bad velocity measurements are common in the lower parts of the profile. Therefore, simple use of the last valid velocity in each measured velocity profile would result in near-bed velocities at various distances from the streambed. The 1/6th 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 1/6th power law through zero at the bed and through the mean velocity of the last two valid velocity measurements in the profile. Velocity is a vector, so both the east and north components of the near-bed velocity must be determined.

$$V_{Enb_i} = \bar{v}_{Enb_i}\left(\frac{z_c}{\bar{z}_{nb_i}}\right)^{\frac{1}{6}} \tag{4}$$

and

$$V_{Nnb_i} = \bar{v}_{Nnb_i}\left(\frac{z_c}{\bar{z}_{nb_i}}\right)^{\frac{1}{6}}, \tag{5}$$

where

V_{Enb_i} is the east component of the computed near-bed velocity for each profile, i;

$\bar{v}_{Enb_i}$ is the east component of the mean velocity of the two velocity measurements nearest the streambed for each profile, i;

z_c is the distance above the bed of the computed near-bed velocity, arbitrarily assigned a value of 0.3 m;

$\bar{z}_{nb_i}$ is the mean distance from the streambed of the two velocity measurements nearest the streambed for each profile, i;

V_{Nnb_i} is the north component of the computed near-bed velocity for each profile, i;

$\bar{v}_{Nnb_i}$ is the north component of the mean velocity of the two velocity measurements nearest the streambed for each profile, i; and

i is the index for each measured velocity profile.

The amount of moving-bed correction applied to each profile is computed from the ratio of the near-bed velocity components and the mean moving-bed velocity. 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. The use of a complex equation, however, would require additional data (such as bed material information) that are not practical to collect during every discharge measurement; therefore, the simplified linear approach shown in equations 6 and 7 was applied.

$$V_{mbE_i} = \bar{V}_{mb}\left(\frac{V_{Enb_i}}{\bar{V}_{nb}}\right) \tag{6}$$

and

$$V_{mbN_i} = \bar{V}_{mb}\left(\frac{V_{Nnb_i}}{\bar{V}_{nb}}\right), \tag{7}$$

where

$\bar{V}_{nb}$ is the mean near-bed velocity defined as

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

and n is the number of velocity profiles.

Equations 6 and 7 convert the mean moving-bed speed 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 as the cross product of the water velocity and boat velocity.

$$Q_m = \sum_{i=1}^{n} \sum_{j=1}^{m} (V_{E_{i,j}} V_{BN_i} - V_{N_{i,j}} V_{BE_i}) bt_i , \tag{9}$$

where

j is an index for bins containing a velocity measurement;

m is the maximum number of bins in each profile, i;

$V_{E_{i,j}}$ is the east component of the water velocity in velocity profile i, bin j;

V_{BN_i} is the north component of the boat velocity in velocity profile i;

$V_{N_{i,j}}$ is the north component of the water velocity in velocity profile i, bin j;

V_{BE_i} is the east component of the boat velocity in velocity profile i;

b is the bin size; and

t_i is the 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.

$$V^C_{E_{i,j}} = V_{E_{i,j}} + V_{mbE_i} \tag{10}$$

$$V^C_{N_{i,j}} = V_{N_{i,j}} + V_{mbN_i} \tag{11}$$

$$V^C_{BE_{i,j}} = V_{BE_{i,j}} + V_{mbE_i} \tag{12}$$

$$V^C_{BN_{i,j}} = V_{BN_{i,j}} + V_{mbN_i} \tag{13}$$

$$Q_{mc} = \sum_{i=1}^{n} \sum_{j=1}^{m} \left(V^C_{E_{i,j}} V^C_{BN_i} - V^C_{N_{i,j}} V^C_{BE_i} \right) bt_i \tag{14}$$

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.

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

The computations associated with the distributed correction are best performed using a computer program. A program, LC, has been developed in the Matlab programming environment (MathWorks, 2005) that performs these computations. LC reads ASCII files that are readily output by standard vendor-supplied ADCP software, which allows all the utilities of the data collection and processing software to be used to validate the measured discharge before applying any corrections. The LC program prompts the user for the ASCII output filename that contains the loop data and computes the magnitude and direction of the distance made good from the starting and ending points of the loop. If the direction of the distance made good is +/– 45 degrees from the upstream direction and the magnitude is greater than the USGS standard thresholds for a moving-bed correction, then a correction is recommended. The program then (1) reads and processes all transects specified by the user and applies the method described herein to each transect, and (2) computes a corrected discharge for each transect and the corrected mean discharge for the whole measurement.

The distributed correction can be demonstrated using the previous example shown in figure 3. The boat velocity from bottom track is assumed to be 1 m/s in the east (cross-channel direction) and equal to the moving-bed speed in the south direction. If the mean velocity for each subsection is assumed to occur at 0.6 of the total depth, the 1/6 power law can be applied to compute the near-bed velocities at 0.3 m from the bed. Making these assumptions and working through equations presented previously yields a corrected discharge of 908.1 m^3/s, an error of 0.2 percent from the actual discharge. In this example, the distributed correction improved the corrected discharge 1.8 percent from the mean 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. A step by step guide to applying the loop method is provided in the Appendix.

Assessment of Errors and Uncertainty

The loop method is valid only if the moving bed is the dominant cause of the loop-closure error. The following are common sources of errors associated with the loop method and are addressed in detail:

- systematic compass errors;
- bottom-tracking bias and 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 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 in widely varying conditions.

Systematic Compass Errors

The most common mistake made in applying the loop method is to ignore the effect of the 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. 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 typically is 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 Rio Grande and RiverSurveyor ADCPs have a built-in compass calibration routine.

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):

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

where,

ε is the compass error,

θ is the compass heading,

A is the coefficient that accounts for compass alignment,

B is the coefficient that accounts for the fore-aft permanent magnetic field across the compass and a resultant asymmetrical vertical-induced effect,

C is the coefficient that accounts for the port-starboard permanent magnetic field across the compass, and a resultant asymmetrical vertical-induced effect,

D is the coefficient that accounts for symmetrical arrangements of horizontal soft iron, and

E is the coefficient that accounts for asymmetrical arrangements of horizontal soft iron.

An example of a hypothetical compass error curve based on equation 1 is shown in figure 4.

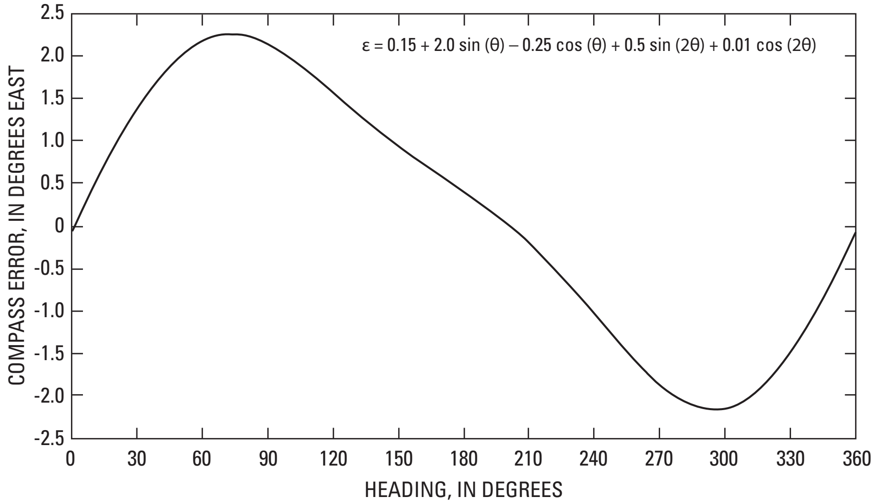


Figure 4. Hypothetical compass error curve.

The effect of compass error on the loop method can be illustrated by again using the example illustrated in figure 3. In this example, flow is assumed to be to the north, so that the loop is made by an east-west transect as shown in figure 5 (the compass error is described in figure 4). For this situation, the closure error caused by the compass would be 14 m in the upstream direction. Thus, rather than measuring a moving-bed velocity of 0.085 m/s using the mean loop correction method, a moving-bed velocity of 0.120 m/s would be measured, an error of 41 percent. This 41-percent error in moving-bed velocity translates to a 2-percent difference in the final corrected discharge.

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

Uncertainty Caused by Systematic Errors

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

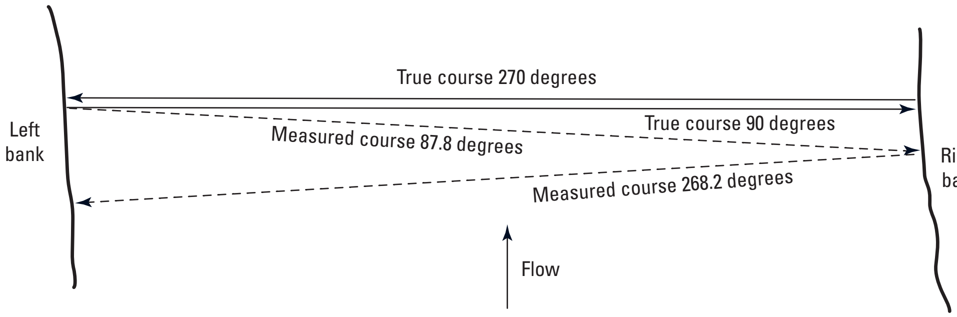


Figure 5. The difference between the true course traversed by the boat (solid line) and the measured course (dashed line) for straight-line, east-west transects with the compass error described in figure 4.

a moving bed. Systematic errors include, but are not limited to, failure to return the ADCP to the exact starting location, ADCP compass errors, and systematic bottom-tracking errors. Loop-closure errors measured where there is no moving bed provide an estimate of these systematic 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 from both the USGS and Environment Canada 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 assigned 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 the measurement time ranged from 0.0116 m/s in the downstream direction to 0.0074 m/s in the upstream direction. Since there was no moving bed at these sites, the measured mean moving-bed velocities were caused by systematic errors.

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, yielding a bootstrap distribution for the statistic (fig. 6). A summary of the bootstrap analysis is provided in table 2, where the bias, mean, standard error values, and confidence levels correspond to the standard deviation calculated from the resampled data. The observed standard deviation for all of the field 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-percent and 99-percent 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-percent confidence level, the bootstrap statistics indicate that the measured mean moving-bed velocity would have an uncertainty of 0.006 m/s because of systematic errors. Users applying the loop method should ensure that this uncertainty is reasonably small when compared to the mean water velocity for the discharge measurement.

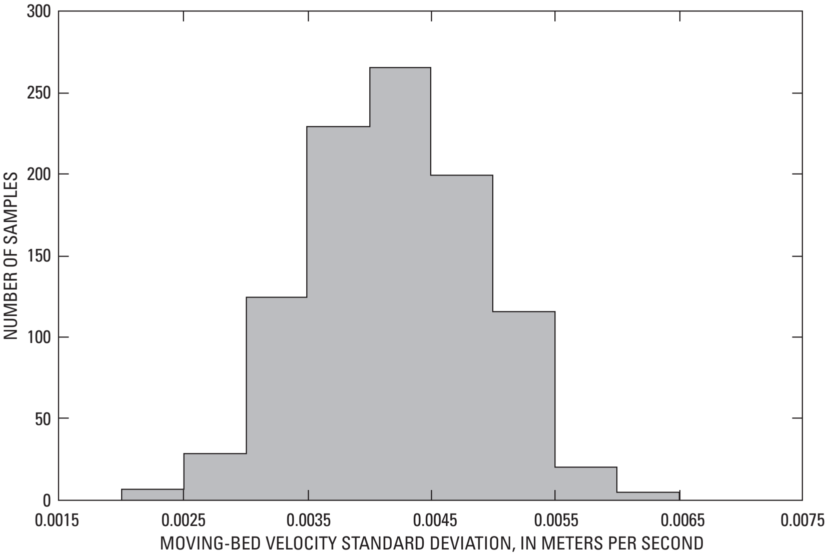


Figure 6. Standard deviations of the resampled moving-bed velocity data (collected in nonmoving bed environments) that were used in the bootstrap analysis.

Table 1. Summary of the field data used to evaluate the uncertainty in the loop method caused by systematic errors.

[m, meter; GPS, Global Positioning System; m/s, meter per second; %, percent; –, a closure error in an upstream direction; —, no data; <, less than]

Site name	Measurement time (seconds)	Stream width (m)	Loop closure error (m)	GPS distance made good (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	0.18	322	0.0038	0.82	0.5	0.4
Kentucky River at Lock 5, Kentucky	342	87.5	–1.48	–12.7	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	–0.94	283	–0.0048	0.94	–0.5	0.7
Kentucky River at Lock 8, Kentucky	192	63.4	2.23	1.86	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	–1.13	75	–0.0019	0.91	–0.2	0.3
Hay River near Hay River, Canada	232	81.4	1.30	–0.76	73	0.0056	0.98	0.6	0.3
St. Lawrence River at 1000 Islands, Canada	769	269.1	1.92	1.25	120	0.0025	0.41	0.6	0.2
St. Lawrence River at 1000 Islands, Canada	818	271.3	3.57	1.74	120	0.0044	0.41	1.1	0.2
St. Lawrence River at 1000 Islands, Canada	783	271.6	–4.57	–1.25	121	–0.0058	0.42	–1.4	0.2
St. Lawrence River near 1000 Islands, Canada	359	134.1	–1.74	–2.80	163	–0.0048	0.42	–1.2	0.2
Pee Dee River at Rockingham, North Carolina	421	110.3	–1.14	–0.37	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	–1.10	292	–0.0006	0.48	–0.1	Method 1[a]
Kissimmee River, Florida (site KQ001)	871	37.8	–0.34	–1.34	292	–0.0004	0.47	–0.1	Method 1[a]
Kissimmee River, Florida (site KQ011)	744	30.2	–1.43	–0.43	44	–0.0019	0.59	–0.3	Method 1[a]
Kissimmee River, Florida (site KQ011)	663	29.9	–1.04	1.19	44	–0.0016	0.58	–0.3	Method 1[a]
Kissimmee River, Florida (site KQ013)	484	21.3	–0.55	–0.73	261	–0.0011	0.65	–0.2	Method 1[a]
Kissimmee River, Florida (site KQ013)	500	21.3	0.27	0.37	261	0.0005	0.63	0.1	Method 1[a]
Androscoggin River near Gorham, New Hampshire	784	35.1	0.43	—	225	0.0006	0.52	0.1	0.3

[a] A compass calibration technique that requires manual input of One Cycle K and One Cycle Offset values, which are computed using Course Made Good, Distance Made Good, and Length values from the Navigation Tabular summary in WinRiver recorded after driving the ADCP in a large (greater than 1,000 meters) circle or 3 to 5 smaller circles, being sure to pass within 30 centimeters of the starting point for each circle. No total compass error is provided for this method.

Table 2. Results of the bootstrap statistical analysis on the standard deviation of systematic loop-closure errors measured in the field.

[m/s, meter per second; %, percent]

Observed data standard deviation (m/s)	Bootstrap statistical results				
	Mean standard deviation (m/s)	Bias	Standard error (m/s)	95% confidence level (m/s)	99% confidence level (m/s)
0.0043	0.0042	–0.00013	0.00066	0.0057	0.0060

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. Therefore, 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.

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.

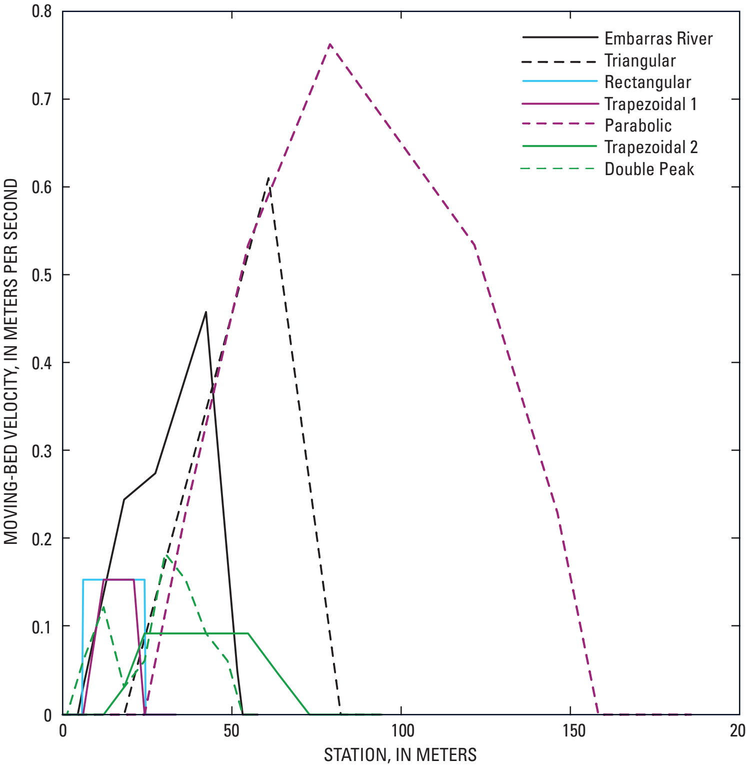


Figure 7. Moving-bed velocity, spatial distributions used to assess the importance of boat speed and variability on the measured mean moving-bed velocity.

The seven spatial distributions of moving bed velocity include an actual distribution from the Embarras River in Illinois and various distributions based on rectangular, trapezoidal, parabolic, and double peak shapes (fig. 7). The distributions were constructed to different widths to aid in simulating stream width.

A theoretical simulation of different uniform boat speeds shows little effect of boat speed on the measured mean moving-bed velocity (fig. 8). The response of the rectangular distribution is somewhat erratic because of the near instantaneous changes in moving-bed velocity, which may not be representative of stream conditions; however, the maximum error is still less than 1.5 percent. The more important effect of boat speed is its influence on 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 systematic errors, such as failure to return to the exact starting location and compass error caused by acceleration and deceleration of the boat. On the basis of the field data and uncertainty analysis presented herein, the recommended maximum boat speed should be the lesser of a boat speed that requires no less than 3 minutes to complete the loop or a boat speed that is less than 1.5 times the mean water speed.

Nonuniformity of boat speed during the loop will result in the moving bed in parts 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, data from 59 loop tests conducted at 39 different sites by different boat operators were used with the seven defined moving-bed velocity distributions to assess the effect of nonuniform boat speed on the measured mean moving-bed velocity. Each of the 59 loop tests was scaled to the seven moving-bed distributions, and a measured mean moving-bed velocity and each moving-bed distribution was computed. After evaluating several different measures of nonuniformity or variability, the most useful method for characterizing the nonuniformity of boat speed was to divide the cross section into 10 uniformly distributed subsections, determine the number of bottom-track observations in each subsection, and compute the coefficient of variation in the number of observations per subsection. 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

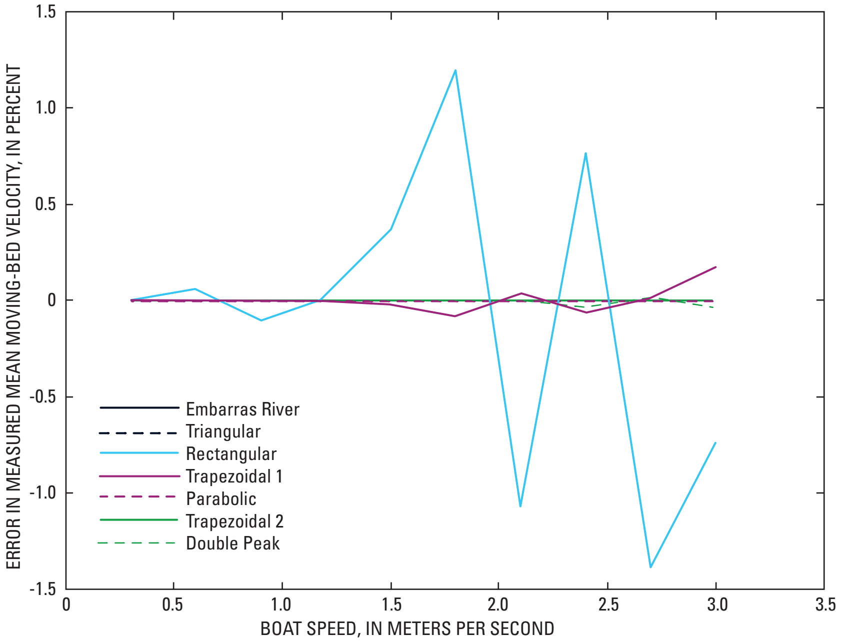


Figure 8. Error in measured mean moving-bed velocity as a function of uniform boat speed.

speed increases (fig. 9). Although the magnitude of these errors appears large, they are errors in moving-bed velocity and not measured discharge. A 20-percent error in measured mean moving-bed velocity for a moving-bed velocity that is 5 percent of the mean water velocity would result in an error in discharge of only 1 percent.

One of the obstacles to maintaining a good spatial average of the moving bed is the time spent near the banks getting started, reversing direction, and returning to the original starting position. Assuming there is little or no moving bed near the banks where flow typically is shallow and slow, any additional time spent in these areas increases the number of samples of no moving bed and will result in the measured moving-bed velocity being biased low. This is the primary reason why most errors shown in figure 9 are negative (fig. 10). The magnitude of this error can be assessed analytically. The total time required to complete the loop (T) is the sum of the time spent traversing the stream (T_L) and the additional time spent near the banks maneuvering the boat (T_B), and is shown as

$$T = T_L + T_B. \tag{17}$$

Equation 3 can be written for the true moving-bed velocity ($\bar{V}^{T}_{mb}$) and the measured moving-bed velocity affected by extra time spent at the banks ($\bar{V}^{M}_{mb}$) as

$$\bar{V}^{T}_{mb} = \frac{D_{up}}{T_L} \tag{18}$$

and

$$\bar{V}^{M}_{mb} = \frac{D_{up}}{T}. \tag{19}$$

Applying equations 18 and 19 to equations 1 and 2 results in equations for the true corrected discharge (Q^{T}_{TC}) and one for the corrected discharge affected by extra time spent near the banks (Q^{M}_{TC}).

$$Q^{T}_{TC} = Q_{TM} + \frac{D_{up}}{T_L}A \tag{20}$$

$$Q^{M}_{TC} = Q_{TM} + \frac{D_{up}}{T}A \tag{21}$$

The percent error in discharge associated with extra time spent near the banks (δ) can be computed from

$$\delta = \left(\frac{Q^{M}_{TC} - Q^{T}_{TC}}{Q^{T}_{TC}}\right)100. \tag{22}$$

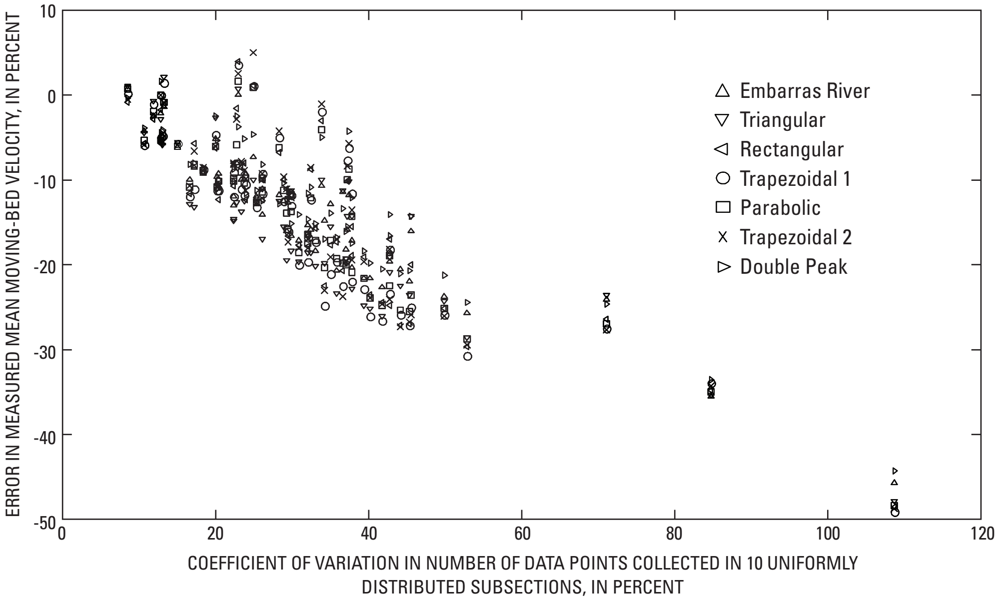


Figure 9. Error in measured mean moving-bed velocity as a function of nonuniformity in boat speed measured as the coefficient of variation in the number of data points collected in 10 uniformly distributed subsections of the cross section.

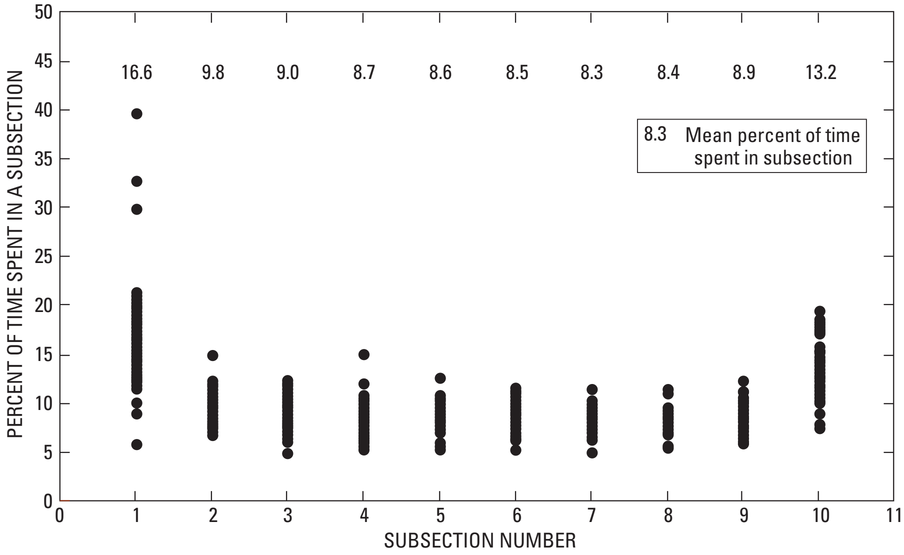


Figure 10. Percentage of time spent in each of the 10 subsections.

Solving equations 17–22 yields

$$\delta = \left(\frac{-\frac{T_B}{T}}{\frac{\bar{V}_{TM}}{\bar{V}^{T}_{mb}} + 1} \right) 100 , \qquad (23)$$

where

$$\bar{V}_{TM} = \frac{Q_{TM}}{A} . \qquad (24)$$

The error caused by spending extra time near the banks is always negative and is dependent on the ratio of the time spent near the banks to the total time for the loop and the ratio of the mean water velocity and the true moving-bed velocity (fig. 11).

Uncertainty in the Loop Method as a Moving-Bed Test

In order to determine if a site has a moving streambed, hydrographers typically conduct a stationary moving-bed test in which the ADCP is held stationary for 10 minutes to determine the magnitude of apparent upstream movement detected by bottom tracking. Stationary moving-bed tests, assuming the ADCP can be held stationary, are a good measure as to the magnitude of an apparent moving streambed; however, these tests represent only one location in the cross section, are time consuming, and do not provide a direct means of correcting biased discharge. An alternative to the stationary moving-bed test is to use the loop method.

In order to evaluate the validity of using the loop method as a moving-bed test, the field data and approach used in the systematic errors analysis will be revisited. Recall from the bootstrap analysis that the uncertainty of the measured mean moving-bed velocity was +/– 0.006 m/s at a 99-percent confidence level; therefore, the moving-bed bias measured on channels with a mean velocity greater than 0.6 m/s has an uncertainty of less than +/– 1.0 percent. For mean channel velocities between 0.3 m/s and 0.6 m/s, the uncertainty in the moving-bed bias is less than +/– 2.0 percent. In order to minimize the potential error in the measured moving-bed bias when using the loop method as a moving-bed test, the hydrographer should utilize the following thresholds in determining and applying a correction for an apparent moving streambed: (1) a moving-bed bias greater than 1 percent of the arithmetic mean of all water velocities should be used for channels with a mean velocity greater than or equal to 0.6 m/s, and (2) a moving-bed bias greater than 2 percent of the arithmetic mean of all water velocities should be used for channels with a mean velocity less than 0.6 m/s and greater than or equal to 0.3 m/s. Therefore, assuming that the other presented recommendations concerning calibrating the internal compass, boat speed/

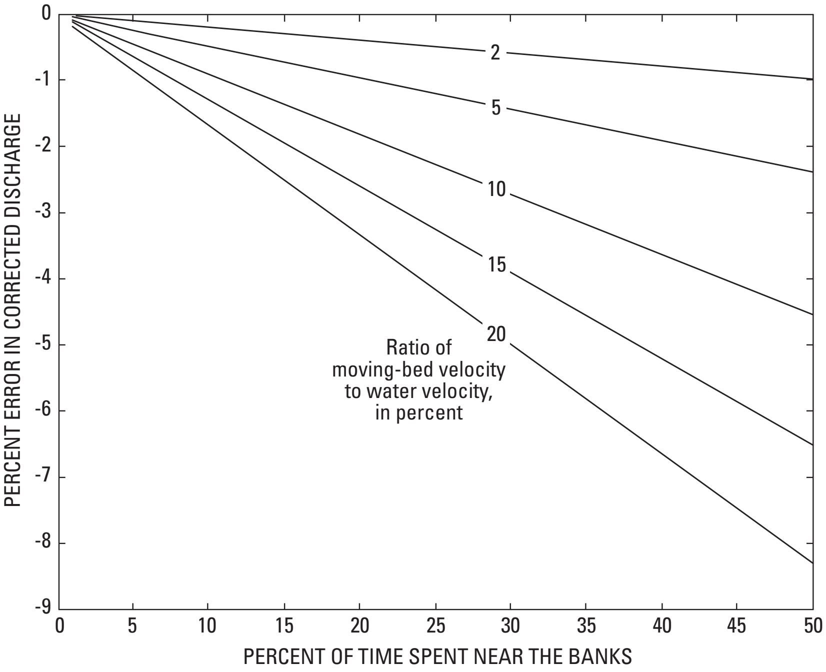


Figure 11. Relation between extra time spent near banks and the resulting error in corrected discharge.

uniformity, and time at the banks are followed, the loop method is an acceptable way to test for a moving streambed in channels with mean velocities greater than 0.3 m/s.

Application to Field Discharge Measurements

The evaluation of the loop-method applicability ultimately requires analyzing field data that represent a wide range of hydraulic conditions and river characteristics. The USGS 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 (mean and distributed) to DGPS-based discharges for sites with moving beds and analyzing the effects of systematic 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, the LC 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 3 for 13 field sites affected by a moving-bed bias greater than 1 percent of the arithmetic mean of all water velocities. The maximum difference between the two correction methods is less than 0.4 percent for all but one observation. All 13 measurement sites included in the comparison had relatively uniform rectangular or trapezoidal channel cross sections; therefore, the minimal variance displayed between the mean and distributed correction methods in table 3 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 correction 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 correction methods and compared to discharges measured using the DGPS (table 3). The comparison shown in table 3 reveals that for the nine sites, discharge corrected using the mean

Table 3. Comparison of discharge collected with differentially corrected Global Positioning System (DGPS) and adjusted by mean and distributed loop method corrections at sites affected by a moving-bed bias greater than 1 percent of the arithmetic mean of all water velocities.

[m^3/s, cubic meter per second; GPS, Global Positioning System; —, no data]

Site name	DGPS discharge (m^3/s)	Mean corrected discharge (m^3/s)	Distributed corrected discharge (m^3/s)	GPS quality
Flat River near the mouth, Canada	313	317	316	Good
South Nahanni River above Virginia Falls, Canada	890	891	893	Excellent
Rocky River near Stanfield, North Carolina	486	462	460	Fair
Yadkin River near Yadkin College, North Carolina	698	697	696	Good
Moose River above Moose River, Canada	1,865	1,868	1,874	Poor
Missouri River at Nebraska City, Nebraska	1,123	1,093	1,096	Good
Missouri River at Nebraska City, Nebraska	866	863	863	Good
Missouri River at Decatur, Nebraska	777	776	777	Fair
Missouri River at Hermman, Missouri	1,101	1,103	1,102	Good
Battle River near the Saskatchewan Boundary, Canada	—	64	66	—
Beaver River below Matson Creek, Canada	—	286	285	—
Porcupine River near International Boundary, Canada	—	1,743	1,740	—
Moose River above Moose River, Canada	—	2,849	2,853	—

loop method is within –5.0 percent and 1.3 percent (standard deviation = 1.93 percent) of the discharge measured using a DGPS as the bottom reference. Discharge corrected using the distributed loop-method correction is within –5.4 percent and 0.96 percent (standard deviation = 1.98 percent) 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 errors, limited satellite reception, and changes in visible satellites can affect the quality of the measured discharge. Table 3 provides an assessment of the DGPS signal quality to provide a level of reliability for the DGPS-referenced discharge data. The quality of the DGPS signal in table 3 was established using the WinRiver (version 10.06) GPS Tabular summary in the following manner (see RD Instruments, 2003, for explanation of GPS Tabular quality indicators):

- Excellent – no GPS parameter was shaded in red;
- Good – one GPS parameter was shaded in red, but no velocity spikes or losses can be attributed to GPS signal problem;
- Fair – multiple GPS parameters were shaded red, but no major velocity spikes or losses are attributed to GPS signal problem; and
- Poor – multiple GPS parameters were shaded red and major velocity spikes and(or) losses correspond to GPS signal problems.

The DGPS signal quality indicated in table 3 represents the worse-case scenario for the individual transects that comprise each of the discharge measurements.

Effect of Systematic Errors on Discharge

The analysis of systematic errors, presented herein, was based on data collected where there was no moving bed. The systematic errors, however, characterized by that analysis 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 0.02 m/s (the bias is 1.3 percent of the water velocity, which is greater than 1 percent, thereby warranting a correction to total discharge). According to the uncertainty analysis, systematic errors of 0.006 m/s at the 99-percent 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 percent of the mean water velocity. The resulting mean correction to discharge would thus range from 0 to 1.7 percent. Applying the uncertainty of the measured mean moving-bed velocity (0.006 m/s) to the 13 field data sets having a moving-bed bias greater that 1 percent of the arithmetic mean of all water velocities results in an uncertainty in final discharge of less than +/– 1.0 percent (table 4).

Summary

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. The uncertainty associated with systematic errors is approximately 0.006 m/s at the 99-percent 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 parts 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. 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 because of the uniformity of the cross sections and flow distributions represented in the data. Both methods provided discharges that were within 5 percent 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.

Table 4. Summary of the effects of systematic errors in the loop method for sites affected by a moving-bed bias greater than 1 percent of the arithmetic mean of all water velocities.

[m/s, meter per second; %, percent]

Site name	Measured mean moving-bed velocity (m/s)	Bed velocity / Water velocity (%)	Measured mean bed velocity – Systematic error (m/s)	Bed velocity / Water velocity (%)	Error in final discharge (%)	Measured mean bed velocity + Systematic error (m/s)	Bed velocity / Water velocity (%)	Error in final discharge (%)
Flat River near the mouth, Canada	0.037	2.23	0.031	1.86	–0.37	0.043	2.60	0.37
South Nahanni River above Virginia Falls, Canada	0.053	5.00	0.046	4.43	–0.58	0.059	5.58	0.58
Moose River above Moose River, Canada	0.052	4.73	0.046	4.18	–0.55	0.058	5.28	0.55
Battle River near the Saskatchewan Boundary, Canada	0.103	16.4	0.097	15.4	–0.97	0.109	17.4	0.97
Beaver River below Matson Creek, Canada	0.028	1.76	0.022	1.38	–0.38	0.034	2.14	0.38
Porcupine River near International Boundary, Canada	0.081	4.56	0.075	4.22	–0.34	0.087	4.90	0.34
Moose River above Moose River, Canada	0.041	3.04	0.035	2.59	–0.45	0.047	3.49	0.45
Rocky River near Stanfield, North Carolina	0.051	2.14	0.045	1.89	–0.25	0.057	2.39	0.25
Yadkin River near Yadkin College, North Carolina	0.028	1.63	0.022	1.27	–0.35	0.034	1.98	0.35
Missouri River at Nebraska City, Nebraska	0.074	6.24	0.068	5.73	–0.51	0.080	6.75	0.51
Missouri River at Nebraska City, Nebraska	0.060	5.24	0.054	4.72	–0.53	0.066	5.77	0.53
Missouri River at Decatur, Nebraska	0.047	4.54	0.041	3.96	–0.58	0.053	5.12	0.58
Missouri River at Hermman, Missouri	0.075	2.22	0.069	2.04	–0.18	0.081	2.40	0.18

References Cited

Callede, Jacques, Kosuth, Pascal, Guyot, J.L., and Guimarães, V.S., 2000, Discharge determination by acoustic Doppler current profilers (ADCP)—A moving bottom error correction method and its application on the River Amazon at Óbidos: Hydrological Sciences-Journal-des Sciences Hydrologiques, v. 45, no. 6, p. 911–924.

Chen, Cheng-Lung, 1989, Power law of flow resistance in open channels, Manning's formula revisited: Proceedings of the International Conference on Channel Flow and Catchment Runoff, Centennial of Manning's Formula and Kuichling's Rational Formula, May 22–26, 1989, Charlottesville, Virginia, v. 8, p. 17–48.

Davidson, A.C., and Hinkley, D.V., 1998, Bootstrap methods and their application: Cambridge, United Kingdom, Cambridge University Press, 556 p.

Mathworks, Inc., 2005, Matlab—The language of technical computing: Natick, MA, Mathworks, Inc., v. 7.1.

Mueller, D.S., 2002, Use of acoustic Doppler instruments for measuring discharge in streams with appreciable sediment transport, *in* Wahl, T.L., Pugh, C.A., Oberg, K.A., and Vermeyen, T.B., eds., Hydraulic measurements and experimental methods 2002, Proceedings of the Specialty Conference, American Society of Civil Engineers, July 28–August 1, 2002, Estes Park, CO.

National Geospatial-Intelligence Agency, 2004, Handbook of magnetic compass adjustment: Bethesda, MD, National Geospatial-Intelligence Agency, 45 p. (formerly publication no. 226, as originally published by Defense Mapping Agency, Hydrographic/Topographic Center, Washington, DC, 1980).

Oberg, K.A., and Mueller, D.S., 1994, Recent applications of acoustic Doppler current profilers, *in* Pugh, C.A., Fundamentals and advancements in hydraulic measurements and experimentation, Proceedings, American Society of Civil Engineers, August 1–5, 1994, Buffalo, NY, p. 341–350.

RD Instruments, 2003, WinRiver user's guide—USGS version: San Diego, CA, RD Instruments P/N 957-6096-00, 156 p.

Rennie, C.D., and Millar, R.G., 2002, Spatial distribution of bedload transport velocity using an acoustic Doppler current profiler *in* Wahl, T.L., Pugh, C.A., Oberg, K.A., and Vermeyen, T.B., eds., Hydraulic measurements and experimental methods 2002, Proceedings of the Specialty Conference, American Society of Civil Engineers, July 28–August 1, 2002, Estes Park, CO.

Simpson, M.R., and Oltmann, R.N., 1993, Discharge measurement using an acoustic Doppler current profiler: U.S. Geological Survey Water-Supply Paper 2395, 34 p.

Appendix — Step-by-Step Procedures for Using the Loop Method

Careful field procedures are absolutely critical to the successful application of the loop method. Failure to accurately return the instrument to the starting point, an uncalibrated or improperly calibrated compass, or loss of bottom track during the loop will result in unpredictable errors that render this technique unusable. Current research (which is limited by the amount of available field data) indicates that site-specific characteristics and data-collection techniques, such as the shape of the measurement section, distribution of the moving-bed velocity, time spent at the banks, boat speed, and uniformity of the boat speed, can affect the discharge correction by 10 percent or greater. When applied properly, however, this technique should consistently yield total corrected discharges that are within 5 percent of the actual discharge.

Field Procedures

1. **Calibrate the acoustic Doppler current profiler (ADCP) compass using internal calibration routines.** A compass calibration accuracy of better than 1 degree is desired. Calibrations with errors greater than 1 degree should be repeated. If after several attempts a calibration of less than 1 degree cannot be obtained, appropriate field notes should be recorded to document the problem. Compass errors greater than 1 degree result in increased errors in the loop-method correction.
2. **Establish a marked starting point where the ADCP can be returned to the exact location.** This point is not required to be as near to a bank as the end of a regular transect. For example, with a tethered boat it can be hard to control the boat at the edge because of conditions such as slack water, eddies, or vegetation; therefore, establishing a point farther out in the flow could make navigating the boat back to the starting point more practical. Use of a buoy or other fixed object is recommended.
3. **Make a steady pass back and forth across the stream as a standard discharge measurement, but do not stop recording at the far bank.** At the starting point make sure the boat is ready to begin the transect before beginning to record. **A uniform boat speed is important.** Do not spend extra time at the edges. Plan the loop so that a smooth change in boat direction can be achieved near the far bank. Too much time near the banks will result in a low bias.
4. **Maintain the proper boat speed.** The recommended maximum boat speed should be the lesser of a boat speed that requires no less than 3 minutes to complete the loop or a boat speed that is less than 1.5 times the mean water speed.
5. **Return to the starting point.** Return position accuracy is very important.

Processing for Moving-Bed Test

1. **Process the loop file to the end.** Record the Distance Made Good (DMG) and the time required to complete the loop. *Note*: The DMG in a moving-bed condition should be in the upstream direction (see figure 1 in main text). If the primary direction of the DMG is in a direction other than upstream, this distance may be the result of compass or bottom-track errors and no moving bed will be assumed.
2. **Compute the mean moving-bed velocity.**

$$\bar{V}_{mb} = \frac{D_{up}}{T},$$

where

$\bar{V}_{mb}$ is the mean velocity of the moving bed;

D_{up} is the Distance Made Good (DMG); and

T is the measurement time required to complete the loop.

3. **Compute the ratio of the mean moving-bed velocity to the mean water velocity.**
4. **Determine if the ratio exceeds the recommended criteria.** In order to minimize the potential error in the measured moving-bed bias when using the loop method as a moving-bed test, the hydrographer should utilize the following thresholds in determining and applying a correction for an apparent moving streambed.
    - For channels with a mean velocity greater than or equal to 0.6 m/s, a DGPS is required or a discharge correction should be applied if the moving-bed bias is greater than 1 percent of the mean flow speed.
    - For channels with a mean velocity less than 0.6 m/s and greater than or equal to 0.3 m/s, a DGPS is required or a discharge correction should be applied if the moving-bed bias is greater than 2 percent of the mean flow speed.

Processing for Discharge Correction

Two processing methods—the mean correction method and the distributed correction method—can be used to correct biased-measured discharge using the measured mean moving-bed velocity from the loop method. 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 and can be applied using the "LC.exe" computer program.

Mean Correction Method

1. **Process the loop file to the end.** Check for excessive bad bottom-track data and other problems that could reduce the accuracy of the loop. Record any observed problems.

2. **Record the DMG and the time required to complete the loop.** *Note:* The DMG in a moving-bed condition should be in the upstream direction (see figure 1 in main text). If the primary direction of the DMG is in a direction other than upstream, this distance may be the result of compass or bottom-track errors, and no moving bed will be assumed.

3. **Compute the mean moving-bed velocity.**

$$\bar{V}_{mb} = \frac{D_{up}}{T} ,$$

where

$\bar{V}_{mb}$ is the mean velocity of the moving bed,
D_{up} is the Distance Made Good (DMG), and
T is the measurement time required to complete the loop.

4. **Change area computation method to "Perpendicular to Mean Flow," if available.**

5. **Review and process the discharge measurement.** Use appropriate U.S. Geological Survey guidance and policies to determine the mean unadjusted discharge.

6. **Record the cross-sectional area.** The cross-sectional area should be the mean cross-sectional area for all transects used to determine the mean discharge.

7. **Compute the final discharge.**

$$Q_{TC} = Q_{TM} + \bar{V}_{mb} A ,$$

where

Q_{TC} is the discharge corrected for the moving-bed bias,
Q_{TM} is the measured discharge,
$\bar{V}_{mb}$ is the mean velocity of the moving bed, and
A is the cross-sectional area perpendicular to the mean flow direction.

Distributed Correction Method

The use of the distributed correction method requires that the program LC.exe and any necessary libraries be installed on the computer being used for processing. The program, installation files, and installation instructions can be found at *http://hydroacoustics.usgs.gov*.

1. **Review the loop file.** Check for excessive bad bottom-track data and other problems that could reduce the accuracy of the loop. Record any observed problems.

2. **Review and process the discharge measurement files.** Use appropriate U.S. Geological Survey guidance and policies to determine the mean unadjusted discharge.

3. **Generate RD instrument-compatible ASCII output files for the loop and discharge measurement files.**

4. **Start the LC.exe computer program.** *Note:* It may take a long time for the program to initialize.

5. **Process the loop file with LC.** Click on the "Select Loop File" button, and browse for the ASCII output of the loop measurement. The program will process the loop and determine if a correction is required. The "Select Measurement Files" button will become active. If no correction is required, proceed to step 7.

6. **If a correction is required, process the discharge measurement files with LC.** Click on the "Select Measurement Files" button. Select the ASCII output for all discharge measurement files using Control and Shift click to select multiple files (standard Windows multiple file collection procedures). The program will distribute the moving-bed correction to all ensembles and provide both an unadjusted and adjusted final discharge.

7. **Save, print, and file the results.** Click on the "Save Results" button to save the results to a text file. Print the text file and attach the printout to the hard-copy field notes. Place the text file in the corresponding directory with the rest of the measurement files for archive.

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