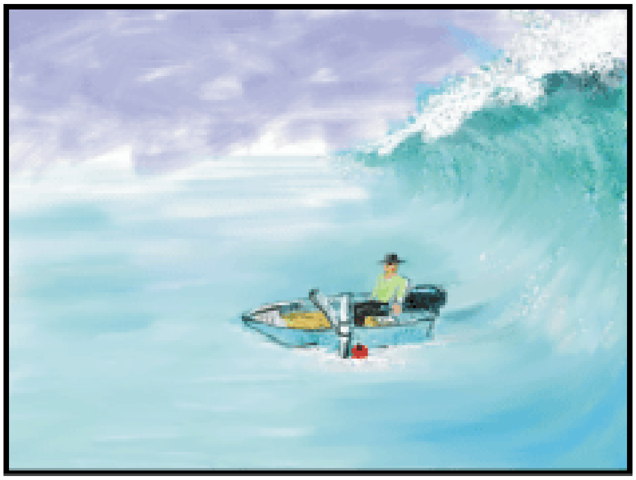

Figure 7.1. Improper discharge-measurement technique.

Figure 7.2. Discharge-measurement cross section on Dutch Slough near Oakely, California.

CHAPTER 7: DISCHARGE-MEASUREMENT PROCEDURE

In this chapter we will discuss procedures for making discharge measurements (fig. 1) utilizing the ADCP and the Transect software. The following topics will be discussed in detail:

- Cross-section reconnaissance
- Premeasurement checkout
- Boat-maneuvering techniques
- Transect software tips and tricks during the discharge measurement
- Alternate discharge-measurement techniques for low-flow conditions
- What constitutes a “good” discharge measurement
- Recent Transect software enhancements

Cross-Section Reconnaissance

Figure 7.2 shows a 91-m- (300-ft-) wide stream with tidally affected flows having a roughly trapezoidal cross section with average depths of 4.5–6 m (15–20 ft). This cross section on Dutch Slough near Oakley, California, is typical of rivers in the northern California Sacramento/San Joaquin River Delta. Proper cross-section reconnaissance is vital to the precision and accuracy of ADCP discharge measurements. The measurement vessel depth sounder or the ADCP depth-range measurements are useful tools in determining the usability of the cross section for ADCP discharge measurements.

In general, the ADCP operator should look for a cross section with a roughly parabolic, trapezoidal, or rectangular shape, having an average depth of at least 1.5 m (5 ft). The measurement sometimes can be made at locations having less depth, if water modes 5 or 8 are employed (chap. 3).

Cross sections with asymmetrical bottom topographies should be avoided, if possible. For example, the operator should avoid a measurement cross section that is very shallow on one side and deep on the other.

Average water velocity also is an important factor in choosing a measurement cross section. Cross sections exhibiting slow [less than 10 cm/s (0.30 ft/s)] average velocities should be avoided. Although measurements can be made under these conditions, special techniques must be employed (discussed later in this chapter).

Premeasurement Checkout

After the boat is launched and the ADCP equipment is set up, care should be taken to obtain an accurate transducer depth measurement.

If a side-swing mount is used, the weight of the operator(s) can cause an unwanted pitch of the ADCP vessel (fig. 7.3). This pitch angle may cause an erroneous reading of the ADCP depth. For example, when the operator moves to the side of the vessel to measure transducer depth, the vessel pitches to that side because of the operator’s shifted weight. The operator notes the depth of the ADCP below water surface, and then returns to his normal position in the vessel causing the vessels pitch to return to the original value. This

Figure 7.3. Broad-band acoustic Doppler current profiler mount being deployed vertically.

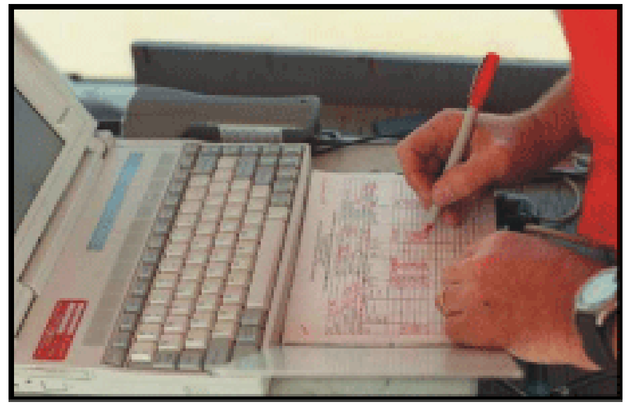

Figure 7.4. Discharge-measurement log sheet/note.

recorded depth measurement will be incorrect. Because the transducer depth measurement is used in the Transect software to compute discharge, the error in ADCP depth sometimes can cause a significant bias of the ADCP discharge measurement. This is true especially for wide, shallow rivers.

Before the discharge measurement begins, the operator should note any conditions relevant to the discharge measurement on the discharge-measurement log sheet (fig. 7.4). Wind, bidirectional flow, eddies, standing waves, passing boats, and sediment conditions are just some of the things that should be noted for later analysis of the discharge measurements.

Before a discharge measurement begins, the operator should complete the following tasks:

- Meet all DOI boat-safety requirements and make sure all required life jackets, throwable devices, fire extinguishers, and horns are in good working condition aboard the ADCP vessel.
- Determine the "unpitched" transducer depth and enter it on the log sheet and in the configuration file.
- Perform a PT200 diagnostic test using BB-TALK or other terminal emulator software. Save the test results to an ASCII file placed in the deployment directory.
- Synchronize the computer, ADCP, and operator watch times.
- Perform a short reconnaissance of the cross section to determine shallow areas and the shape of the cross section so that unmeasured areas near the bank can be characterized. If the cross section is unsuitable for any reason (too shallow in places, for example), select another measurement cross section.
- If buoys are used to aid the estimation of edge distances, they should be deployed and the distance to shore from each buoy should be measured and noted on the discharge-measurement log sheet.
- If range finders are used to determine edge distances, they should be checked for proper calibration.
- Record weather, hydrological, and other physical phenomena pertinent to the discharge measurement on the discharge-measurement note.
- Make sure that the right configuration file has been loaded properly into the Transect software.
- Make sure that the power supply has been turned on and the ADCP has been "awoken."

Boat-Maneuvering Techniques

Boat-maneuvering techniques for discharge measurements when using the ADCP and the Transect software do not require the precision once needed for conventional moving-boat discharge measurements. However, there are some basic maneuvers that improve accuracy and allow smooth transitions between measurements.

Starting the Cross-Section Traverse

For a typical measurement, the operator must maneuver the boat close to, and parallel with, the riverbank (fig. 7.5). The boat should be maneuvered in as close as possible to the bank without grounding (bottoming out) the boat motor propeller or the

Figure 7.5. Acoustic Doppler current profiler vessel at the beginning of a discharge measurement.

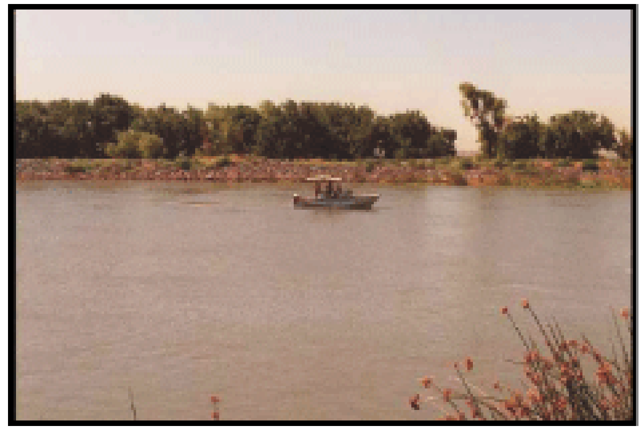

Figure 7.6. Acoustic Doppler current profiler vessel near center channel.

BB-ADCP transducer assembly. Performing this maneuver takes practice.

While the boat is somewhat stationary, the operator should start the Transect software and set the Acquire display to tabular velocity mode (initial setting). The tabular mode setting is optional as the Transect software will collect data in any display mode. However, the tabular mode enables the operator to determine if there is an adequate number of depth cells (having good discharge) before starting the measurement traverse. This capability provides the greatest advantage over the other display modes, especially when starting and ending the discharge measurement.

At this point, the operator is beginning the discharge measurement and must accomplish several tasks quickly:

- The distance to shore must be estimated by some means and recorded.
- The operator must turn the ADCP data recording off by pressing the F5 key and must start the ADCP pinging by pressing the F4 key.
- While looking at the tabular display, the operator must verify that the ADCP is collecting at least two good bins of velocity data.
- When the operator is satisfied that accurate data are being collected and the boat is in the correct position to start the discharge measurement, he must press the F5 key to begin recording and wait until two good ensembles have been collected. During this period (about 5 s), the boat should be barely moving toward center channel.

During the Cross-Section Traverse (Transect Tips and Tricks)

When the Transect software begins collecting data, the operator should verify that there is an “ADCP PINGING” message near the upper right of the monitor display and that a transect recording file is opened (file name visible at the lower right of the Transect software screen). At this time the boat should have just begun traversing the river cross section. The operator must quickly scan the initial ensemble display to determine if everything is operating correctly. Signs of improper operation are flagged “bad” in all columns and rows or “bad” in all rows of an individual column. The display columns correspond to north velocity, east velocity, vertical velocity, error velocity, and percent good. If the incoming data appear correct, the operator should continue the transect with the same course and a slightly increased speed (approximately that of the water or slightly less). As the boat enters faster flow, engine revolutions per minute (rpm) and boat heading may have to be adjusted slightly to enable a smooth traverse (fig. 7.6).

Uniform boat speed during a transect is more important than steering a straight course. The course may be allowed to change slightly and slowly, if necessary, during the traverse. However, rapid course and boat heading changes can introduce errors into the measurement. The key element here is to DO EVERYTHING SLOWLY, including course changes, the speed of the vessel itself, and even the speed of persons moving around onboard the measurement vessel. Sharp accelerations of the measurement vessel in any direction should be minimized or eliminated.

Ending the Cross-Section Traverse

As the vessel approaches the opposite edge of the measuring section, the boat should be slowed by slowly changing the heading to a more upstream direction and slowing the boat motor. The boat then can creep (crab) toward the bank. When the operator decides that the approach cannot be continued further, an edge value is determined, and the F5 key is pressed to end the transect.

At the end of a cross-section traverse (fig. 7.7), the boat heading is changed just enough so that the boat stops its bankward movement and begins to slowly creep in the direction of center channel. At this point, the operator may press the F5 key again to begin another transect and obtain a starting distance value. Slow “crabbing” at the start and finish of each cross section works better than nosing the boat into the bank and then backing away. The ADCP should not be allowed to pass over the boat propeller vortex during the discharge measurement. Entrained air in the vortex will cause failure of the BB-ADCP bottom track and result in lost ensembles.

The operator should practice the above described technique a few times before an actual transect session is begun so that you (and the boat operator) can become accustomed to the flow conditions at this location. The more practice you have in making these measurements, the more uniform will be the measurement results. When maneuvering near the riverbank, you must remember that making a large heading adjustment away from the bank (swinging the bow away from the bank) will bring the stern (and, therefore, the engine prop and shaft) into contact with the bank or bottom. This maneuver can produce highly undesirable results. The boat will crab slowly away from the bank with only minor adjustments needed in the boat steering.

Figure 7.7. Acoustic Doppler current profiler vessel at the end of a cross-section traverse.

Alternate Techniques Used During Low-Flow Conditions

The above described technique works only when there is sufficient stream velocity to allow the boat to crab. At very low stream velocities [less than 10 cm/s (0.33 ft/s)], the boat must be turned VERY SLOWLY to enable a direct crossing of the stream. In some cases, the best approach is to raise the engine and pull the boat slowly (at the stream velocity or less) across the stream with ropes or a tag-line (fig. 7.8).

The winching system shown in figure 7.8 was used to measure leakage through control structures in the USGS Illinois District (Oberg and Schmidt, 1994). Because the velocities measured were very slow

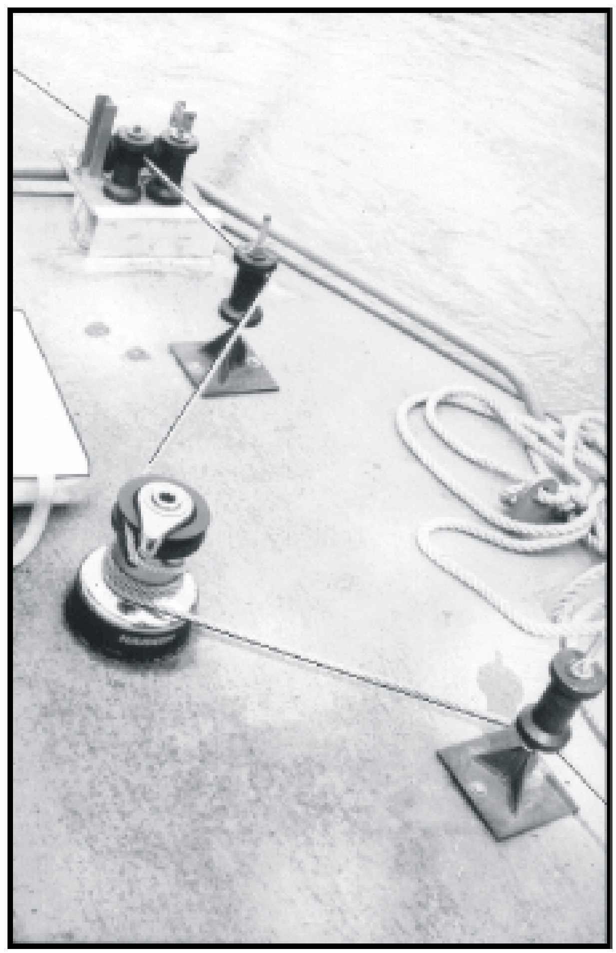

Figure 7.8. Winching system used to move an acoustic Doppler current profiler vessel at slow speeds.

[around 10 cm/s (0.3 ft/s)], the ADCP was winched slowly across the control structure opening to reduce the random error in the discharge measurement (chap. 9).

To gain reasonably accurate measurements in very slow moving water, special setup commands must be used to increase the measurement pulse lag times (chap. 5). The use of these long lag times causes the ambiguity velocity to be very low. Therefore, the boat must be moved across the stream ever so slowly (as if rows of dominoes were balanced on the gunnels).

What Constitutes a "Good" Discharge Measurement?

The ADCP operator should consult Lipscomb (1995) for guidelines on discharge-measurement requirements and documentation procedures. However, because these instruments are relatively new and sometimes used for special purposes, common sense also will dictate the procedures in some cases. General procedures conforming to the quality-assurance plan are presented here, but the ADCP operator is cautioned to observe conditions and to document as much information as possible during the transect session. With the advent of electronic instruments used for data recording, valuable information can sometimes "fall through the cracks" and may not be missed until the ADCP operator reviews the data back at the office.

Because a BB-ADCP transect may be made much faster than a conventional discharge measurement, multiple transects usually are averaged to increase discharge-measurement accuracy. During fairly uniform conditions, a group of four or more transects usually are averaged for a final discharge-measurement value. If one transect differs significantly (±5 percent) from the rest, and there is no rationale to discard it, at least four additional transects should be obtained and the average recomputed. The average of these transects can be reported as an individual discharge measurement and logged on a USGS ADCP discharge-measurement note (fig. 7.9). The back of the USGS measurement note has space for 14 transects, their edge-value estimates, and other pertinent data (fig. 7.10).

In figure 7.10, the values labeled standard error (range) and standard error (percent) near the bottom of the note are critical for measurement results in steady-flow conditions. For fairly uniform flow conditions, at least four ADCP discharge measurements should be made to determine mean and standard-deviation values. From these data, the standard error, in percent of mean discharge, should be calculated. The standard error, in percent of mean discharge, also is known as the coefficient of variation (CV). The CV is calculated by dividing the standard deviation (in discharge units) of the four transect discharges by the mean discharge. If the CV is larger than 5 percent, additional measurements should be made. A large CV can be an indication that the ADCP ping rate is too slow, or that the boat should be slowed during the cross-section traverse to collect more pings. Outliers or single, bad, transects can cause a large CV, however, they should not be simply thrown out without an attempt to discover the reason for their imprecision. When in doubt, it is always advisable to collect additional transects.

For measurements of net flow in tidally affected estuaries and rivers, many discharge measurements may have to be made (more than can be logged on the example ADCP discharge-measurement form). Figure 7.11 shows a series of transects made at a tidally affected gaging station on a tributary of the San Joaquin River.

In these cases, a discharge-measurement log sheet (fig. 7.12) may be used with pertinent data logged on a discharge-measurement note (fig. 7.9) that is attached to the log sheet. This log sheet is used by the USGS California District. Standard-deviation calculations for tidally effected discharge measurements are meaningless unless the "true mean" discharge can be calculated. Because of the difficulty in calculating the coefficient of variation for tidally effected discharge (or any dynamically changing discharge), its inclusion on the discharge-measurement note example (fig. 7.9) is of questionable significance.

Where tides or discharge conditions are changing rapidly, the operator may not wish to average transects and, in these cases, a single transect constitutes a discharge measurement. In most cases, many measurements will be required to have as much coverage as possible of the dynamic flow time series. Single measurements should be logged on a BB-ADCP discharge-measurement note (fig. 7.9) and if many are made, they should be logged on a discharge-measurement log sheet (fig. 7.12) with an attached USGS discharge-measurement note. Again, standard-deviation calculations or coefficient of variation calculations, in these cases, are of questionable value.

Archival of Acoustic Doppler Current Profiler Discharge-Measurement Data

Transect software data files should be placed on archival media in the following form:

U.S. DEPARTMENT OF THE INTERIOR
Geological Survey
WATER RESOURCES DIVISION
ADCP DISCHARGE MEASUREMENT NOTES

Meas. No. 186
Comp. by MRS
Ck'd by RMM

Sta. No. 11-4670.50

Sacramento River near Sacramento

Date August 11, 1996 Party Simpson, Adorador, Posey
Index Vel 1.15 G.H. 9.23 Rt. Area tidal -- see back of sheet Disch. ____ Rt. vel ____
Firmware Ver 5.43 Transect Ver 2.80 Water mode 4 Bottom mode 5
ADCP S/N 296 X-ducer Freq. 1200 Boat/motor used Mercury 45
X-ducer depth 0.30m Blank Dist 0.50m Cell depth 0.25m ADCP set to watch yes
No. water pings 5 No. bottom pings 4 ADCP diag. test pt200 passed

GAGE READINGS						
Time		Inside	Outside			Vel
1230	s	9.20	9.19			1.11
	see back for meas					
1240		9.22				1.14
1250		9.24				1.15
1300		9.25				1.17
1310	f	9.26	9.25			1.20
Weighted Mean						
Correction						
Corrected Mean		9.23				1.15

EDL DATA
Downloaded before meas. ✓
File name f081196
DATA OK? Yes-good rcrd
EDL set for meas.:
Time 1220 Interval 10m
EDL reset
Time 1320 Interval 15m
EDL set to watch 1220

ADCP DATA
Config. fre5.cfg
Nav file n/a
Vel. file fre50xx.000

Check bar, chain found 23.34 changed to ____ at ____
Wading, cable, ice, boat, upstr., downstr., side bridge 100 feet, mile, above, below gage
Measurement rated excellent (2%), good (5%), fair (8%), poor (over 8%) based on the following
Flow Uniform except for eddy on right bank
Cross section roughly trapezoidal, shallow on RB side
Control channel/tidal reach -- no visible riffle or water level change
Weather cloudy/light rain Wind spd. 2 mph Direction NE
Stratification normal profile
Visual Vel 1.00 upstr, downstr.

Water Density Conditions

Time	Temp	Cond	Depth
1200	19c	100 mS	5m
1202	19.2	110ms	0m

Gage operating No Lost Record Battery voltage 13.5 Manometer Pressure Tank 1900
HWM Tidal seed line @ 10.22 ft outside in well
Remarks Eddy on RB causing a flow reversal from bank out to 20 feet or so.

Figure 7.9. Example of an acoustic Doppler current profiler (ADCP) discharge-measurement note (front).

Measurement						Computation									
	Beginning		Ending			Beginning		Ending		Discharge					
										Est.		Estimated			
Filename	Distance to Bank	Time	Time	Distance to Bank	Made good Discharge	Ensemble #	Distance added	Ensemble #	Distance added	Top	Measured Middle	Bottom	Begin side	End side	Total
fre5001r.000	22	L R 1246	1248 R L	15	41769										
fre5002r.000	16	L R 1250	1253 R L	25	42284										
fre5003r.000	24	L R 1255	1257 R L	14	42640										
fre5004r.000		L R	BAD R L												
fre5005r.000	16	L R 1302	1305 R L	16	43436										
		L R	R L												
		L R	R L												
		L R	R L												
		L R	R L												
		L R	R L												
		L R	R L												
		L R	R L												
		L R	R L												
		L R	R L												

Estimation method: Top POWER; Bottom POWER; St. Error (range) (TIDAL); St. Error (%) (TIDAL); Mean ____; Meas. % of total ____; Mean ____

Figure 7.10. Example of an acoustic Doppler current profiler discharge-measurement note (back).

- Site deployment directory name NNNN (where NNNN is the four-letter site designator)
- Set of transect raw data files

```
{NNNN001R.00
  |
  |
 \/
 NNNN0XXR.00
}
```

where XX is the last transect number in the series,

- Transect session *.CFG file NNNN.CFG
- Transect session documentation file NNNN.DOC

The operator must create an ASCII file, using a text editor, to be archived with each set of Transect data. This electronic NNNN.DOC file is needed to preserve Transect edge-value estimates and other site-specific information in the event that hard copies of log sheets are lost or misplaced. This DOC file must be drafted as soon as possible after the completion of the Transect session and stored in the Transect session directory. At a minimum, the file should contain the following information:

- Site location
- Date, start time, and end time
- Names of measurement staff
- Description of measurement vessel and equipment
- Transducer depth (depth from water surface to the center of the transducer assembly faces)
- BB-ADCP serial number and firmware-revision number
- An electronic copy of the measurement log, which is helpful for reconstituting ADCP discharge measurements. The log copy should include: start time; Transect file name; start-edge estimate; end-edge estimate; discharge; and remarks about site conditions, including indication of eddies or reverse flow at bank edges; and remarks about passing boat traffic and wind conditions (pitch and roll)
- Any pertinent information about instrument setup or changes to the setup during the Transect session

These data should be archived to safe media as soon as possible following a Transect session. Safe

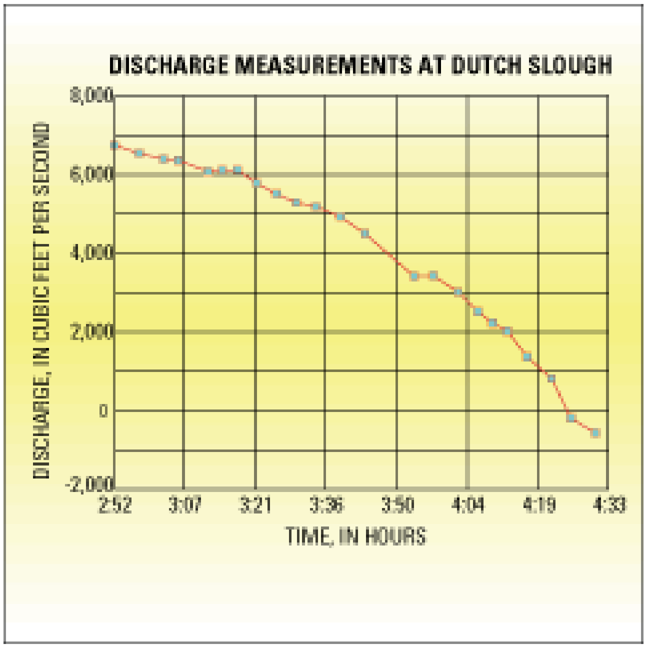

Figure 7.11. Discharge-measurement data from a tidally affected gaging station on a tributary of the San Joaquin River.

media may consist of a compact disk, read-only-memory (CD-ROM), optical media (30-year), or a disk drive on a computer system that is backed up regularly. The computer hard disk of the laptop used for data collection is not considered “safe media.”

Summary

A smooth bank-to-bank transect technique is essential for accurate discharge measurements. The operator always should remember that slow, smooth boat movements are desirable.

For steady-state flows, at least four transects should be made and the results averaged to calculate a “discharge measurement.” If one measurement is more than 5 percent from the mean, four additional transects should be collected and averaged. A CV should be calculated from the discharge-measurement series by dividing the standard deviation, in units of discharge, by the mean of the series. If the CV is greater than 5 percent, the ping rate should be increased or the boat slowed during the transect to collect more pings per transect. Additional transects should be made until a series of four is obtained having a CV of less than 5 percent.

For discharge measurements made in tidally affected rivers and estuaries, the CV value and standard deviations cannot be computed easily and, therefore, are not used. However, comparison and common sense sometimes can detect inaccurate transect discharges. In these cases, a single transect can be used as a discharge measurement, although many measurements usually are made during a discharge-measurement session to define the dynamic flow conditions.

Suitable log sheets and discharge-measurement notes must accompany the discharge-measurement series. The operator should store a copy of the configuration file that is used for the series in the Transect software deployment directory with a documentation file containing edge values and other pertinent information (described above). A documentation file should be stored with the Transect software data files describing stream conditions and pertinent information not collected by the Transect software.

All Transect data files and accompanying configuration and documentation files should be archived to “safe” media as soon as possible after the measurements are made. Although paper-copy records can be kept for records computation, acoustic Doppler current profiler discharge-measurement archives should be such that the discharge measurements could be wholly recreated from data stored on electronic media.

United States Department of the Interior
Geological Survey
Water Resources Division

ADCP Discharge Measurement Notes

Sta. No.: 11-4670.50 Name: Sacramento River @ Freeport, CA

Date: Aug 31, 1996 Party: Simpson, Abrador, Posey

Width: 530 Area: 1019 Vel. ≈ 1.40 G.H. 1.20-1.40 Discharge Tidal

ADCP Information

Ser. No. 296 Firmware 5.43 Software 2.72 Diagnostic Test Pass

ADCP draft: 0.34 m Depth Cell Size: 0.25 m

	Hour	Minute	Second	Circle	
Recorder	12	45	05	CST	CDT
ADCP	12	45	20	CST	CDT
Watch	12	46	10	CST	CDT

Transducer Frequency: 1200

Beam Angle: 20

Shore Description — Left: Sloping / Vertical; Right: Sloping / Vertical

Transect Number	Watch Time	Distance to Shore Start	Distance to Shore End	Start Bank	Sum Q	Edge Estimate	Total Discharge	Config File	Remarks
001	1220	50	40	L R	12433	320		FRE6.CFG	file fre6001R.000
002	1225	42	60	L R	12524	298		"	Passing Boat (wake)
003	1228	38	43	L R	12632	265		"	wind picking UP 5.0 mph
004	1232	49	60	L R	12722	300		"	
005	1235	58	37	L R	12845	305		"	
BAD				L R					
006	1239	42	50	L R	12963	235		"	Small white Caps
007	1243	53	39	L R	13005	242		"	
008	1247	36	62	L R	13107	303		"	Large Ship Passed (wake)
009	1252	64	37	L R	13152	312		"	
010	1256	56	63	L R	13098	320		"	
011	1301	66	39	L R	13005	301		"	Getting More Windy 10 mph
012	1305	42	54	L R	12970	259		"	
013	1310	57	39	L R	12920	288		"	
014	1314	43	62	L R	12860	276		"	was not Too good (WAKE)
015	1319	60	39	L R	12740	300		"	
016	1323	32	57	L R	12610	296		"	
017	1328	56	37	L R	12500	299		"	really windy ≈ 20 MPH
018	1342	39	62	L R	12320	276		"	
019	1346	61	38	L R	12200	300		"	Went to Dutch Slough
				L R					

Page 1 of 1

Figure 7.12. Discharge-measurement log sheet. ADCP, acoustic Doppler current profiler.

This page left blank intentionally.

CHAPTER 8: DISCHARGE-MEASUREMENT REVIEW AND ASSESSMENT

Individual transects should be checked for discharge-measurement errors and inconsistencies as soon as possible after collecting the discharge-measurement series. In most cases, this examination is done at the office or in a motel suite, but it can be done at the measurement site. The data are examined by using the Transect software to reconstruct the measurement from the stored raw data and configuration files. This is termed “playing back” the discharge measurement. During playback, the edge discharges also can be estimated, and the power-curve (or other) estimation scheme used near the top and bottom of the profile can be examined for correctness and changed, if necessary.

Proper review and assessment of ADCP discharge measurements is almost as important as the techniques and instrument setup used to collect the original data. Improper instrument setup and faulty measurement techniques can be revealed during post processing and, in some cases, corrections can be made to improve discharge-measurement accuracy.

Review of ADCP discharge measurements should include the following steps.

- Configuration file review with focus on the applicability of the following sections to river conditions:
  - ADCP hardware setup
  - ADCP direct commands
  - ADCP calibration constants
- Transect software playback with focus on the following subjects:
  - Missing data ensembles
  - Possible bottom-sediment movement
  - Magnitudes of discharge in the unmeasured (estimated) parts of the cross-section near the top and bottom of the profile
  - Technique used for low-velocity [< 10 cm/s (0.33 ft/s)] measurements
  - Power-curve-fit applicability
  - Reasonableness of edge values
  - Shiptrack examination

These assessment procedures are discussed in the following paragraphs.

Configuration-File Review

The first thing that should be checked is the applicability of the configuration file to the data file and to river conditions. The ADCP discharge-measurement notes should indicate the location of the configuration file used for the discharge-measurement series or contain a listing of the file.

River Conditions

The configuration file should be examined in a text editor to determine if the proper setup and configuration commands were used for the stream or river being measured. All sections should be checked, but the most important are the ADCP hardware, the direct command, and the calibration sections:

Acoustic Doppler Current Profiler Hardware

- First examine the ADCP Hardware section of the configuration file.

(example)

```
ADCP HARDWARE
{
Firmware       (5.45)
Angle (20)
Frequency (1200)
System (BEAM)
Mode (4)
Orientation (DOWN)
Pattern (CONCAVE)
}
```

Are these entries compatible with the ADCP used to make the discharge measurements? Is the proper mode being used for the river or stream in question?

Acoustic Doppler Current Profiler Direct Commands

- Next examine the Direct Commands section of the configuration file.

(example)

```
DIRECT COMMANDS
{
WS25
WF50
BX200
WN060
WD111100000
WP00001
BP001
WM1
BM5
ES0
WE0450
}
```

Is the blanking distance (WF) adequate for the transducer frequency? Is the bin size (WS) proper for the transducer frequency? Are enough depth bins specified (WN) to cover the range of depth measured? A few playback profiles may have to be examined before this question is answered. Is the bottom track maximum depth (BX) greater than the maximum stream depth? If BX is less than the maximum depth, there will be missing ensembles. Are the bottom and water modes (BM,WM) specified correct for the measurement application? Is an ES0 (salinity of zero) command present?

Calibration Section

•Finally, examine the calibration section.

(example)

```
CALIBRATION
{
ADCP depth (.40 m)
Heading/Magnetic offset (0.00
        0.00°)
Transducer misalignment (0.00°)
Intensity scale [0.43 decibels (
 dB) per count)]
Absorption (0.440 dB/m)
Salinity [0.0 parts per thousand
  (ppt)]
Speed of sound correction (YES)
Pitch and roll compensation (YES)
Tilt Misalignment (0.00°)
Pitch_Offset (0.000°)
Roll_Offset (0.000°)
Top discharge estimate (POWER)
Bottom discharge estimate
 (POWER)
Power curve exponent (0.16670)
```

Does the transducer draft correspond to the draft entered on the ADCP discharge-measurement notes? Have the proper offsets (if any) been entered? Is the proper estimation scheme being used for the bottom and the surface, and is the proper power-curve exponent being used?

Transect Software Playback

When the configuration file has been verified, the Transect software data files should be loaded and replayed using the Transect software playback menu. When the playback section is first entered, the software looks for the last loaded configuration file (in TRANSECT.PTR) for information about file locations. The operator either can load a new configuration file or load an individual data file by pressing the F3 key. The operator can load a list of files from a deployment by pressing the F8 key. During playback, the data should be examined with a critical eye for the anomalies discussed in the sections below. Common sense also should be used when reviewing Transect software data files.

Missing Ensembles

A velocity contour plot of the ADCP discharge measurement should first be examined for missing ensembles. Missing ensembles show as vertical black lines in the contour plot, as shown in figure 8.1. Figure 8.1 shows a transect containing missing

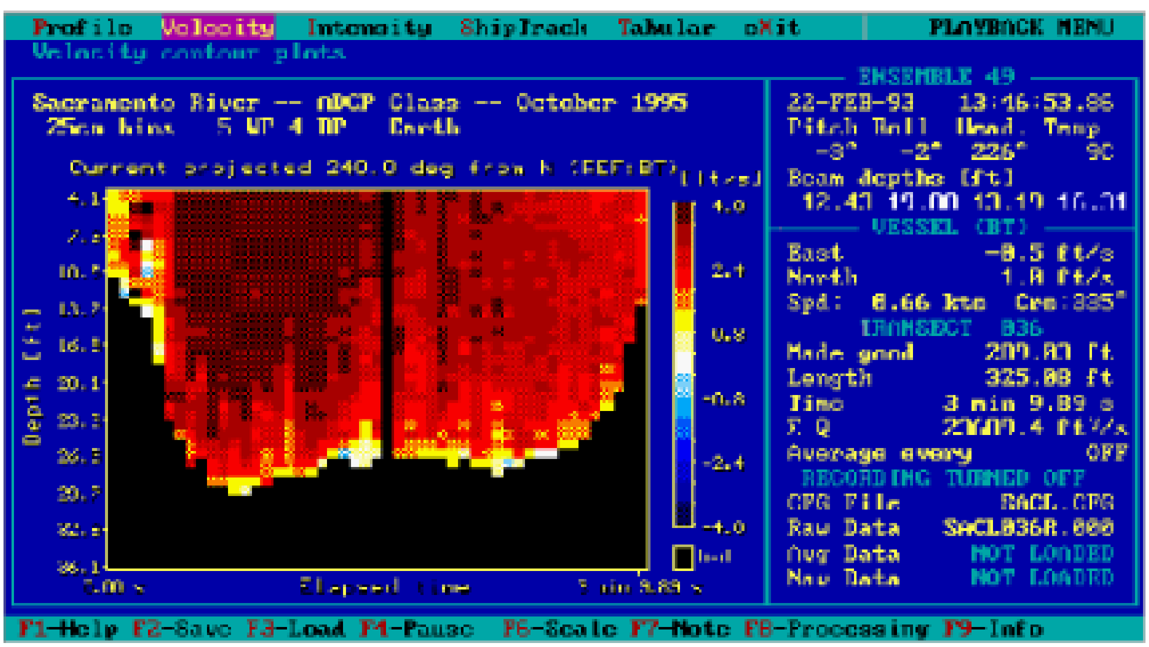

Figure 8.1. Transect containing missing ensembles caused by a loss of bottom tracking.

ensembles caused by a loss of bottom tracking. Note that, in this case, the missing ensembles would contain a significant amount of flow if they were present. The discharge calculated from the transect described above will be underestimated unless the missing data are estimated.

The following procedure can be used (using one of Transect's hidden commands) to correct transects containing bad bottom-track velocities:

- •In the playback section of Transect, load the file to be used in the normal way.
- •Put playback into single-step mode by toggling the F4 key, and rewind the file using the ALT W command.
- •Type F6 to open the 'scale menu' and enter 7 m/s (20 ft/s) for the water-speed (current sticks) value. Type F10 to return to the main menu.
- •Hit the space bar to single step through the data. Write down the ensemble number for any ensemble that has anomalously long current sticks, or high or bad speed indicated in the bottom-track portion (near the right side of the screen). After stepping through the entire file, type ALT W to rewind the file. Let's assume ensemble 40 was bad.
- •Set caps lock, scroll lock, and num lock on.
- •Single step through the file to the ensemble preceding the bad ensemble (39). Type CTRL-END (simultaneously). A small window will open in the upper left corner of the screen with the message ENTER ACCESS CODE:. Type 3200 then ENTER (on a laptop computer, the zero key may be remapped to another location on the keyboard as a result of pressing num lock). The bottom-track velocity now is locked into its present value. Single step to the next ensemble (40). The bottom-track velocity should be the same as the preceding ensemble (39). If the next ensemble (40) is good, open the access code window again and type 3200 to release the lock. If the next ensemble (41) is bad, continue stepping through the file until the ensemble preceding the last bad ensemble is reached and then release the lock. The locking procedure described above is then repeated until all bad ensembles have been corrected and the end of the file is reached. The total discharge will then include estimates for missing ensembles, based on extrapolated bottom-track velocities.
- •Edge estimates should be done in the usual way.

The method described above should be used with caution. It only should be used to "fill in" one or two missing ensembles, at most. When the method is used, it should be so noted on the discharge-measurement log sheet and the discharge measurement should be rated accordingly. If most of the measurements collected during a measurement session contain missing ensembles, the discharges should be remeasured at a more favorable cross section (usually with slower velocities) or should be remeasured when conditions become favorable.

Error Caused By Sediment Movement Near the Bottom

Errors caused by bottom movement generally show as negatively biased discharge measurements. These errors are introduced into the discharge-measurement cross product as apparent upstream boat movement. Sometimes the quantity of sediment moving near the bottom is enough to completely attenuate the bottom echo, causing catastrophic loss of bottom track, which shows as missing ensembles in the playback data. Figure 8.1 shows a velocity contour plot with missing ensembles caused by loss of bottom track.

When the ADCP is affected by bottom-sediment movement but has not lost bottom track, one might expect the resulting shiptrack plot to be curved in the upstream direction, even though the vessel is moving normal to the flow. In reality, the boat usually is pushed downstream by the current and, therefore, the information from the shiptrack plot can be misleading.

If bottom movement is suspected, the vessel should be anchored near the highest flow area in the cross section and data collected for at least 10 minutes. Examination of the resulting shiptrack plot will reveal the magnitude of the bottom-track error as a upstream-going shiptrack. The length of the track, in meters, multiplied by the elapsed time can be used to calculate the speed of the apparent upstream boat movement.

Figure 8.2 shows a shiptrack plot taken with the boat at anchor. The plot shows an apparent upstream boat movement of 18.7 m (61.5 ft) and an elapsed time of 612 s. This indicates an apparent velocity measurement error of 0.03 m/s (0.10 ft/s). It would be tempting to use this value to correct discharge measurements, however, the bottom probably is moving at different speeds in the cross section (slower near the edges and faster near the center, for example). A correction based on a single bottom-movement measurement would be questionable. Again, ADCP measurements sometimes can be made during conditions of bottom-sediment movement by substituting differential GPS-positioning inputs for

ADCP bottom-tracking data. See the manufacturers' web sites for information on using GPS systems for bottom tracking (www.rdinstruments.com) and (www.sontek.com).

Large Magnitudes of the Unmeasured Layers

Figure 8.3 shows the ending edge estimate (ALT E) screen with the show unmeasured discharge (ALT U) switch invoked. The unmeasured discharge magnitudes near the top and bottom of the channel are summed with the measured discharge (circled area in fig. 8.3). If the magnitude of the discharge in these unmeasured areas is greater than 30 percent of the measured discharge, special attention must be paid to the applicability of the power-curve estimation scheme used. A deeper cross section should be located and used, if possible.

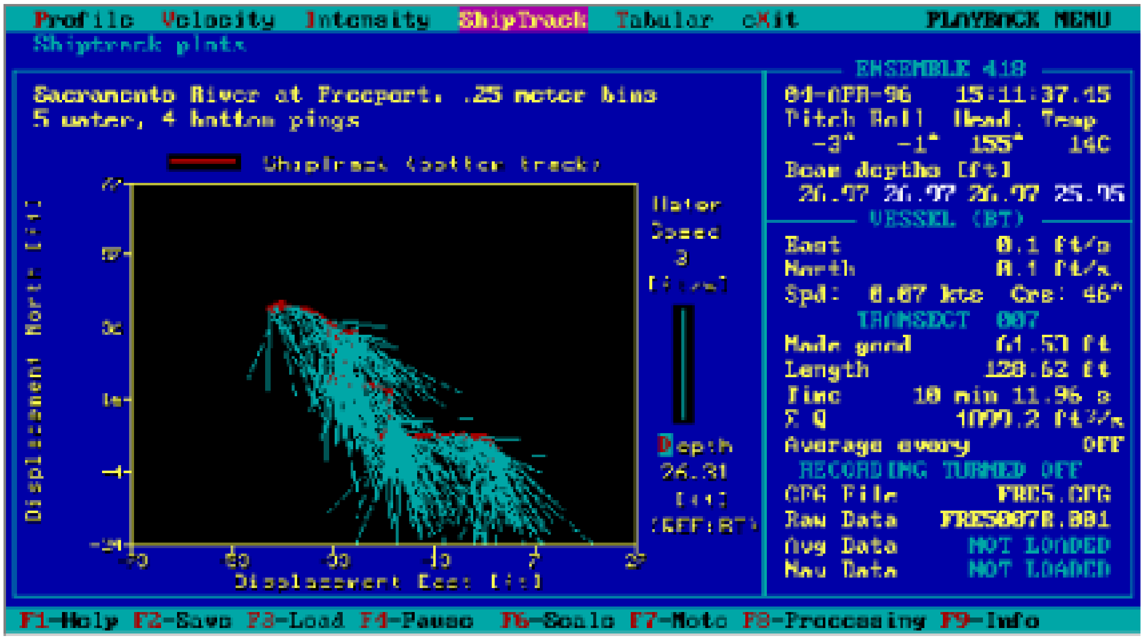

Figure 8.2. Transect software shiptrack plot of an anchored vessel.

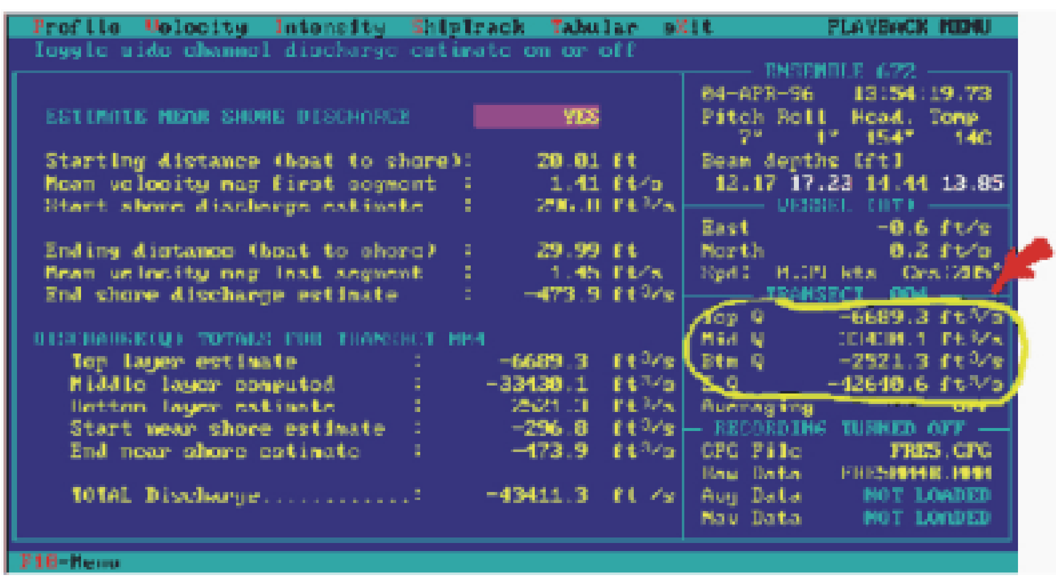

Figure 8.3. Transect software edge-value screen showing unmeasured layers.

Low-Velocity Measurements

Most of the errors seen during Transect software playback are caused by too few ensembles being collected for a given river velocity. Even seasoned ADCP operators sometimes fall prey to this error. It cannot be over emphasized that SLOWER river traverses are BETTER when it comes to the measurement of discharge in rivers having slow mean velocities. Slow traverses allow more ensembles to be collected, thereby reducing the amount of random error in the discharge measurement. In general, the boat should traverse the river at about the same velocity as the water. In large, wide rivers, this often is not possible (or feasible), and in such cases, equation 9.1 in chapter 9 should be used to estimate the proper boat velocity. The large standard deviation of ADCP-measured (slow) velocities can be seen in the shiptrack plot of figure 8.4.

The boat speed for the traverse (fig. 8.4) was close to that of the water. Even though there was a large single-ping standard deviation, the standard deviation of the resulting group of discharge measurements was small. If any single discharge measurement has a coefficient of variation larger than 5 percent, the ADCP and boat operator should be cautioned to decrease vessel speeds during discharge measurements at the site in question for similar or lower velocities.

Power-Curve-Fit Applicability

Figure 8.5 shows a discharge profile with measured data, cross-product curve fit, and the resulting discharge profile.

As can be seen from figure 8.5, the actual measured profile differs significantly from the one-sixth power-curve fit. In this profile, velocity near the surface is less than the velocity in the middle of the profile (as shown by the arrow). This may be caused by such things as wind shear or a flow reversal near the surface. If many or all of the measured profiles differ in this manner, then the TOP estimation scheme should be changed from POWER to CONSTANT in the configuration file, and the data replayed. The circled area indicates the profiled area where measurement bias can occur because of incorrect top layer discharge estimates. Generally, the bottom estimation scheme should be left at POWER. The exception to this rule is when significant numbers of profiles are bidirectional. A bidirectional profile is one wherein the velocities are stratified with the top-most velocities moving in a different direction than the bottom-most velocities. In cases of stratified flow, the estimation scheme should be set to CONSTANT at the top and CONSTANT at the bottom. This method will introduce some errors but the errors will pnot be as great as those caused by setting the estimation scheme to POWER.

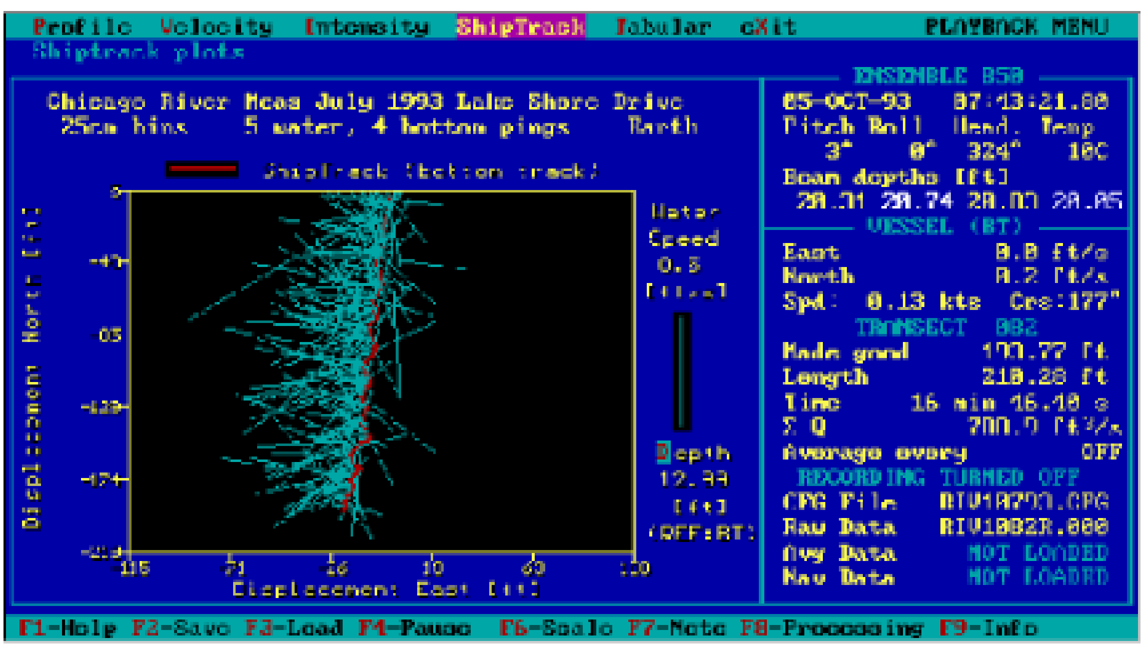

Figure 8.4. Transect shiptrack plot of acoustic Doppler current profiler-measured velocities on a slow-moving river.

Edge Values

Figure 8.6 shows the Transect software playback edge-value estimate screen, which is accessible by pressing ALT-E after Transect playback. Note! This feature is available only during playback at this time. This menu allows the operator to insert start and end edge distance estimates. The software then calculates an estimated discharge for each edge and adds it to the total discharge. Transect software version 2.80 (and later versions) allows the operator to enter edge values while acquiring the discharge measurement. These edge values are saved in the configuration file and can be loaded during playback.

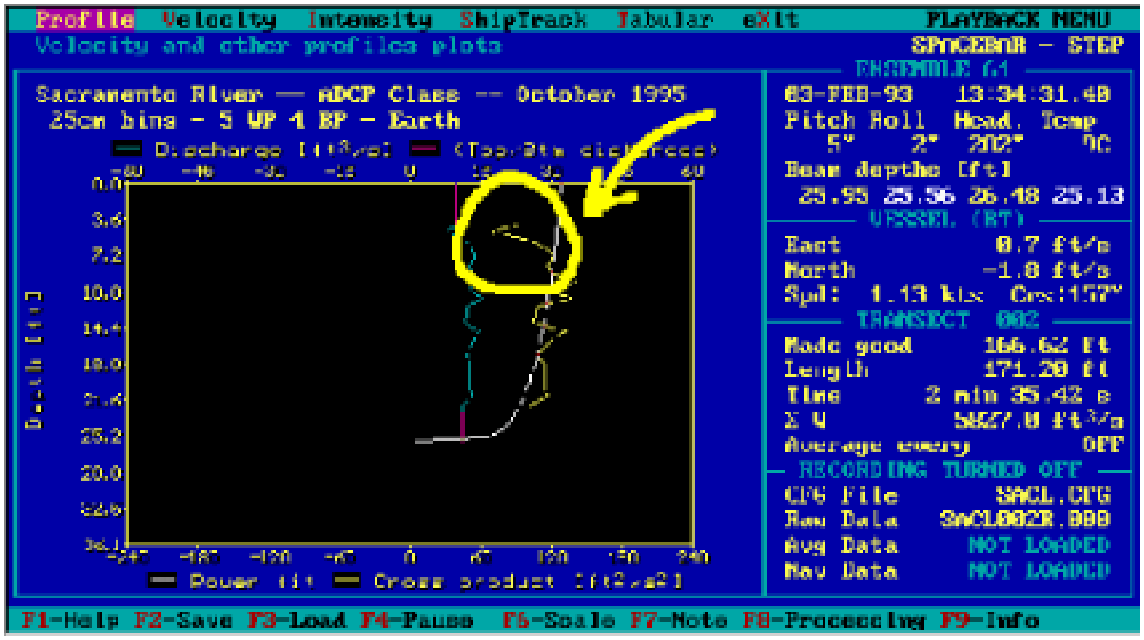

Figure 8.5. Transect software discharge profile plot. ADCP, acoustic Doppler current profiler.

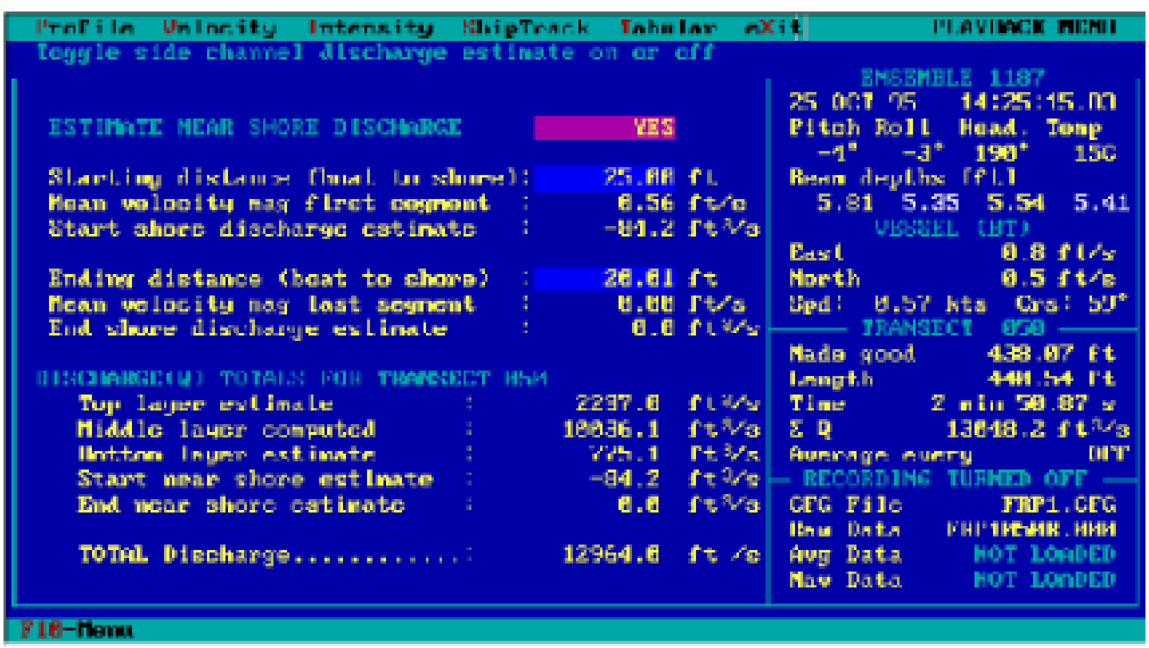

Figure 8.6. Transect software edge-value screen.

Note that in figure 8.6, the start edge-discharge estimate is negative, the main body of discharge is positive, and the end edge discharge is positive. This phenomena can be caused by two things:

- •The start-edge discharge is moving in the opposite direction from the main body of discharge and the end-edge discharge [this can occur because of eddies or momentum effects (fig. 8.7)].
- •Initial boat movement was toward the starting shore rather than away from it.

The sign (+ or –) assigned to the cross-product calculation is based on the boat course, in relation to the flow direction. If the water is flowing uniformly in one direction and the boat is traversing the flow uniformly without changing course, the sign of the cross product should remain constant. If the boat reverses course (or the flow changes direction during the traverse), the sign of the cross product will change. If this occurs at either or both edges, the edge velocities will have a sign that differs from that of the main flow body (fig. 8.6). In recent versions of the Transect software (version 4.00 and later), corrections have been made to eliminate incorrect signs (+ or –) near the riverbank edges, however, the operator still should carefully examine the edge-value water velocities.

Shiptrack

The operator should take care to start the Transect software only after the boat begins the cross-section traverse and to stop the Transect software before making the course reversal at the end of the traverse. During the discharge measurement, the ADCP operator also should note any observed longitudinal-flow reversals on the discharge-measurement log sheet. Longitudinal-flow reversals can take place at high flow (due to eddies) and near slack tide (due to momentum effects). Longitudinal-flow reversals should be noted during the review of shiptrack plots. Then the reviewer should determine whether the reversal is actual or caused by initial boat movement toward shore.

The shiptrack plot shown in figure 8.7 also should be examined for discrepancies in the motion of the discharge-measurement vessel. In general, a good discharge measurement occurs when the measurement vessel makes a smooth traverse from bank to bank. An extreme example of irregularities in the shiptrack is illustrated in figure 8.8. Examination of the velocity-profile data in figure 8.9 does not reveal these irregularities. If the shiptrack plot of this measurement had not been examined, it may have been erroneously labeled as a good measurement.

The shiptrack plot should be examined for "hooks" (fig. 8.10) near the edges that indicate that the F5 key was either pressed too early in the transect (before the vessel had started its move toward the far bank) or too late (after the boat operator has reversed course at the end of the transect). Such "hooks" can be edited out of the data using the F8 subsectioning menu (fig. 8.11).

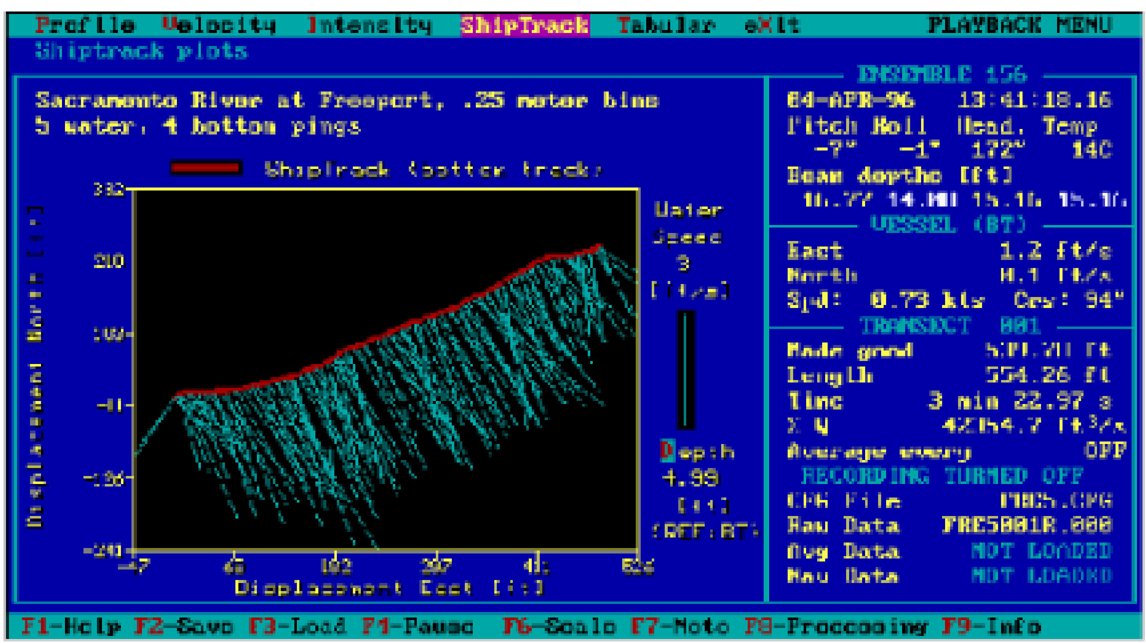

Figure 8.7. Transect software shiptrack plot.

Summary

Transects should be replayed as soon as possible after being collected to check for possible errors in acoustic Doppler current profiler (ADCP) setup and discharge-measurement technique. Configuration files should be examined to see if proper ADCP setup parameters were used for the measurement. The power-curve estimation scheme should be checked for correctness and the edge-value estimates should be checked.

Discharge-measurement technique should be checked for correctness. In particular, the boat speed should be slow enough to reduce the discharge-measurement standard deviation to a value under 5 percent (of mean discharge). In tidally affected areas or large shallow, slow-moving rivers, equation 9.1

Figure 8.8. Transect software shiptrack plot with operator's initials.

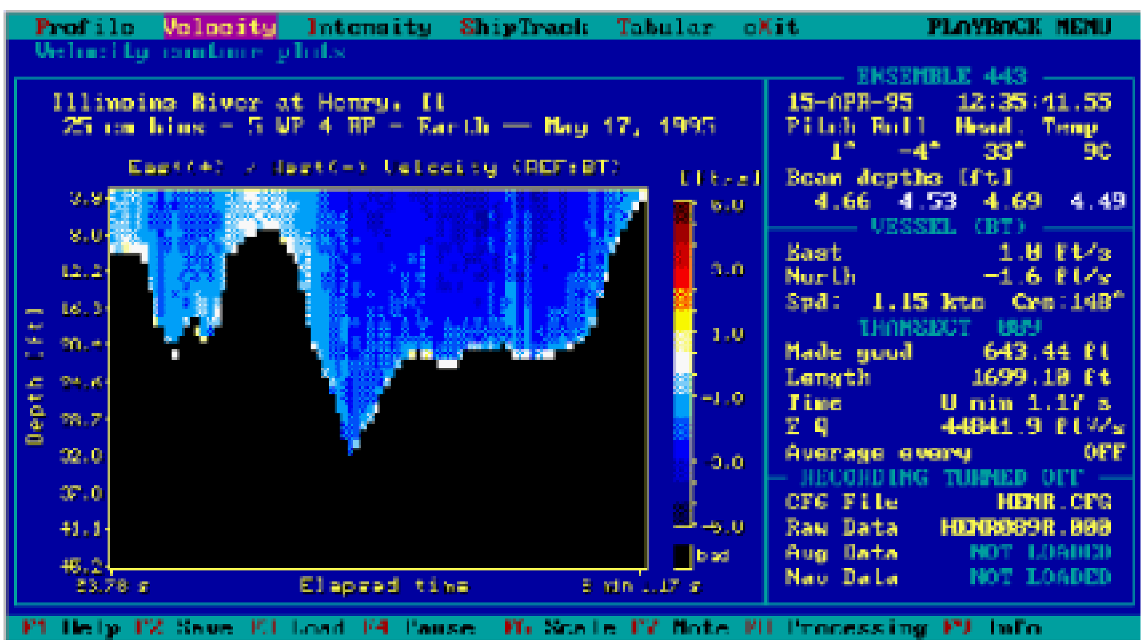

Figure 8.9. Transect software profile plot of "initials".

(chap. 9) can be used to assess discharge-measurement standard deviation.

If bottom movement is suspected, the boat should be anchored in an area of the highest channel flow and transects should be collected for at least 10 minutes. The resulting shiptrack plot should be examined for apparent upstream boat movement.

If a few missing ensembles are discovered during playback, they can be estimated using the technique described in this chapter. If there are many missing ensembles present in the transect data, the discharges should be remeasured at a different cross section or when conditions become more favorable.

Magnitudes of the discharges in the unmeasured layers should be examined and, if they comprise a significant portion of the total discharge, the operator should attempt to locate a deeper cross section for future measurements.

Figure 8.10. Transect shiptrack screen. ADCP, acoustic Doppler current profiler.

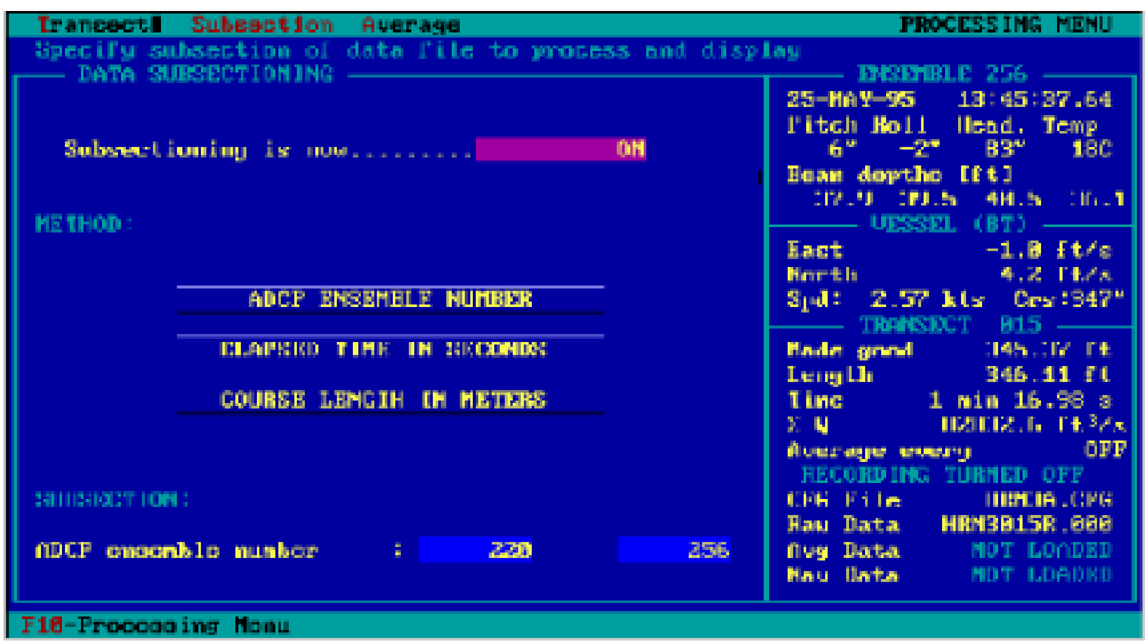

Figure 8.11. Transect subsectioning menu screen.

This page left blank intentionally.

CHAPTER 9: DISCHARGE-MEASUREMENT ERROR

In this chapter we will discuss the major sources of error in ADCP discharge measurements. We will first review velocity-measurement uncertainty (chap. 1) and then discuss random and systematic ADCP discharge-measurement errors. A simple discharge-measurement error model is presented to aid the operator in premeasurement planning and error assessment.

A Review of Major Acoustic Doppler Current Profiler Velocity-Measurement Limitations and Uncertainties

A short review of ADCP velocity-measurement uncertainty and measurement limitations will help in understanding discharge-measurement errors. Detailed explanations and examples of these uncertainties are discussed in chapter 1.

Limitations

Range Limitations

The signal strength of an acoustic pulse decreases logarithmically with distance from the transducer face (range). As the signal strength and signal-to-noise ratio decreases, the spectral width of the returned signal increases. This increase in spectral width with range causes an increased standard deviation of the measured velocity with range. At some range the return echo is unusable. This limiting range is largely dependent on transducer frequency and, to a much lesser extent, on transmit pulse length and beam angle for any given ADCP. The usable range of an ADCP also is affected by the number of scatterers in the water column. Below is a conservative estimate of ADCP maximum range for several transducer frequencies (table 9.1).

Table 9.1. Approximate maximum depth range for 300-, 600-, and 1,200-kilohertz acoustic Doppler current profiler (ADCP) systems

[kHz, kilohertz; m, meter; ft, foot]

ADCP frequency (kHz)	Range (m) (ft)
300	20 m (390 ft)
600	48 m (157 ft)
1,200	15.4 m (50.5 ft)

Side-Lobe Interference

When a parasitic side lobe strikes the bottom, the returning echo drowns out the reception of the echo from the main beam. In an ADCP with 20º-beam angles, this loss of reception occurs at a point equal to about 94 percent of the total depth. This area of side-lobe interference near the bottom (equal to 6 percent of total depth) can be calculated using equation 1.4. Using this equation, the Transect program “throws out” discharge data in the area of side-lobe interference and then estimates the velocities near the bottom using power-curve fits or other estimation techniques. However, if the operator is collecting velocity profiles, the velocities may not be flagged “bad” by the Transect software. To determine the depth at which the side-lobe interference will affect the data, the operator must examine backscattered intensities. In a normal profile, the backscattered intensities start at around 140 counts (or higher) and “drop off” with depth. Velocity measurements become questionable at the point where intensities increase (or stop decreasing). Looking at beam 1 in the tabular plot in figure 9.1, we see that the intensities start at 145 and increase to 147 in the following bin because of ringing (mechanical and electronic resonance). This error in the top-most bin occurs if the blanking distance is set too short (see the next section on Blanking Distance). The intensities decrease until about 123 counts where they “flatten” and then begin to increase. The depth at which the counts flatten and do not decrease is the depth at which the velocities may become affected by side-lobe interference. The area between the last good bin center and the bottom must be estimated by some means to obtain mean velocity in the vertical profile.

Unmeasured Velocity Due to Blanking Distance and Transducer Draft

After transmitting the acoustic signal, the ADCP transducers and electronics must “recuperate” briefly before they can receive the incoming echoes. During recuperation, the acoustic signal travels a short distance (blanking distance). Acoustic reflections cannot be received within the area between the transducer face and the blanking distance.

The transducer assembly must be submerged adequately so that it does not break the water surface during pitch and roll events. The depth of the transducer faces below water surface is called transducer draft.

To calculate the distance to the center of the first bin, it is necessary to use the BB-SETUP software module, available from RDI, as part of the Transect software package. From the screen capture shown in figure 9.2 it can be seen that if you are using a

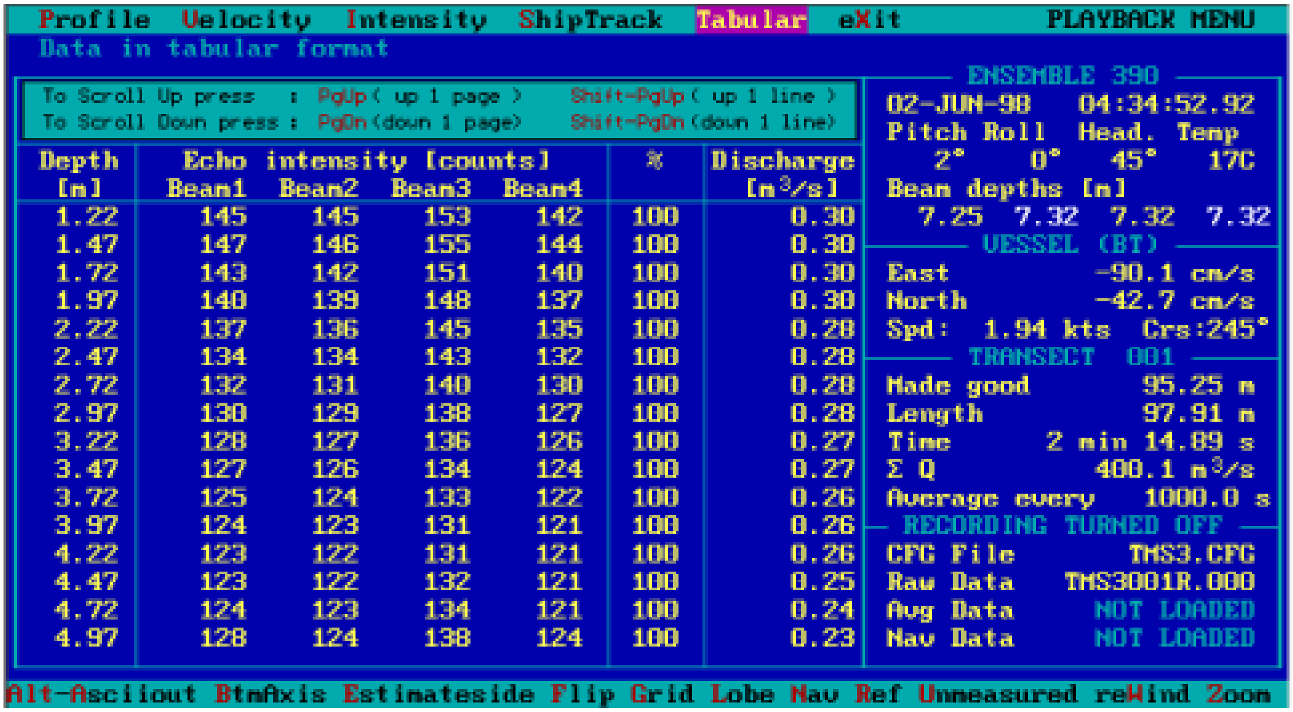

Figure 9.1. Screen shot of Transect software showing tabular output.

1,200-kHz BB-ADCP with 0.25-m (0.82-foot) bins, a blanking distance of 0.5 m (1.64 ft) and an ambiguity velocity (WV) of 190 cm/s (6.2 ft/s), the center of bin 1 will be at a range of 0.85 m (0.28 ft) from the face of the transducers. If the transducer draft is 0.25 m (0.82 ft), the center of the first bin is 0.85 + 0.25 = 1.10 m (3.6 ft) below water surface. Water velocity in the area between the water surface and the first bin center must be estimated to calculate mean water velocity in the vertical profile.

Random and Systematic Uncertainty

In chapter 1, we discussed ADCP velocity-measurement uncertainty in detail. In the following paragraphs we will touch on each of the major sources of ADCP velocity-measurement uncertainty so that we can more readily grasp the causes of discharge-measurement error.

ADCP velocity-measurement uncertainty can take two forms:

•Random uncertainty

•Systematic uncertainty (bias)

Random uncertainty can be reduced by data averaging, but systematic uncertainty cannot. If the magnitude of systematic uncertainty is known, it can sometimes be corrected using adjustment factors or coefficients.

Random Uncertainty Due to Self Noise and Lag Distance

The most significant source of random uncertainty in a BB-ADCP water-velocity measurement is caused by self noise (freeway analogy in chap. 1). The magnitude of this uncertainty is affected by ADCP transducer frequency, transmit pulse width, lag distance, and many other factors. This uncertainty directly affects ADCP water-velocity measurement precision. Techniques such as pseudo random phase encoding, data averaging, and increasing the lag distance are used to help reduce the effects of this uncertainty. The magnitude of this uncertainty can be predicted using the BB-SETUP program that is shipped with the Transect software files. Figure 9.2 shows a screen shot of a typical 1,200-kHz broad-band ADCP setup scenario.

In mode 1 operation, the operator can control the lag distance by changing the value of the ambiguity velocity (WV command). Notice that for an ambiguity velocity of 190 cm/s the single-ping standard deviation (an indicator of velocity-measurement random uncertainty) is 14.08 cm/s (0.46 ft/s). If the operator lowers the ambiguity velocity to 90 cm/s (2.95 ft/s) for example, the single ping standard deviation drops to 10.3 cm/s (0.34 ft/s). There are practical upper and lower limits to the ambiguity-velocity setting; setting the ambiguity velocity too high will produce unacceptable random uncertainty in the velocity measurement and setting the ambiguity velocity too low may introduce ambiguity uncertainty (chap. 1). In

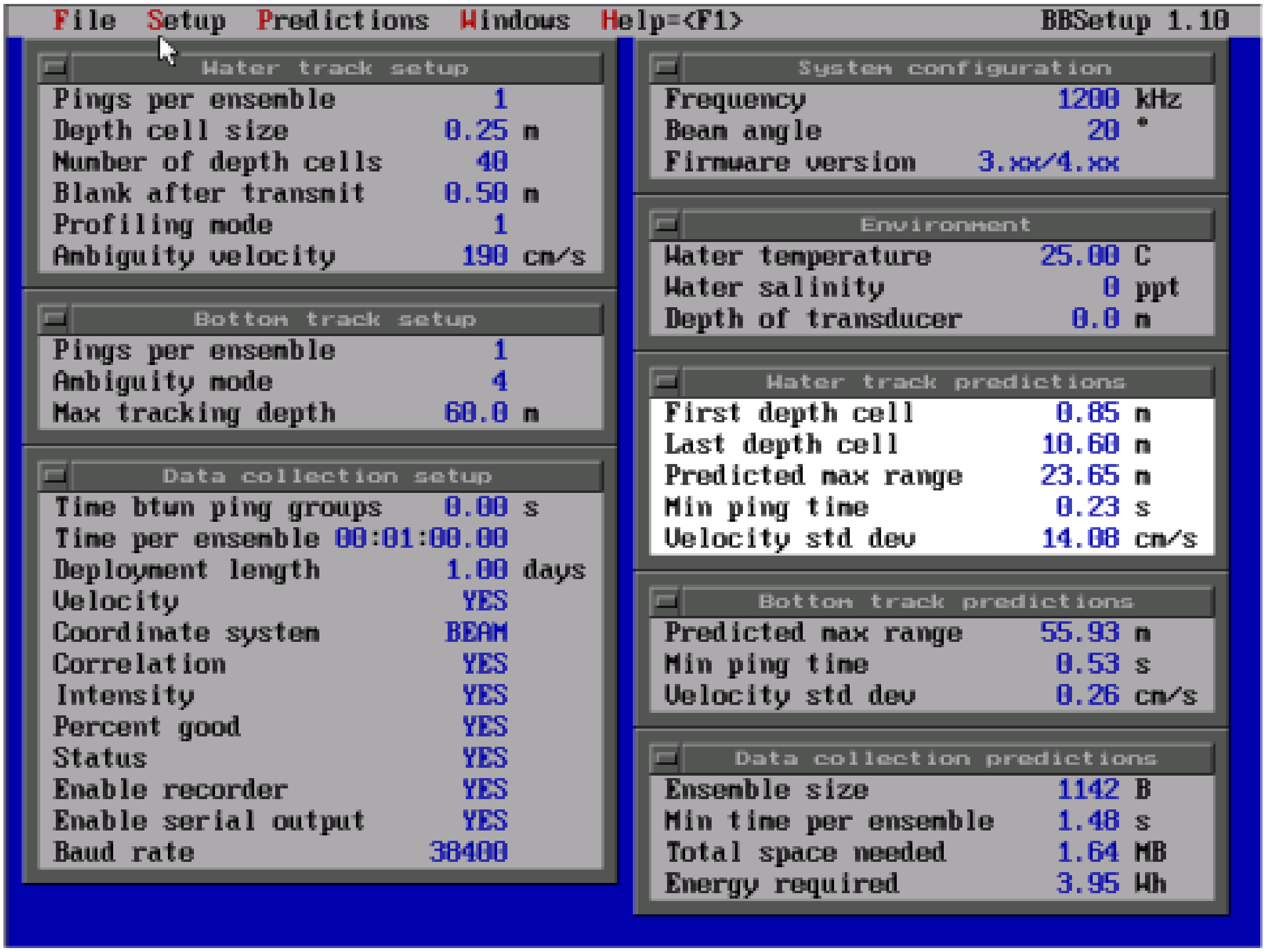

Figure 9.2. Screen shot of BB-SETUP software showing a typical setup for a 1,200-kilohertz broad-band acoustic Doppler current profiler.

mode 5 operation, the velocity-measurement uncertainty is greatly reduced (by about a factor of 10) because of the large lag spacing. However, because this large lag spacing lowers the ambiguity velocity, mode 5 only can be used in conditions where the bottom and water velocities are low [less than 50 cm/s (1.64 ft/s)], relative to the ADCP.

Systematic Uncertainty Due to Velocity Ambiguity

If the operator is recording single-ping ensembles, velocity-ambiguity uncertainties show as “spikes” in the data that are the opposite sign of the “true” velocity. The difference between the “true” velocity and the erroneous velocity is twice the magnitude of the ambiguity velocity (WV command in mode 1). A detailed explanation of this uncertainty is in chapter 1. For mode 1 operation, the operator can raise the value of the ambiguity velocity to eliminate these uncertainties, but the single-ping velocity-measurement standard deviation will increase, causing decreased measurement precision. The ambiguity-velocity setting is a trade off and usually can be set to a “safe” value using equation 3.1 in chapter 3. If the ambiguity-velocity values are set to a high value because of possible ambiguity uncertainties, the operator may have to slow the boat during the cross-section traverse to improve the discharge-measurement standard deviation (discussed later in this chapter).

For mode 5 operation, the ambiguity velocity (WZ command) is set automatically by the ADCP, depending on water depth and depth-cell length. If, during mode 5 operation, ambiguity uncertainties are encountered, the operator either must switch measurement modes or look for a cross section having lower velocities and (or) current shear.

Systematic Uncertainty in Speed of Sound Due to Temperature

Speed-of-sound calculations that are not corrected for temperature can cause velocity-measurement errors and depth errors as great as 7 percent. Fortunately the Transect software uses data from a thermistor in the transducer assembly to correct speed-of-sound calculations for temperature variations in the water near the transducer. Under normal stream conditions, this correction reduces speed-of-sound errors to insignificant levels. Sometimes, however, the water column becomes temperature stratified. Unlike horizontal water-velocity errors, depth-measurement errors can be introduced by temperature gradients in a stratified water column. Figure 9.3 shows depth errors, in percent, due to improper temperature compensation for speed of sound. Fortunately temperature gradients must be extremely high (10ºC or more) to cause a significant error in a BB-ADCP depth measurement. Gradients of this magnitude sometimes can occur during the summer in slow-moving water.

Speed-of-sound errors also can be caused by a faulty thermistor in the transducer assembly. An error in temperature causes an erroneous calculation of water density, which results in a speed-of-sound uncertainty.

Systematic Uncertainty in Speed of Sound Due to Salinity

The speed-of-sound equation in the Transect program (R.D. Instruments, Inc., 1995) depends on a user-supplied salinity value to calculate speed-of-sound corrections (as discussed in the velocity-measurement error section in the first part of this chapter). This value is specified in the Transect software configuration file. If the operator has entered an incorrect value or has forgotten to enter the proper value, depths (as well as velocities) are calculated incorrectly. Depth errors as high as 3 percent can be caused by speed-of-sound calculations that are not corrected for salinity (fig. 9.4). Fortunately "ball park" salinity values usually will reduce this error to less than 1 percent.

Velocity errors due to salinity-caused speed-of-sound variations can be at least as serious, therefore, many boat operators carry a salinimeter (or conductivity meter) with them to the discharge-measurement site. Salinity can be calculated and entered into the configuration file prior to the discharge measurement, however, a better approach is to enter zero salinity into the configuration file (ES0). The correct salinity can be plugged into the configuration file during playback. An incorrectly entered salinity using the ES direct command can be very hard to correct after the fact.

Systematic Uncertainty Due to Incorrect Beam Geometry

The largest source of systematic uncertainty in an ADCP is caused by uncorrected errors in the measurement of the beam-pointing angles. These uncertainties usually are in older BB-ADCP units that were sold before the manufacturer instituted stringent quality-control procedures. Late model BB-ADCPs and Workhorse Rio Grandes have transducer assemblies that meet more exacting beam-angle tolerance requirements. Each ADCP is tested on a distance course and corrections are saved in the ADCP firmware for any measured beam-angle discrepancies. Older ADCPs can be upgraded by the manufacturer and then tested in a lake to identify and correct beam-angle uncertainties.

Minimizing Uncertainty in Velocity Profiles

Many scientific studies require accurate water-velocity profile measurements and discharge measurements. Many of the velocity-measurement errors described above can be minimized or eliminated by using the following common sense rules:

- Use the proper water mode for the job. If the velocities are dynamically changing, or the vessel is affected by pitch and roll, use water mode 1. In shallow water that is placidly moving, mode 5 may be used. In shallow, fast-moving water, mode 8 may be used.

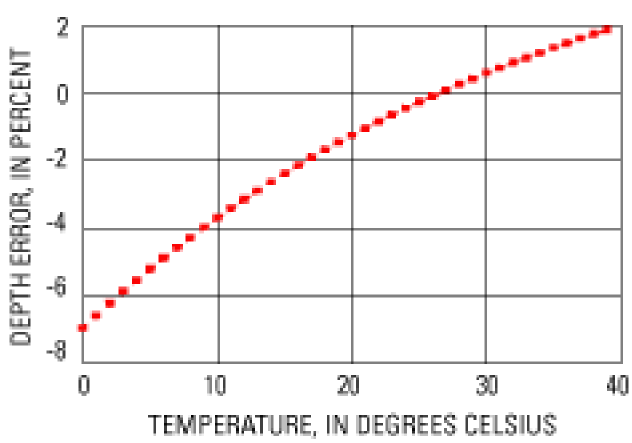

Figure 9.3. Depth error due to speed of sound that is uncorrected for temperature.

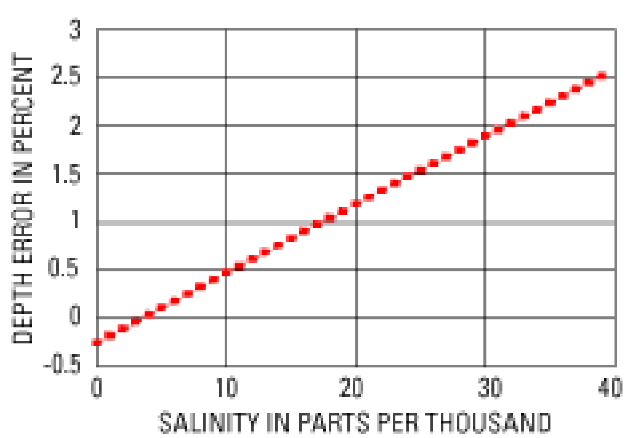

Figure 9.4. Depth error due to speed of sound that is uncorrected for salinity.

- •Collect enough data at the profile location to ensure that the measured water-velocity standard deviation is within usable limits (after the data are averaged).
- •If the unmeasured bottom and top velocities are to be estimated, ensure that the measured portion of the profile (after averaging) is congruent with the estimation scheme used. For example, if the measured part of the profile is bidirectional, a one-sixth power-curve estimation scheme is improper.

Errors Affecting the Accuracy of Discharge Measurements

If heavy sediment loads are not present and a moving river bed problem does not exist, errors in ADCP discharge measurements usually are caused by improper river traverse rates or erratic movements of the discharge-measurement vessel. These random errors usually cause imprecision in the discharge measurement (scatter). Reducing the traverse rate and eliminating erratic vessel movements can reduce random error.

The next most common error types are depth errors caused by incorrect transducer draft, depth errors due to speed-of-sound variations, and cross-product errors due to improper application of the power-curve fitting scheme. These sources of error are biases that cannot be improved by slowing the traverse rate or averaging the data (see bias error section later in this chapter). Random errors in discharge measurements made with the BB-ADCP system roughly can be predicted if the following values are known:

- •ADCP water-velocity measurement precision
- •ADCP bottom-track velocity measurement precision
- •The standard deviation of naturally occurring water-velocity pulsations (at the ADCP-measurement time scale)
- •Approximate average cross-sectional water depth
- •Approximate average water speed
- •BB-ADCP bin size
- •BB-ADCP ping rate

Table 9.2 gives the approximate depth-averaged, water-velocity standard deviation for 1,200-, 600-, and 300-kHz BB-ADCPs with 20º beam angles using mode 1 operation with an ambiguity velocity of 190 cm/s (6.23 ft/s).

Mode 5 bottom-track standard deviation is much less than the water-velocity standard deviation for all ADCP frequencies [0.2–0.3 cm/s (0.006–0.009 ft/s)].

Table 9.2. Approximate depth-averaged single-ping precision for 1,200-, 600-, and 300-kilohertz broad-band acoustic Doppler current profiler-measured water velocities using mode 1 operation, 20° beams, and WV190

[kHz, kilohertz; m, meter; ft, foot; cm/s, centimeter per second; ft/s, foot per second]

Frequency (kHz)	Depth cell size	Average standard deviation for depth range
1,200	0.25 m (0.8 ft)	14.1 cm/s (0.46 ft/s)
600	.50 m (1.64 ft)	14.1 cm/s (.46 ft/s)
300		14.1 cm/s (.46 ft/s)

Simplified Random-Error Model

The precision of a discharge measurement may be computed using the following algorithm in equation 9.1:

$$\sigma_q = \frac{\sqrt{\left[\left(100\frac{X_w}{V_m}\right)^2 + \left(100\frac{X_b}{V_m}\right)^2 + \sigma_p^2 + \sigma_z^2\right]}}{\sqrt{0.75 N_b N_s}} \qquad (9.1)$$

where

σ_q = standard deviation of discharge measurement, in percent;

V_m = estimated approximate mean stream velocity, in centimeters per second;

X_w = BB-ADCP water-velocity precision, in centimeters per second (table 9.2.);

X_b = BB-ADCP bottom-track precision, in centimeters per second (table 9.2.);

σ_p = estimated standard deviation of natural pulsations, in percent of mean velocity; a value of usually 8–12 percent (at the time interval used for an ensemble by the BB-ADCP);

σ_z = depth error due to round off and resolution limitations;

N_b = average number of bins in the vertical; and

N_s = total number of subsection measurements.

Equation 9.1 is derived using the following assumptions:

- •A 15-percent bin-to-bin correlation
- •A 0-percent subsection-to-subsection correlation
- •A smooth rectangular channel

The 0.75 constant in equation 9.1 is a rough approximation of the Markov model output when there is a sample (bin-to-bin) correlation of 15 percent (Matalas and Langbein, 1962). Matalas and Langbein (1962) present an equation for the calculation of effective N for any correlation coefficient, and this equation should be used in error models that are developed for the estimation or prediction of BB-ADCP (or narrow-band ADCP system) discharge-measurement error.

Depth error due to BB-ADCP round off and resolution limitations (σ_z) is estimated by the manufacturer to be 4 percent of the measured vertical depth range on an individual beam (Joel Gast, R.D. Instruments, Inc., oral commun., 1997). Because four beams are averaged for the depth measurement, the error becomes $\frac{4}{\sqrt{4}} = 2$ percent for each ping averaged during the discharge measurement.

Figure 9.3 shows graphs of mode 1, 1,200-kHz, error model output for a 61-m- (200-foot-) wide river, with boat speeds of about 0.3 and 0.9 m/s (1.0 and 3.0 ft/s). Figure 9.3 reveals that a boat operator traversing a 61-m- (200-foot-) wide, 4.6-m- (15-foot-) deep river could use a boat speed of about 0.3 m/s (1 ft/s) for the measurement of all mean river velocities above 0.15 m/s (0.5 ft/s). Figure 9.5 also shows that discharge-measurement error increases with the boat speed. This increase occurs because the BB-ADCP is collecting fewer pings during the cross-section traverse, with a resultant increase in random error (because fewer data are averaged). The boat operator must remember that the precision of a discharge measurement can change dramatically with changes in the total number of pings and the total number of bins sampled during the traverse. The total number of depth bins depends on the water depth. Figure 9.6 shows the same scenario as in figure 9.5, but with an average cross-section depth of 9 m (30 ft) rather than 4.3 m (15 ft). Note that the discharge-measurement error decreases to magnitudes similar to those shown in figure 9.5. This decrease occurs because there are twice as many bins averaged in the vertical profile.

Although equation 9.1 can be programmed into a spreadsheet and used to predict discharge-measurement uncertainty, a small executable software application (QERROR) has been developed (for mode 1 use) that is more easily used in the field. Figures 9.7–9.9 show screen shots from the QERROR application. Figure 9.7 shows the input screen. The measurement units are in mixed systems on the input screen for two reasons:

•USGS field office personnel are more adept at estimating widths and depths in the standard-measurement system.

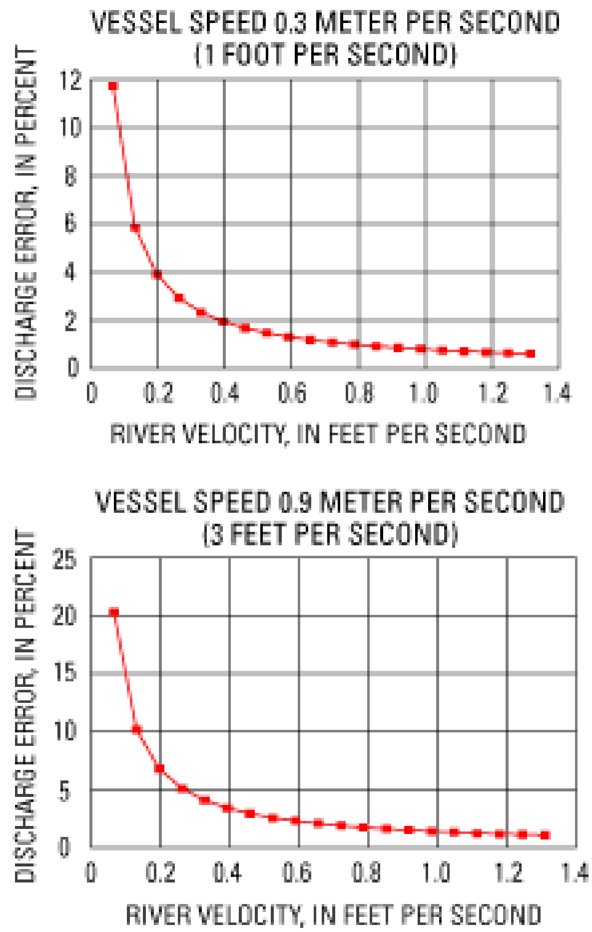

Figure 9.5. Discharge error using a boat speed of about 0.3 meter per second (1 foot per second) and about 0.9 meter per second (3 feet per second).

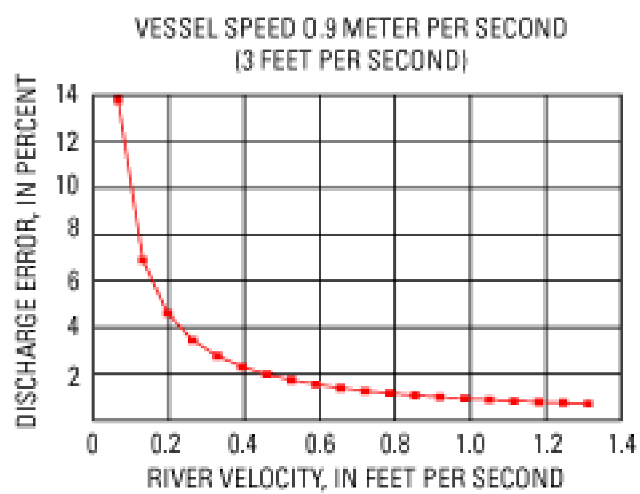

Figure 9.6. Discharge error using a boat speed of about 0.9 meter per second (3 feet per second) in 9 meters (30 feet) of depth.

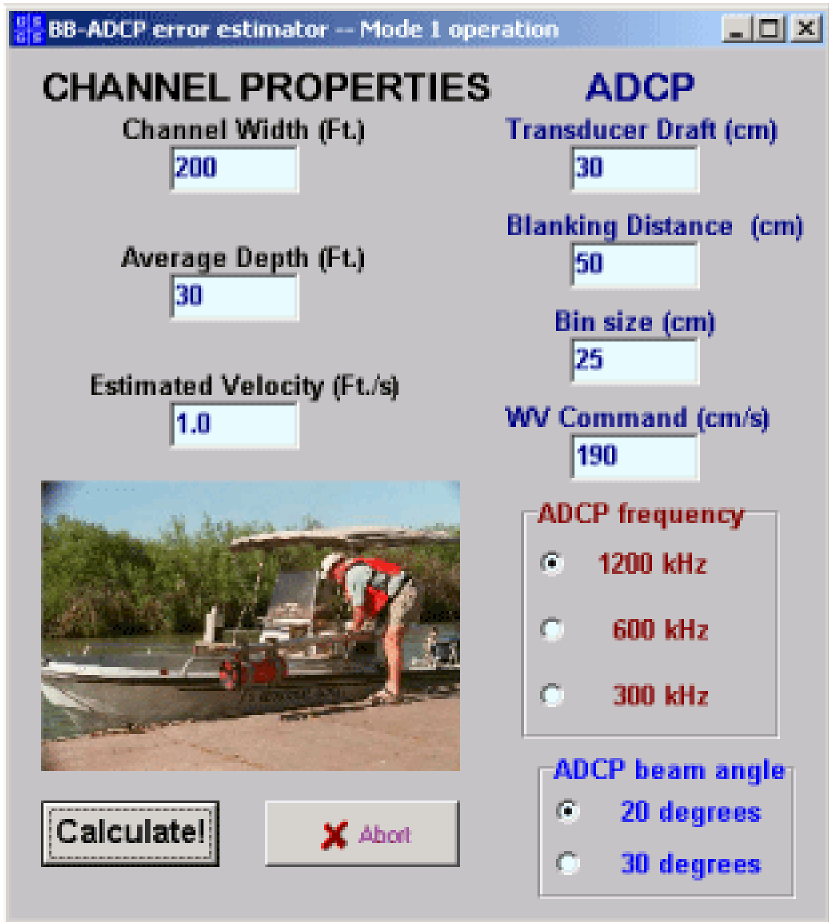

Figure 9.7. QERROR setup screen. ADCP, acoustic Doppler current profiler.

- ADCP input parameters always are requested in SIS units.

Figure 9.8 is the output screen from the QERROR application and it illustrates the importance of slow-vessel traverse rates when measuring rivers with slow mean velocities. Note that the error is reasonable when the boat is moving at speeds less than, or equal to, the water velocity. A good rule of thumb is to traverse the river at about the same speed as the mean water velocity. However, this rule becomes inapplicable when measuring wide, deep rivers, with slow water velocities. The operator would not be able to complete such a measurement within a reasonable time frame. In cases of wide, deep rivers, the operator can use equation 9.1 or the QERROR application to estimate discharge-measurement error based on boat speed, average water depth, and estimated mean water velocity.

Figure 9.9 shows the same measurement scenario as used for figure 9.8 with a mean river velocity of 0.15 m/s (0.5 ft/s). Notice that boat speeds as high as 0.6 m/s (2 ft/s) could be used for accurate measurement of the above described river, partly because the river (figs. 9.6 and 9.7) is 9 m (30 ft) deep. If the river depth were shallow [3 m (10 ft) or less], the boat would have to be slowed to the mean water velocity to maintain a reasonable precision (a CV of less than 5 percent) (fig. 9.10).

Examination of fig. 9.6 reveals that the length of time required for the river traverse increases exponentially as mean river velocities approach 0. The requirement for this extended averaging period begins to defeat the purpose of the BB-ADCP measurement system at very shallow depths and low velocities. Water mode 5 should be used, if possible, in these cases because it will reduce the above described discharge-measurement errors by almost an order of magnitude, however, its use is limited to rivers having little shear or turbulence. For 600-kHz BB-ADCPs, water mode 8 can be useful in shallow water if the vessel is slowed to reduce the higher random error of mode 8 operation.

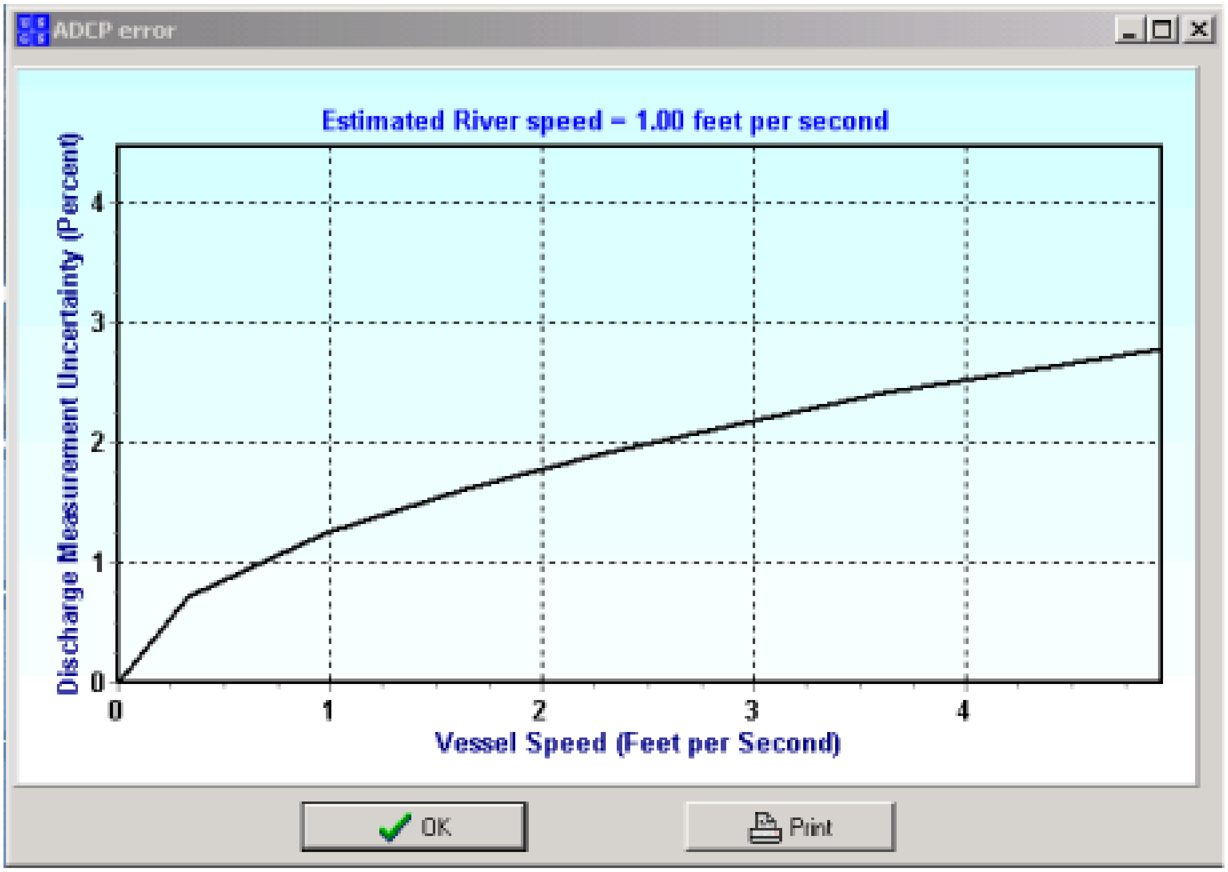

Figure 9.8. Discharge error with a mean water velocity of about 0.3 meter per second (1.0 foot per second). ADCP, acoustic Doppler current profiler.

Bias Error

Discharge-measurement random error can be reduced by data averaging (slowing the vessel speed for the measurement transect), as discussed above. Bias (systematic) errors cannot be reduced by data averaging.

Bias error can be separated into two classes: instrument error and operator error. Instrument error is due to physical, electrical, or acoustical limitations of the BB-ADCP instrument (or defects in the BB-ADCP hardware and firmware). Operator error is caused by improper BB-ADCP installation, setup, and, in some cases, application.

Instrument-Caused Bias Error

There are many sources of instrument bias error. Some are more significant than others. This report will not attempt a discussion of ADCP systematic error sources related to the physics of the acoustic signal (other than beam-pointing angles and depth measurements) because many of these sources are not yet documented and are beyond the scope of this report.

The manufacturer is aware of many of these types of errors and reports that the two most important of these are water-velocity measurement errors, due to selective absorption (nonuniform signal absorption in the water mass over the transmitted signal spectrum), and bottom-track errors due to terrain effect (the leading edge of the acoustic beam is far20ther away from the transducer than is the trailing edge when it impinges the channel bottom). These and other errors are thought by the manufacturer to be small and insignificant for most applications (Joel Gast, R.D. Instruments, Inc., oral commun., 1992). The following paragraphs will discuss or revisit instrument errors that significantly can affect the accuracy of an ADCP discharge measurement. These errors are as follows:

- Beam-angle errors.
- Depth-measurement errors.
- Speed-of-sound errors due to temperature and salinity.
- Bias errors caused by improperly estimating the unmeasured portions of the cross section.
- Operator-caused bias errors.

Figure 9.9. Discharge error in deep water [9 meters (30 feet)] with a mean river velocity of about 0.15 meter per second (0.5 foot per second). ADCP, acoustic Doppler current profiler.

Beam-Angle Errors

Errors in the beam-pointing angles (discussed in the velocity-error section) have an equivalent affect on the accuracy of discharge measurements.

Depth-Measurement Errors

The Transect software uses depth measured from the four acoustic beams to calculate mean depth for each discharge-measurement subsection. These depth-measurement errors can come from two sources:

- Depth sampling errors due to limitations of the acoustic beams and bin sizes.
- Depth errors due to improper estimation of speed of sound.

Figure 9.11 shows an exaggerated instance of depth error due to limitations of the acoustic beams. If only a few depth measurements were taken, per cross-section traverse, this type of error would be significant. However, the averaged depth is calculated using all four beam depths for each ensemble and, if the ensembles are kept short enough, the mound (fig. 9.8) will be integrated into the total cross-section averaged depth. A typical BB-ADCP discharge measurement collects many more depth measurements during the cross-section traverse than are collected using conventional methods.

Near the bank edges, the BB-ADCP beams oriented toward shore will show shallow depths, whereas the beams oriented toward the channel will show greater depths. An average of all four beams will approximate the vertical depth from the center of the BB-ADCP transducer assembly to the bottom. In pitch and roll conditions, averaged depth measurements from all four acoustic beams will be more accurate than depths measured by a single, vertically placed, depth sounder because of the large beam “footprint” or pattern.

Speed-of-Sound Errors Due to Temperature and Salinity Gradients

Speed-of-sound errors (discussed in the ADCP Velocity-Measurement Limitations and Uncertainties section of this chapter) affect the accuracy of discharge measurements in the same way that they affect the accuracy of velocity measurements. These uncertainties

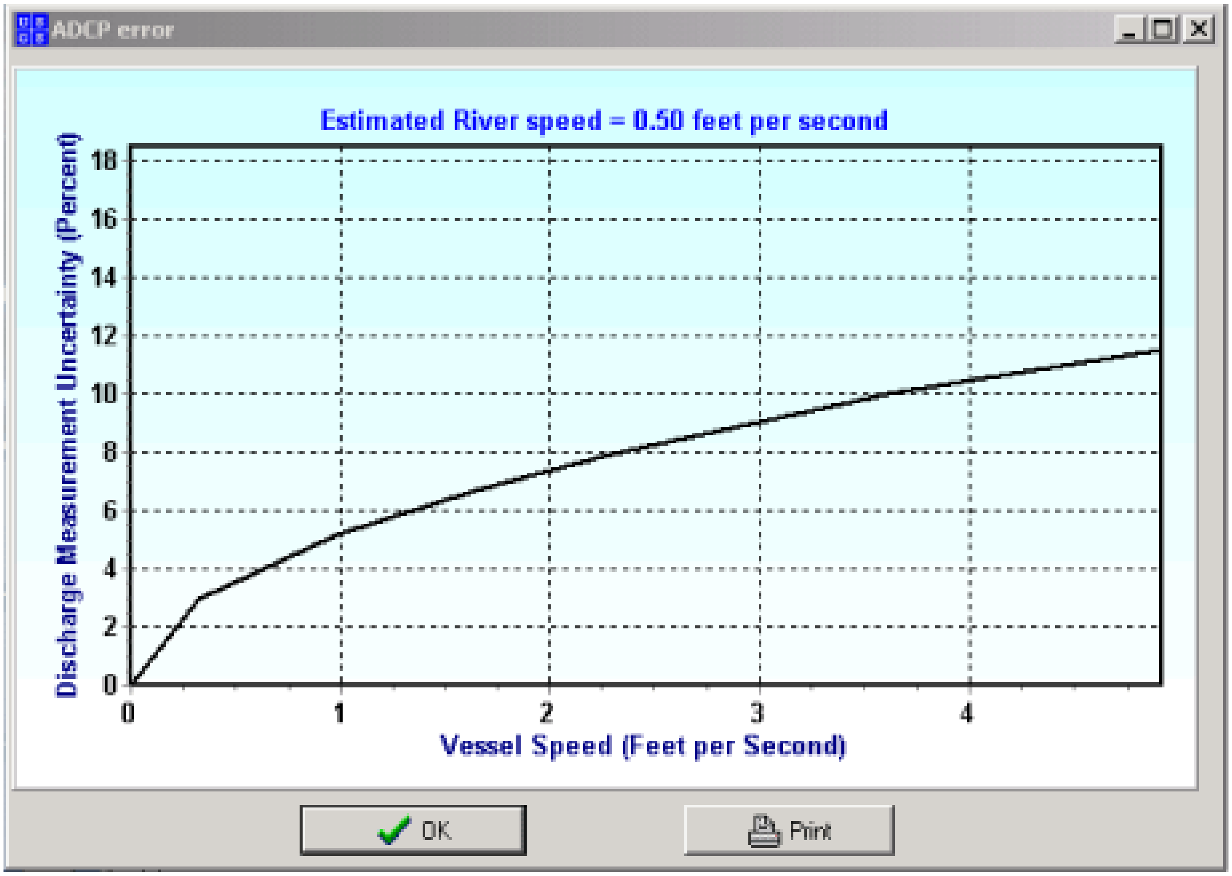

Figure 9.10. Discharge error in shallow water [3 meters (10 feet)] with a mean river velocity of about 0.15 meter per second (0.5 foot per second). ADCP, acoustic Doppler current profiler.

are subtle and hard to spot in the collected data. Close attention to detail is required by the ADCP operator to eliminate speed-of-sound uncertainties.

Bias Error Due to Incorrect Estimation of Unmeasured Velocities Near the Water Surface and Channel Bottom

Errors of this type are called extrapolation errors. An example of a nonstandard velocity profile is shown in chapter 8 to illustrate this error. The extrapolation scheme used to estimate cross products near the water surface and channel bed assumes a “Manning-like” velocity profile. The unmeasured area near the bottom usually is not a problem because the velocity must go to zero at some point close to the bed. However, the unmeasured area near the water surface is problematic, particularly in wind-affected cross sections and in estuaries. Wind effects can cause nonstandard profiles that are significantly biased (near the water surface). In these cases, the POWER estimation scheme (used in the Transect program) can be changed to CONSTANT.

In the estuaries and other backwater-affected sites, gravitational circulation sometimes can cause nonstandard profiles as well as bidirectional flow. Examination of the Transect program playback files can sometimes reveal nonstandard profiles and can provide the basis for a revised power-fit coefficient (chap. 8). In cases of bidirectional flow, the estimation scheme should be changed to CONSTANT on the bottom and CONSTANT at the surface because a power function extrapolation mathematically cannot cross zero. In bidirectional flows, the velocities may be positive (flowing downstream) in the upper portion of the water column and be negative (flowing upstream) in the lower portion of the water column.

Fortunately, extrapolation errors can be corrected during data playback. The raw recorded data are not affected by changing the extrapolation scheme, and the operator and office analyst can use trial-and-error techniques to reduce bias error that is due to incorrect estimation of unmeasured cross products.

Operator-Caused Bias Error

Operators can introduce a number of bias errors affecting a discharge measurement. Many of these

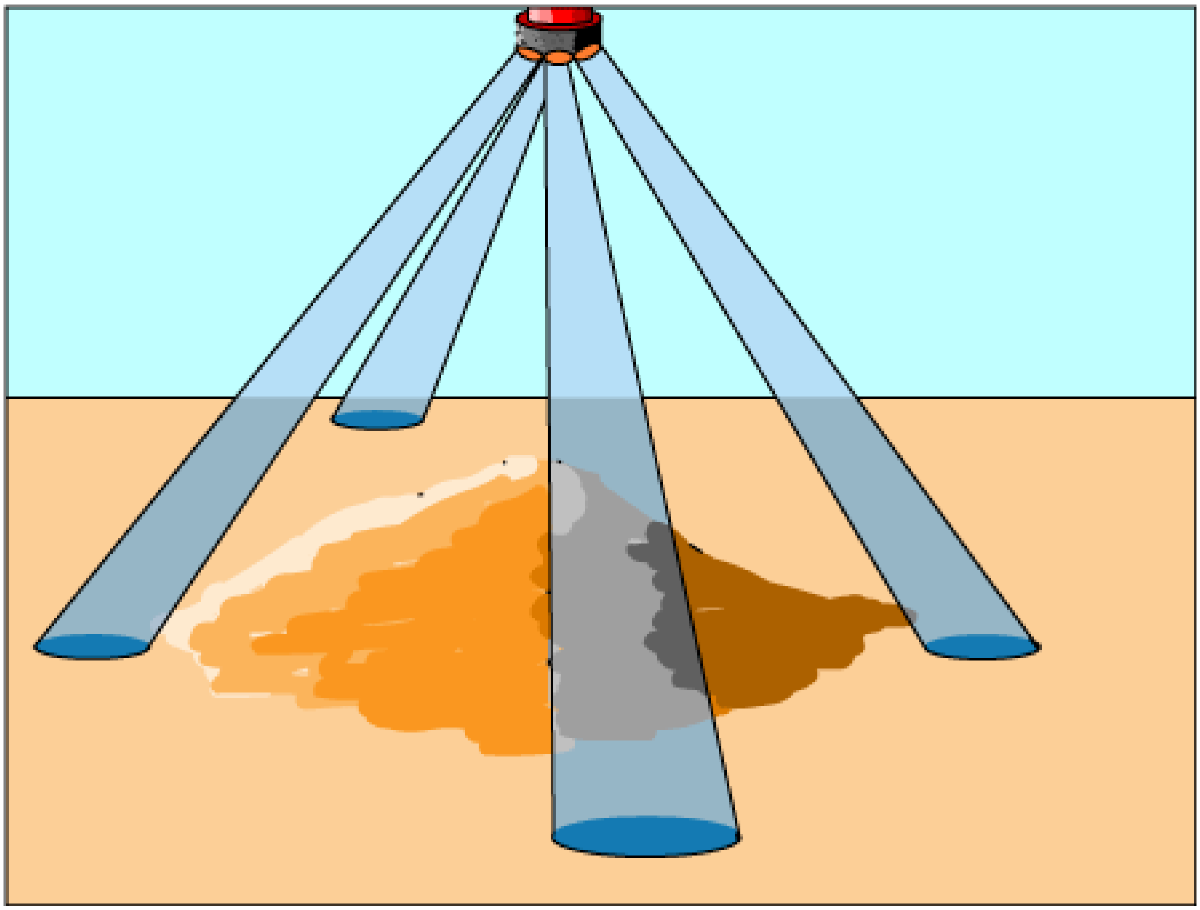

Figure 9.11. Exaggerated instance of depth error due to limitations of the acoustic beams.

errors have been covered in previous chapters, but are summarized here.

Incorrect Transducer Draft

This error probably is the most common operator-caused bias error. Missetting the transducer draft can cause significant discharge-measurement errors, particularly in wide, shallow channels.

Improper Broad-Band Acoustic Doppler Current Profiler Mounting

If the BB-ADCP is mounted to the side of the boat keel and in the boat wake, entrained air can cause occlusion of one or more BB-ADCP beams. A BB-ADCP that is mounted too high near the boat hull can suffer from the “good side/bad side” effect. The “good side/bad side” effect manifests itself in a series of discharge measurements that seem to be directionally biased. For example, discharges measured from right to left bank seem to be significantly different from discharges measured from left to right bank. Victor Levesque (U.S. Geological Survey, oral commun., 1996) has quantified this error and has associated it with the venturi effect of the boat hull on flowing water: water passing under the boat hull is slowed on the streamward side of the boat, and accelerated on the downstream side of the boat. This effect causes bias in the uppermost bins. Averaging <u>even</u> numbers of transects can help reduce this error.

Incorrect Edge-Distance Estimates

Distances to the riverbank are almost always underestimated unless the operator is very close to the riverbank when the distance is estimated. This underestimation can cause a significant bias error, if undetected.

Incorrect Estimated Edge Shapes

In narrow channels, significant bias errors can result from incorrectly characterizing the near-bank geometry. Rectangular-shaped edge-discharge areas can contain significant amounts of unmeasured discharge if the triangular edge algorithm is used for edge-discharge estimation.

Bottom Movement

As a general rule of thumb, all discharge measurement series taken where velocities are greater than 1 ft/s or where bottom movement is suspected should be followed or preceded by a bottom movement check (chap. 8).

Configuration-File Error

Every BB-ADCP operator undoubtedly has collected transects with the wrong configuration file or has inserted incorrect direct commands in the configuration file (at least once). Attention to detail will help eliminate this error.

Poor Choice of Cross Sections

Because the BB-ADCP is such a versatile instrument, it is easy to measure discharge in a cross section that normally would be rejected for use with conventional methods. “Pan-handle”-shaped cross sections with deep channels near one side of the river are examples of poor cross sections. The beam “foot-print” (with accompanying side lobes) becomes larger as depths increase. Discharge in a submerged canyon may be unmeasurable because the beams and side lobes impinge the canyon walls. Proper reconnaissance and experience will help in choosing a cross section that eliminates bias problems due to this effect.

Common Sense Rules

By following the common sense rules listed below, errors in discharge measurements can be reduced or eliminated:

- Be a smooth operator! The BB-ADCP discharge-measurement system will give more consistent results if rapid movements and course changes are kept to a minimum. Smooth boat motion is more important than a straight-line course
- Be observant! Are the edge flows moving in the same direction as the main body of flow? Did the wind come up? Did a motorboat pass the bow of the measurement vessel during the transect? This information may be needed during playback to properly evaluate the discharge measurement
- Is the discharge-measurement vessel moving slowly enough? The more pings collected during a discharge measurement, the more precise the measurement
- Examine discharge data on site, if possible. Problems with improper setup may not appear until the measurements are replayed
- Don’t trust an “eyeball” edge estimate. Most people tend to underestimate the distance to shore unless the vessel is very close to shore when the estimation is attempted
- Don't be afraid to ask for help! Experienced BB-ADCP operators carry a cellular phone, a long list of phone numbers, and are not afraid to ask, “What gives here?” Only novice operators are too proud to ask for help.

Summary

If high sediment loads are not present, errors in acoustic Doppler current profiler (ADCP) discharge measurements usually are caused by traversing the river too fast during the discharge measurement. As a rule, the vessel should traverse the river at the approximate speed of the mean water velocity to obtain consistently precise discharge measurements. When measuring wide, deep rivers or estuaries, the operator should use equation 9.1 to estimate correct vessel traverse rates, if possible. If the operator checks the standard deviation of the discharge measurements at the measurement site he or she can easily determine if the discharge measurements have too much scatter (5 percent or greater). If such is the case, the boat traverse rate can be slowed and the measurements can be redone. Most bias errors can be eliminated with proper attention to detail.

REFERENCES CITED

Buchanan, T.J., and Somers, W.P., 1969, Discharge measurements at gaging stations: Techniques of water resources investigations of the United States Geological Survey, book 3, chap. A8, 68 p.

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

Chereskin, T.K., Firing, Eric, and Gast, J.A., 1989, On identifying and screening filter skew and noise bias in acoustic Doppler current profiler instruments: Journal of atmospheric and Oceanic Technology, v. 6, p. 1040–1054.

Christensen, J.L., and Herrick, L.E., 1982, Mississippi River Test, Volume 1. Final report DCP4400/300, prepared for the U.S. Geological Survey by AMETEK/Straza Division, El Cajon, California, under contract No. 14–08–001–19003, p. A5–A10.

Doppler, J.C., 1842, Über das farbige Licht der Doppelsterne und einiger anderer Gestirne des Himmels: Abn.königl.böhm.Ges.Wiss, v. 2, p. 465–482.

Fulford, J.M., and Sauer, V.B., 1986, Comparison of velocity interpolation methods for computing open-channel discharge *in* S.Y. Subitsky (ed.) Selected papers in the hydrologic sciences: U.S. Geological Survey Water-Supply Paper 2290, 154 p.

Hansen, S.D., 1986, Design and calibration issues for current profiling systems. High-frequency volumetric backscattering in an oceanic environment: IEEE Third Working Conference on Current Measurement, January 22–24, 1986, Airlie, Virginia, (Proc.), p. 191–202.

Lipscomb, S.W., 1995, Quality assurance plan for discharge measurements using broad band acoustic Doppler current profilers: U.S. Geological Survey Open-File Report 95–701, 7 p.

Matalas, N.C., and Langbein, W.B., 1962, Information content of the mean: Journal of Geophysical Research, v. 67, no. 9, p. 3,441–3,448.

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

Minkoff, John, 1992, Signals, noise, and active sensors. Radar, sonar, laser radar: John Wiley and Sons, Inc., New York, 249 p.

Oberg, K.A., U.S. Geological Survey acoustic Doppler current profiler Office of Surface Water support pages. http://il.water.usgs.gov/adcp. Accessed July 1998.

Oberg, K.A., and Schmidt, A.R., 1994, Measurements of leakage from Lake Michigan through three structures near Chicago, Illinois, April–October 1993: U.S. Geological Survey Water-Resources Investigations Report 94-4112, 48 p.

R.D. Instruments, Inc., 1989, Acoustic Doppler current profilers—Principles of operation. A practical primer: R.D. Instruments, San Diego, California, 36 p.

———, 1994, Users manual for R.D. Instruments' Transect Program for use with broadband acoustic current profilers: R.D. Instruments, Inc., San Diego, California, 190 p.

———, 1995, Direct reading and self contained broadband acoustic Doppler current profiler technical manual for Firmware version 5.XX: R.D. Instruments, Inc., San Diego, California, 460 p.

———, 1996, Principals of operation. A practical primer for broadband acoustic Doppler current profilers (2nd ed.): R.D. Instruments, Inc., San Diego, California, 51 p.

———, 1999, Workhorse Rio Grande technical manual. P/N 957-6101-00. http://www.rdinstruments.com. Accessed February 2000.

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.

Theriault, D.B., 1986, Incoherent multibeam Doppler current profiler performance: IEEE Journal of Oceanic Engineering, v. 11, no. 1, p. 7–25.

Urick, R.J., 1975, Principles of underwater sound. (2nd ed.): McGraw-Hill, San Francisco, California, 375 p.