

Discharge-Measurement System  
Using an Acoustic Doppler Current  
Profiler with Applications to Large  
Rivers and Estuaries

United States  
Geological  
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# Discharge-Measurement System Using an Acoustic Doppler Current Profiler with Applications to Large Rivers and Estuaries

By MICHAEL R. SIMPSON and RICHARD N. OLTMANN

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## Conversion Factors

Multiply	By	To obtain
centimeter (cm)	0.3937	inch
centimeter per second (cm/s)	0.03281	foot per second
meter (m)	3.281	foot
meter per second (m/s)	3.281	foot per second
cubic meter per second (m <sup>3</sup> /s)	35.31	cubic foot per second
kilometer (km)	0.6214	mile
square kilometer (km <sup>2</sup> )	0.3861	square mile

# Discharge-Measurement System Using an Acoustic Doppler Current Profiler with Applications to Large Rivers and Estuaries

By Michael R. Simpson and Richard N. Oltmann

## Abstract

Discharge measurement of large rivers and estuaries is difficult, time consuming, and sometimes dangerous. Frequently, discharge measurements cannot be made in tide-affected rivers and estuaries using conventional discharge-measurement techniques because of dynamic discharge conditions. The acoustic Doppler discharge-measurement system (ADDMS) was developed by the U.S. Geological Survey using a vessel-mounted acoustic Doppler current profiler coupled with specialized computer software to measure horizontal water velocity at 1-meter vertical intervals in the water column. The system computes discharge from water- and vessel-velocity data supplied by the ADDMS using vector-algebra algorithms included in the discharge-measurement software. With this system, a discharge measurement can be obtained by engaging the computer software and traversing a river or estuary from bank to bank; discharge in parts of the river or estuarine cross sections that cannot be measured because of ADDMS depth limitations are estimated by the system. Comparisons of ADDMS-measured discharges with ultrasonic-velocity-meter-measured discharges, along with error-analysis data, have confirmed that discharges provided by the ADDMS are at least as accurate as those produced using conventional methods. In addition, the advantage of a much shorter measurement time (2 minutes using the ADDMS compared with 1 hour or longer using conventional methods) has enabled use of the ADDMS for several applications where conventional discharge methods could not have been used with the required accuracy because of dynamic discharge conditions.

## INTRODUCTION

Accurate discharge measurement of large rivers and estuaries has been a problem faced by hydrologists for many years. If a suitable bridge is not available from which to make conventional current-meter measurements, a tag line is suspended across the river and a small boat is attached to the tag line. (Use of a tag line is generally restricted to channels with widths of 250 m or less.) The boat then

traverses the river cross section, stopping at 25 or more positions where depth and two or more velocity measurements are made. Measurements of this type usually take 1 hour or longer, while the tag line poses a significant navigational hazard. The tag line often must be dropped to permit passage of boat traffic, thereby increasing the duration of the discharge measurement and increasing the chance for accidents. In estuaries, the duration of a discharge measurement is critical because of the dynamic discharge conditions. In these conditions, conventional, stationary-boat, current-meter measurement techniques cannot be used to measure river discharge accurately (Smoot and Novak, 1969).

## Previous Attempts to Measure River Discharge From a Moving Boat

Since 1967, in an attempt to eliminate the problems described above, the U.S. Geological Survey has developed or encouraged the development of equipment designed to measure river discharge from a moving vessel. Ingerson (1955), Prych and others (1967), N.A. Kallio (U.S. Geological Survey, written commun., 1968), Smoot and Novak (1969), and Smith (1971) have designed moving-boat discharge-measuring systems that have had varying degrees of success. All of these systems, however, have deficiencies that limit their use when accuracy (5 percent or better) and speed are desired and when used in estuaries. One major stumbling block found in all of these systems is that their accuracy depends on the skill of the vessel driver and, to a lesser extent, of the measurement crew. Errors in velocity measurement can be as high as 20 percent when vessel velocities are in excess of 120 cm/s and water velocities are less than 30 cm/s (Smith, 1971). These systems typically measure velocity at only one or two points in the water column, and corrections must be applied to these measurements to obtain a mean velocity for the water column; it has been shown that one or two

points in the vertical do not always adequately define the vertical velocity distribution in estuaries (Smith, 1971).

In 1982, a system using an acoustic Doppler current profiler (ADCP) was used to measure the discharge of the Mississippi River at Baton Rouge, Louisiana (Christensen and Herrick, 1982). ADCP-measured discharges differed less than 5 percent from simultaneous conventional discharge measurements, which was encouraging. However, the computer software and hardware were incapable of converting the velocity data provided by the profiler on a real-time basis; the discharge values had to be computed later. Although this technology looked very promising at the time of these tests, computer and Doppler signal-processing technology had not progressed to the level needed to collect and compute reliable river and estuarine discharge measurements.

## Purpose and Scope

The purpose of this report is to describe the development of a discharge-measurement system that uses a vessel-mounted ADCP to measure river and estuarine discharges. The ADCP, when used with the discharge-measurement software, is referred to as the acoustic Doppler discharge-measurement system (ADDMS) in this report. The ADCP system used is a different version of the one used during the 1982 Mississippi River measurements (Christensen and Herrick, 1982). This report describes the operation of an ADCP, the computer program (software) that calculates discharge from velocity data provided by the ADCP, field testing of the system, and several applications of the system.

## DESCRIPTION OF AN ACOUSTIC DOPPLER CURRENT PROFILER AND ITS APPLICABILITY FOR DISCHARGE MEASUREMENT

The U.S. Geological Survey purchased a model VM-1200 ADCP system from RD Instruments in 1985. The purpose of this acquisition was (1) to evaluate the use of the ADCP for velocity profiling in rivers and estuaries and (2) to use the ADCP to collect velocity information to support the Survey's investigation of water circulation in San Francisco Bay and the Sacramento/San Joaquin River Delta. The ADCP also was to be evaluated for possible use as part of a moving-boat discharge-measurement system.

### Description of the Acoustic Doppler Current Profiler

The ADCP system uses an acoustic Doppler technique to measure vertical profiles of horizontal water currents from a moving vessel. The ADCP transmits 1.2-MHz

(megahertz) acoustic pulses (using a transducer assembly) along each of four beams that are positioned 90° apart horizontally and directed downward into the water column at an angle of 30° from vertical (fig. 1). Part of the transmitted acoustic energy is reflected back toward the transducers by particulate matter (scatterers) moving with the water. The frequency of these reflected signals is shifted because of Doppler effect (Urlick, 1975, p. 254–257), and the magnitude of the frequency shift is a function of the speed of the scatterers along the acoustic beams. The ADCP converts these frequency shifts into water speeds. By using simple trigonometry and water speeds calculated from adjacent beams, the ADCP is capable of resolving both horizontal water speed and direction. The ADCP samples reflected signals from each beam at discrete time intervals during the progress of the advancing acoustic wave front; this allows horizontal water velocities to be determined at each of these intervals (bins). In practice, however, these bins do not have distinct boundaries and overlap somewhat; the distance between bin centers is accurately controlled by timing circuits in the ADCP. These bins can be thought of as vertical "windows" in the water column, containing horizontal water-velocity information. The height of these bins can be adjusted by manipulating ADCP software parameters.

The vessel velocity relative to the channel bottom is measured by the ADCP system using the results of a Doppler-shift measurement (from each beam) of bottom-reflected acoustic signals. This measurement is distinct from the water-velocity measurement and is referred to as a bottom-track measurement. Speed of sound used in the calculation of water and vessel velocities is calculated using temperature measured at the transducer face and estimated values of salinity. Because of the effects described by Snell's law, variation of sound speed with depth will not affect the estimate of either the horizontal current or vessel velocities (see RD Instruments, 1989).

The ADCP system consists of transducers, sensors, and data-processing equipment that interconnect to form an integrated system (fig. 2). These components consist of the following:

1. A 17.1-cm-diameter ADCP transducer assembly that includes four acoustic transducer elements, transmit/receive amplifiers, and a thermistor. The thermistor data are used by the ADCP to calculate the speed of sound in water.
2. A heading gyroscope, an attitude-sensing gyroscope, and a 400-Hz (hertz) gyroscope alternating-current (AC) supply.
3. A depth sounder/digitizer combination with a separate 200-kHz (kilohertz) transducer.
4. An electronics unit (deck unit) that contains data-acquisition and signal-processing electronics for the transducer assembly, heading and vessel-attitude-sensing gyroscopes, and the depth sensor. This electronics unit

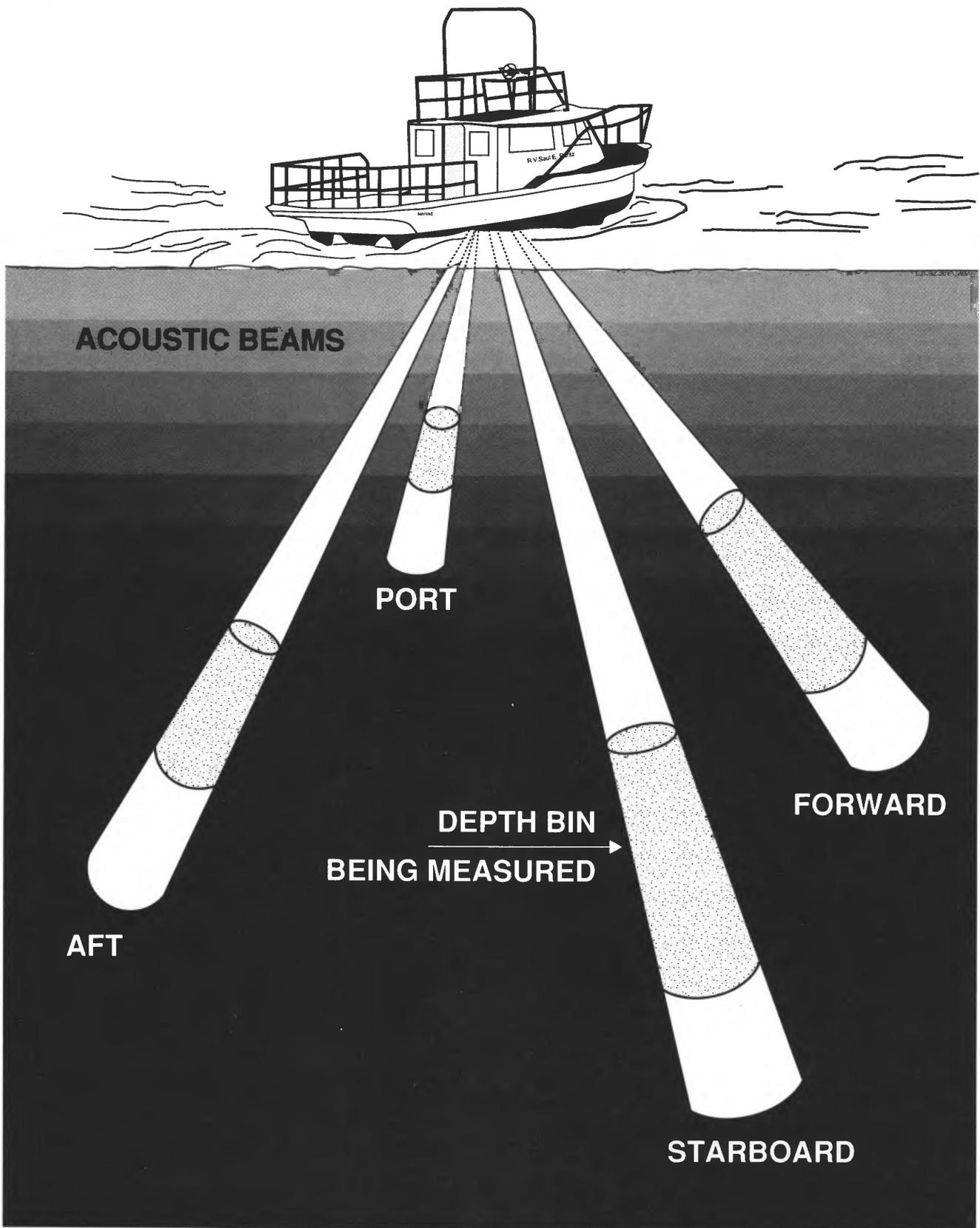


Figure 1. Beam configuration of acoustic Doppler current profiler.

also contains serial and parallel interface electronics for communication to outside data-processing equipment.

5. A computerized data-acquisition system with dual 9-cm diskette drives, a high-capacity (67-megabyte) cartridge tape recorder, and a 10-megabyte hard disk.

The ADCP can transmit and acquire acoustic data and can calculate water velocity for each depth bin at a rate of up to 10 profile measurements (pings) per second. For most profiling applications, 8 to 10 pings are averaged for each bin and are recorded along with several vessel-velocity (bottom-track) pings. The ratio of profile pings to bottom-track pings is controlled by the ADCP software and can be manipulated by the ADCP operator. A group of velocity-profile data and vessel-velocity data is called an ensemble. The length of time to collect an ensemble depends on the ping averaging required by the application.

For profiling use, the ADCP is controlled through the computer using a program provided by the ADCP manufacturer. Velocity-profile data from an ensemble are displayed on the computer monitor, and individual ensembles can be stored on magnetic media for later replay and analysis.

## Current-Profiler Accuracy

Profiling accuracy tests were done in both lake and river environments. The lake environment provided near-zero water velocities that facilitated bottom-track accuracy determinations and also provided a stable setting for determining the variance of individual bin velocity measurements. The river environment provided an avenue for comparing ADCP-measured water velocities with water velocities measured with other types of current-measuring devices.

Lake tests (Simpson, 1986) revealed that the ADCP bottom-tracking accuracy on a 1,405-m distance course was within 2.0 percent of the distance as measured by an electronic distance meter. Results from the lake tests also showed that the ADCP short-term random error of water-velocity measurement from a moving vessel averaged 6.5 cm/s using a 1-second averaging period and was reduced to 2.3 cm/s using a 20-second averaging period. The standard deviation of ADCP-measured water velocity compared with averaging periods for the lake test is

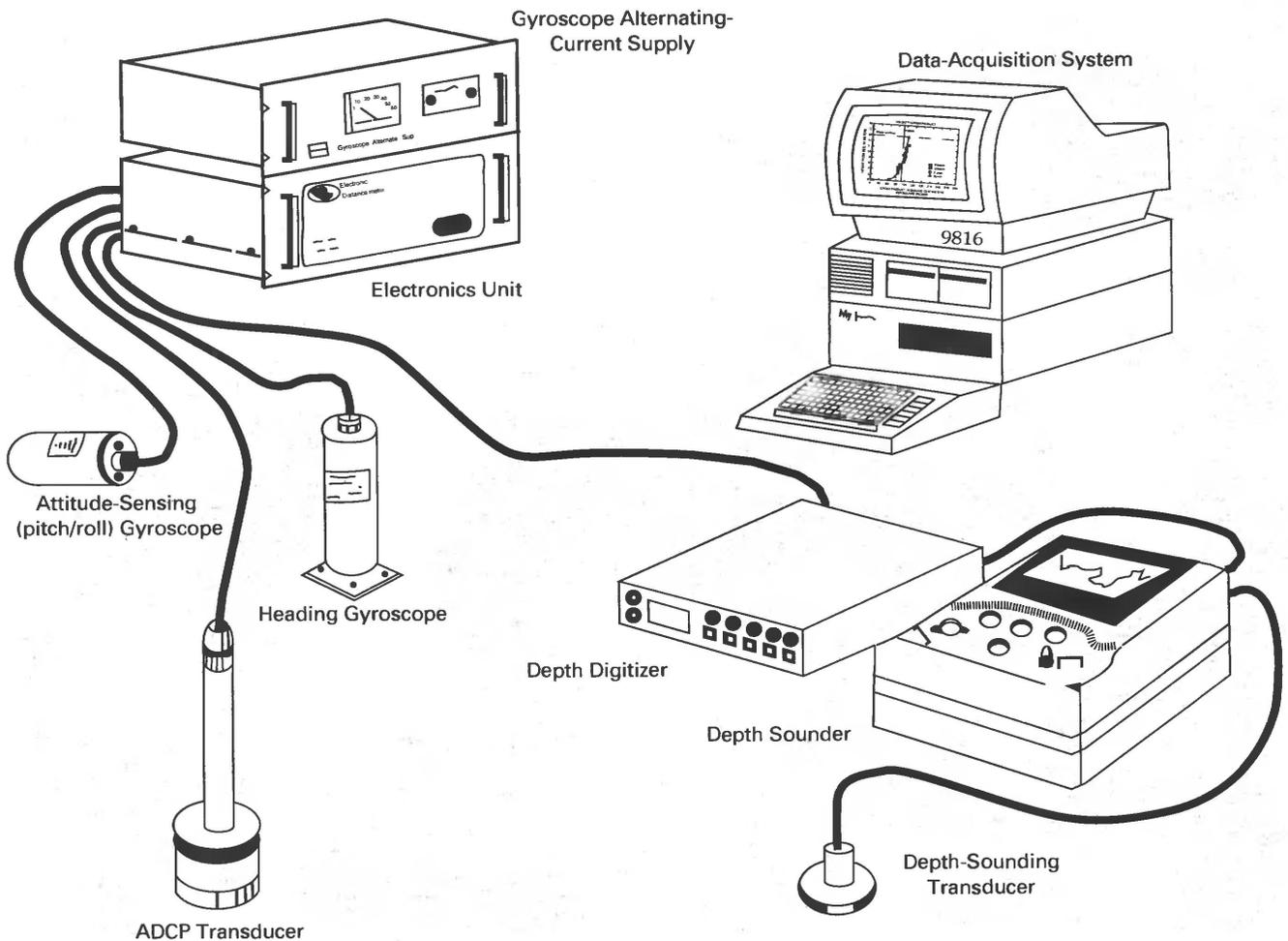


Figure 2. System components of acoustic Doppler current profiler (ADCP).

shown in figure 3 (taken from Simpson, 1986). Tests performed using different vessel compass headings and vessel speeds detected no discernible directional bias. The near-zero lake water velocities were verified using conventional current meters.

The river tests indicated differences of 3.0 percent or less among ADCP-measured velocities, Price AA current-meter-measured speeds, and Neil Brown acoustic-velocity-meter- (SACM) measured velocities.

The lake and river tests demonstrated that the ADCP provided an accurate measure of water velocity if an adequate averaging interval (20 seconds or more) was maintained. The test results indicated that the ADCP system could be used for collecting moving-boat discharge measurements (Simpson, 1986).

### Current-Profiler Limitations

The RD Instruments model VM-1200 ADCP system, when used for moving-boat discharge measurements and for velocity profiling in shallow water, has limitations. The transducers supplied with the ADCP (and most other transducers designed using present technology) emit parasitic side lobes about 30° off their main axes (fig. 4). When the main beams are directed 30° from the vertical, the more vertical side lobes are strongly reflected off the bottom and interfere with the ADCP-measured velocity profiles in the lower 15 to 25 percent of the water column. Additionally, after transmitting the acoustic pulses, the transducers and associated electronics must recover for a short time before being used to receive the incoming acoustic reflections. The acoustic pulses travel about 0.3 m during this time, and velocity data cannot be collected within this distance

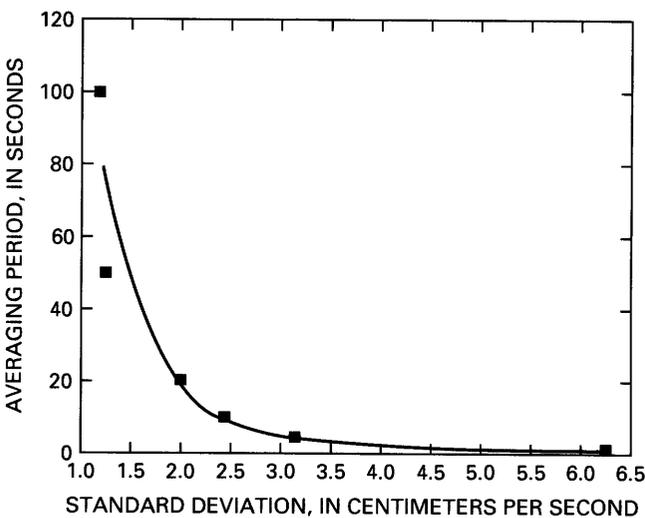


Figure 3. Standard deviation of acoustic Doppler current-profiler velocity data compared with averaging periods for the lake test (from Simpson, 1986).

(blanking distance) (fig. 4). The center of the first bin is 1 m below the 0.3-m blanking distance. Thus, if the ADCP is profiling in 30 m of water, and the transducer draft (or depth) is 0.6 m, the actual profiled range starts at the top of the first bin, which is 1.4 m (1.9–0.5 m) below the water surface and ends at a depth of about 25 m.

Because of these limitations and a minimum depth limitation imposed by the bottom-track pulse length (3 m), the ADCP has a minimum profiling depth of about 3.4 m. Therefore, velocity-profile data cannot be collected within a certain distance of the bank of a river channel. The size of this unmeasured area will depend on the channel depth near the shore and the vessel's maneuverability and draft. In narrow, nonrectangular channels, a significant part of the discharge can occur in these unmeasured areas.

## DEVELOPMENT OF THE ACOUSTIC DOPPLER DISCHARGE-MEASUREMENT SYSTEM

### Discharge-Measurement Algorithms

An algorithm for computing discharge from ADCP water-velocity profile and bottom-track data was developed by K.L. Deines for tests on the Mississippi River in 1982 (Christensen and Herrick, 1982). An advantage of this measurement algorithm was that the vessel did not have to maintain a straight course while traversing a river. In fact, the vessel could traverse a river diagonally or along any arbitrary path (bank to bank) and still collect an accurate discharge measurement.

The general equation for determining river discharge through an arbitrary surface  $s$  is

$$Q_t = \int_s \bar{V}_f \cdot \bar{n} \, ds, \quad (1)$$

where

$Q_t$  = total river discharge,

$\bar{V}_f$  = mean water-velocity vector,

$\bar{n}$  = a unit vector normal to  $ds$  at a general point, and

$ds$  = differential area.

For moving-boat discharge applications, the area of  $s$  is defined by the vertical surface beneath the path along which the vessel travels. The dot product of  $\bar{V}_f \cdot \bar{n}$  will equal zero when the vessel is moving directly upstream or downstream and will equal  $|\bar{V}_f|$  when the vessel is moving normal to  $\bar{V}_f$ . (Both vectors are in the horizontal plane.)

Because the ADCP provides both vessel-velocity and water-velocity data in the vessel's coordinate system, it is convenient to recast equation 1 in the following form (from Christensen and Herrick, 1982):

$$Q_t = \int_0^{Td} \iint (\bar{V}_f \times \bar{V}_b) \cdot \bar{k} \, dz \, dt, \quad (2)$$

where

$T$  = total cross-section traverse time,  
 $d$  = total depth,  
 $\bar{V}_b$  = mean vessel-velocity vector,  
 $\bar{k}$  = a unit vector in the vertical direction,  
 $dz$  = vertical differential depth, and  
 $dt$  = differential time.

The derivation of this equation by Christensen and Herrick (1982) is summarized in Appendix A. Converting  $(\bar{V}_f \times \bar{V}_b) \cdot \bar{k}$  into rectangular coordinates yields

$$\bar{V}_f = a_1 \bar{i} + a_2 \bar{j},$$

$$\bar{V}_b = b_1 \bar{i} + b_2 \bar{j},$$

and then

$$(\bar{V}_f \times \bar{V}_b) \cdot \bar{k} = a_1 b_2 - a_2 b_1, \quad (3)$$

where

$a_1$  = cross component of the mean water-velocity vector,  
 $a_2$  = fore/aft component of the mean water-velocity vector,  
 $b_1$  = cross component of the mean vessel-velocity vector,

$b_2$  = fore/aft component of the mean vessel-velocity vector,

$\bar{i}$  = unit vector in the cross-component direction, and

$\bar{j}$  = unit vector in the fore/aft-component direction.

For brevity, let  $f = a_1 b_2 - a_2 b_1$ .

The ADCP provides velocity data both in vessel-related coordinates and in earth-related coordinates. Either coordinate system can be used to compute discharge as long as both water and vessel velocities are described in the same system.

In practice, the discharge integral is approximated by a summation of many sections of measured discharge. The equation takes the form

$$Q_m = \sum_{i=1}^{N_s} \left[ \int_0^{d_i} f_i dz \right] t_i, \quad (4)$$

where

$Q_m$  = measured channel discharge (does not include the unmeasured near-shore discharge),

$N_s$  = number of measured discharge subsections,

$i$  = index for a subsection,

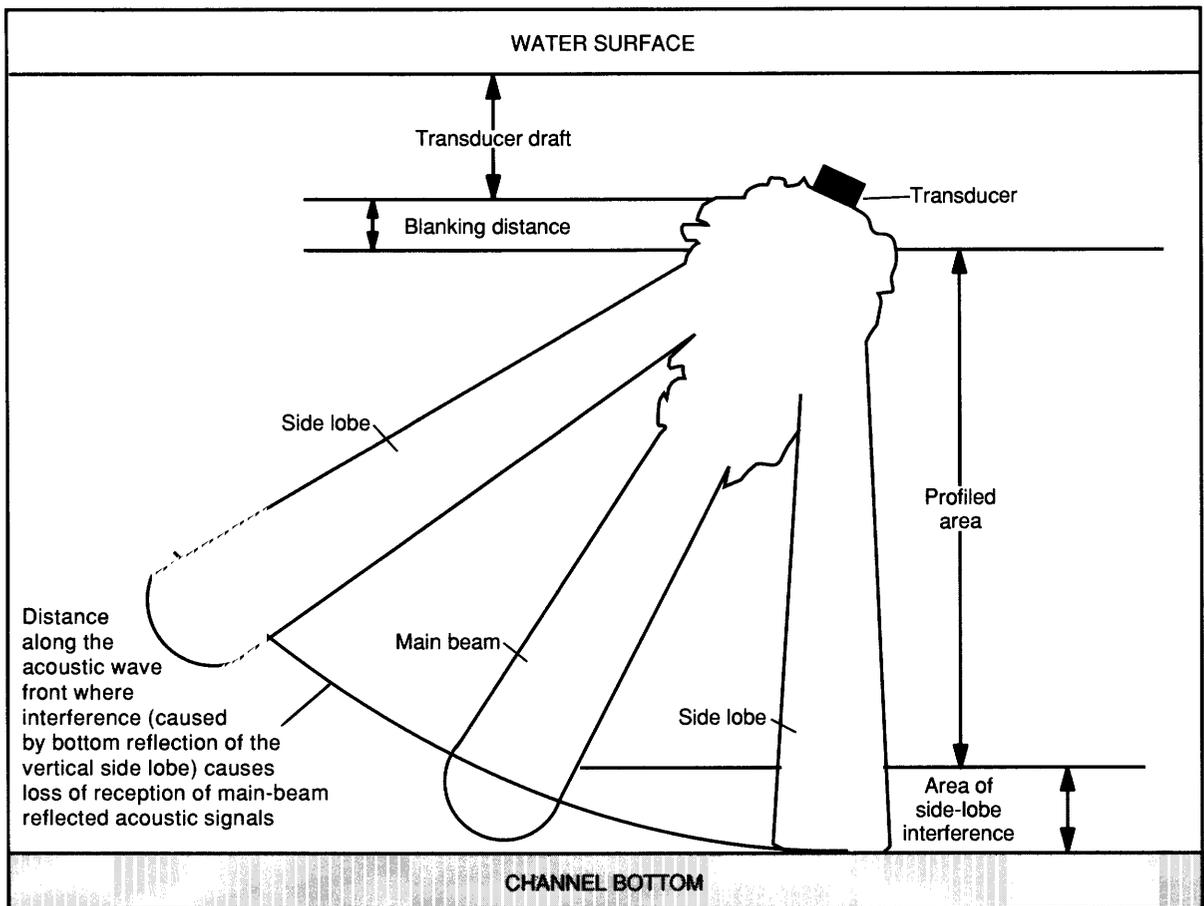


Figure 4. Beam pattern of acoustic Doppler current profiler, showing side-lobe interference and blanking distance.

- $d_i$  = depth of the subsection,
- $f_i$  = integrated  $f$  value for subsection  $i$ ,
- $dz$  = differential vertical depth of subsection  $i$ , and
- $t_i$  = elapsed traveltime between the ends of subsections  $i$  and  $i-1$ .

One significant drawback of the 1982 discharge-measurement system was the omission of an algorithm for estimating the discharge not measured by the ADCP.

## Development of the Discharge-Measurement System Software

During February 1988, the U.S. Geological Survey began development of software for use in computing discharge measurements from a moving vessel using a high-resolution ADCP data-acquisition system and the discharge computational algorithm developed by Deines (Christensen and Herrick, 1982).

The initial step in the development of the ADDMS software was to provide a means to record all velocity-profile data, time tags, and error information output by the ADCP during a traverse of a river channel. This capability enabled repeated simulation of actual field-measured velocities for testing various software and computational modifications.

Four major problems had to be addressed during the development of the software to provide accurate discharge measurements from data provided by the ADDMS.

1. The  $f$  value in equation 4 is assumed to be a mean  $f$  value for the entire discharge-measurement subsection  $i$ . However, in practice, the profiler does not provide  $f$  values over the entire depth within a given measurement subsection; instead, it provides  $f$  values for discrete bins over about 75 percent of the subsection. If we let  $f_j$  equal the discrete  $f$  value in bin  $j$  and  $z_j$  equal the vertical height of bin  $j$ , the  $f dz$  integral in equation 4 could be approximated by a simple summation of all the products of  $f_j$  and  $z_j$ . However, because  $f$  values are not available at or near the surface of the water and for the bottom 15 to 25 percent of the water column (as previously described), this method would not correctly approximate the value of the integral for the entire water column. Therefore, a method had to be devised to estimate these missing  $f$  values.
2. The unmeasured near-shore discharges had to be estimated by some means if the total river discharge was to be determined.
3. During the course of a discharge measurement, Doppler-shift measurement failures can occur on one or more acoustic beams due to conditions in the water. These failures can occur during determinations of water velocity or vessel velocity or when the vessel crosses a shallow midchannel bar. A method had to be found to estimate Doppler shifts on one or more acoustic beams

during these periods of failure. Throwing away the suspect data could introduce unacceptable errors.

4. At medium to high river flows, bottom-sediment movement can occur. The movement of this bottom sediment causes an upstream bias in the vessel-velocity determination. The resultant  $f$  values are of less magnitude than  $f$  values calculated during periods when no bottom-sediment movement occurs. Adjustment of ADCP bottom-track acquisition controls can reduce this unwanted bottom-sediment movement bias but cannot completely eliminate it. A method had to be devised that would estimate the average velocity of the bottom sediment and then use those data to define an adjustment coefficient that could be applied to the biased measured discharge.

A considerable amount of time and effort was expended solving these problems, and the software was modified numerous times before reasonable solutions were reached. These problems are discussed in the order that they are presented above.

### Estimating Missing Parts of the Velocity Profile

As shown in figure 5,  $f$  values are not provided at or near the water surface and below a point equal to 75 to 85 percent of the total depth of the water column. These unknown values are labeled as  $f_1$  at the water surface and  $f_n$  at the bottom. The simplest method for estimating these  $f$  values would be simply to let  $f_1$  ( $f$  at the surface) equal  $f_2$  and let  $f_n$  ( $f$  at the bottom) equal  $f_{n-1}$  and approximate the integral in equation 4 by using a trapezoidal calculation:

$$g_i = \sum_{j=1}^{n-1} ((f_j + f_{j+1})/2) (z_{j+1} - z_j), \quad (5)$$

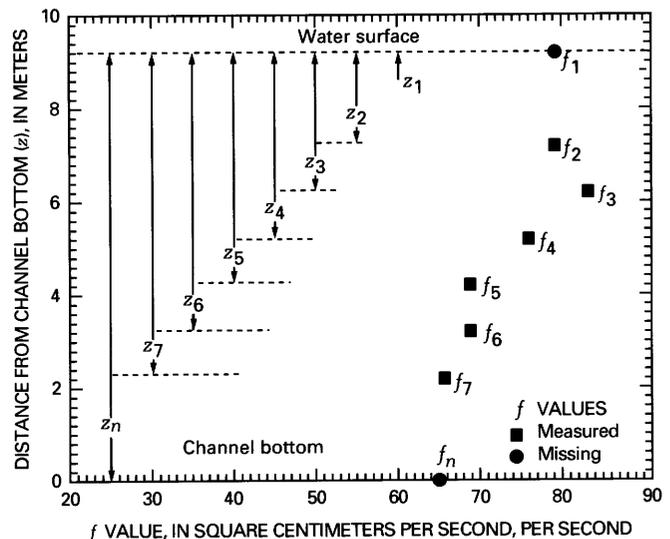


Figure 5. Typical vertical distribution of measured  $f$  values, using an acoustic Doppler discharge-measurement system, and locations where  $f$  values are needed.

where

$g_i$  = depth-weighted mean  $f$  value in measurement subsection  $i$ ,

$z_1, \dots, z_j$  = depth from water surface of respective measured and estimated  $f$  values,

$j$  = index of depths and respective  $f$  values, and

$n$  = number of measured and estimated  $f$  values.

A similar method may have been used by Christensen and Herrick (1982) during the Mississippi River tests, although no description was provided. One of the biggest drawbacks of this method is that it does not adequately adhere to accepted hydrologic descriptions of the vertical distribution of horizontal water velocities in open channels, particularly near the bottom boundary where the velocity drops off to zero.

Water-velocity distribution in pipes and open channels for fully developed turbulent flow has been extensively presented in the literature. Two widely accepted general velocity-distribution laws that can be used in open channels are the logarithmic velocity-distribution law, commonly known as the Prandtl-von Kármán velocity-distribution formula, and the power velocity-distribution law, which has been used in various forms by numerous investigators.

Initially, both laws were used along with a least-squares curve-fit procedure to estimate mean  $f$  values. The  $f$  values provided by the ADCP were curve fit to both the power and the logarithmic formulas, and mean  $f$  values were calculated by integrating the generated curves. The results were disappointing at times because the variability of the data resulted in unrealistic shapes of the generated velocity-distribution curves. This error was partly due to the absence of data points in the lower portion of the water column.

A method using a 1/6-power law (Chen, 1989) was eventually chosen.

The power velocity-distribution formula in its general form is

$$\frac{u}{u^*} = a \left( \frac{z}{z_0} \right)^m, \quad (6)$$

where

$z$  = distance from the channel bed,

$u$  = velocity at distance  $z$  from the bed,

$u^*$  = shear velocity,

$a$  = a constant,

$z_0$  = a value based on roughness, and

$m$  = an exponent.

Chen (1989) has shown that the power-law equivalent of Manning's formula for open channels is

$$\frac{u}{u^*} = 9.5 \left( \frac{z}{z_0} \right)^{1/6}. \quad (7)$$

Consolidating the terms not provided by the ADCP yields

$$u = \left[ \frac{9.5 (u^*)}{z_0^{1/6}} \right] z^{1/6}. \quad (8)$$

If we let  $a' = \left[ \frac{9.5 (u^*)}{z_0^{1/6}} \right]$ , then equation 8 becomes

$$u = a' z^{1/6}. \quad (9)$$

Solving equation 9 using ADCP measured values of  $u$  and  $z$  will provide a value for  $a'$ . However, as previously described, values of  $u$  are not used to directly compute discharge in the ADDMS. The  $f$  values used to compute discharge are cross products calculated from values of  $u$  and the vessel velocity. Because the vessel velocity remains constant for each subsection, the  $f$  values can be described as

$$f = \Phi(u), \quad (10)$$

where  $\Phi$  is a constant vector function applied to each measured  $u$  value in the profile. From equations 9 and 10 it can be seen that, although the magnitude of  $f$  values in an individual profile will be different from the magnitude of  $u$  values, the shapes of their respective vertical distribution curves are identical. Because we are interested in estimating unmeasured  $f$  values based on a hydrologically acceptable extrapolation of the vertical distribution curve formed by measured  $f$  values, and not in the absolute values of measured water velocities, equation 9 can be recast as

$$f = a'' z^{1/6}, \quad (11)$$

where  $a''$  is a coefficient to be calculated from values of  $f$  rather than  $u$ .

To calculate  $a''$ , a least-squares curve fit is calculated using ADDMS measured values of  $f$  and  $z$ :

$$a'' = \frac{\sum_{j=1}^n [f_j(z_j)^{1/6}]}{\sum_{j=1}^n [(z_j)^{1/6}]^2} \quad (12)$$

where

$n$  = total number of  $f, z$  determinations, and

$j$  = an individual  $f, z$  determination.

Once  $a''$  is determined for an individual profile, equation 11 can be used to estimate the  $f$  values that cannot be collected by the ADCP. In practice, the ADDMS software (using eqs. 11 and 12) provides estimated  $f$  values at the water surface and at 90 and 98 percent of the total depth (fig. 6).

This estimation scheme is only an approximation and emulates a Manning-like vertical distribution of horizontal water velocities. Powers as high as 1/2 and as low as 1/10 can be used to adjust the shape of the curve fit to emulate

profiles measured in an estuarine environment or in areas that have bedforms that produce “nonstandard” vertical distributions of water velocities. Work is in progress that will enable the ADDMS software to recognize “nonstandard” hydrologic conditions and provide alternative estimation schemes under those circumstances.

A typical  $f$ -value distribution profile is shown in figure 6. The dashed curve is a 1/6-power curve fit to the ADCP data using equation 11, and the circles are  $f$  values estimated using equation 11. The three estimated  $f$  values are included with the ADDMS measured  $f$  values and integrated over the depth using equation 5 to obtain a  $g_i$  value.

The discharge summation in equation 4 is accomplished using the following algorithm:

$$q_i = g_i t_i, \quad (13)$$

where

- $q_i$  = midsection discharge between measurement subsection  $i$  and subsection  $i-1$ ,
- $g_i$  = depth-weighted mean  $f$  value in measurement subsection  $i$ , and
- $t_i$  = vessel traveltime between measurement subsection  $i$  and  $i-1$ .

Total channel discharge  $q_m$  is the sum of all  $q_i$  determinations, not including estimates of the unmeasured near-shore discharges.

When discharge measurements are attempted at or near slack tide, the vertical distribution of horizontal water velocities in a measurement section can be bidirectional. That is, water near the surface can be moving in the opposite direction from water near the bottom. Under these conditions, curve-fitting procedures, as previously described,

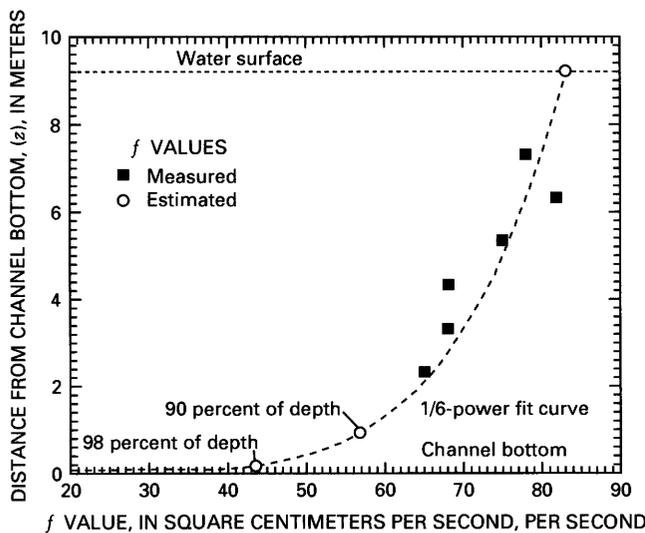


Figure 6. Example velocity profile showing measured  $f$  values, using an acoustic Doppler discharge-measurement system, 1/6-power curve fit, and location of estimated  $f$  values.

will not work. Occurrence of bidirectional flow is monitored by the software; if that condition exists, a simple depth-weighted mean of the measured  $f$  values is computed. The ADDMS operator is informed when bidirectional flow is occurring. The number of bidirectional measurements are totaled and can be used as an indicator of the accuracy of the discharge measurement.

### Estimating Near-Shore Discharge

Because of the previously described depth limitation of the ADCP, the software includes an algorithm for estimating discharge in those shallow regions that cannot be measured.

Fulford and Sauer (1986) described a ratio interpolation equation for estimating unknown velocity between the riverbank and the first or last known mean velocity in a cross section. The equation for an ADDMS estimate is

$$\frac{V_e}{\sqrt{d_e}} = \frac{V_m}{\sqrt{d_m}}, \quad (14)$$

where

- $e$  = a location midway between the riverbank and first or last ADDMS measured subsection,
- $V_e$  = estimated mean velocity at location  $e$ ,
- $V_m$  = mean velocity at the first or last ADDMS measured subsection,
- $d_e$  = depth at location  $e$ , and
- $d_m$  = depth at the first or last ADDMS measured subsection.

Fulford and Sauer (1986) defined  $d_m$  and  $V_m$  as depth and velocity at the center of the first or last measured subsection and not the near-shore edge of the subsection as presented in equation 14. However, because the ADCP subsections are purposely kept very narrow at the start and finish of each measurement, the differences between the two applications are not significant.

If a triangular discharge area is assumed between subsection  $m$  and the riverbank, equation 14 reduces to

$$V_e = 0.707 V_m. \quad (15)$$

Thus, the algorithm for determining edge discharge is

$$Q_e = \frac{0.707 V_m L d_m}{2}, \quad (16)$$

where

- $Q_e$  = estimated edge discharge, and
- $L$  = distance to the riverbank from the first or last ADDMS-measured subsection.

The software obtains depth ( $d_m$ ) for the ADDMS subsections from an external depth sounder. The distance ( $L$ ) to the riverbank from the first or last discharge-measurement subsection is provided by the measurement-system operator.

Several methods were investigated for estimating the distance to shore from the first or last measured subsection. The best results were obtained using an inexpensive optical rangefinder, which does not require specialized on-shore target devices.

A schematic diagram of the areas that are estimated using the methods previously discussed is shown in figure 7.

### Estimating Doppler Shifts When Beam Failure Occurs

Although the ADCP uses Doppler-shift information from four acoustic beams to compute velocities, only three beams are required to compute velocity in three orthogonal coordinates. The fourth beam is redundant and is used for additional accuracy of the Doppler-shift determination and as an error check. If a failure occurs on only one acoustic beam, a three-beam solution can be used to calculate a Doppler shift for the missing beam. This is done by adding together the frequency-count data from the two beams that are directly opposite each other, and subtracting the data from the beam that was directly opposite the missing beam to obtain an estimated frequency count for the missing beam.

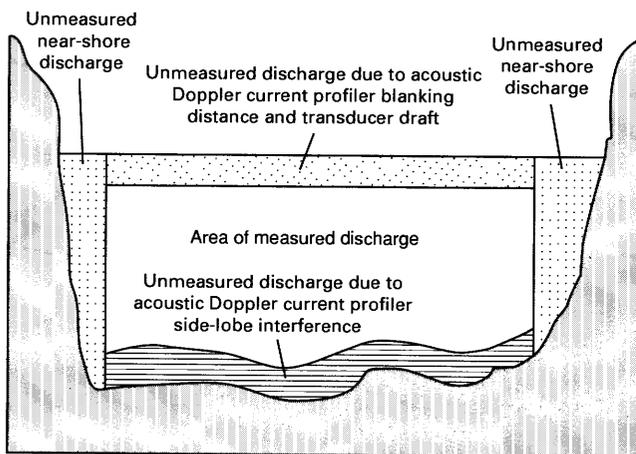
This method works well when only one acoustic beam fails but will not work if a second beam failure occurs simultaneously. If more than one beam failure occurs in a given bin, an estimate for each missing beam is provided by a low-pass filter algorithm that uses frequency counts from previous profiles. The low-pass filter algorithm takes the form

$$LP_n = (1 - T_c) (D_n) + (T_c) (LP_o), \quad (17)$$

where

$LP_n$  = new low-pass filtered value,

$LP_o$  = last low-pass filtered value,



**Figure 7.** Measured and unmeasured discharge areas for a typical river cross section, using an acoustic Doppler discharge-measurement system.

$T_c$  = a time constant between 0 and 1, and

$D_n$  = latest measured value.

Trial and error has shown that an optimum value for the time constant is 0.9.

The software includes provisions for three-beam solutions for all bins, and low-pass filters for each bin for all four beams during the profiler water-velocity determination. The software also uses three-beam solutions and low-pass filters to estimate missing beam data during the separate measurement of vessel velocity. Low-pass filters also are used for estimating  $g_i$  values (eq. 5) in the event that the vessel crosses a small part of a cross section that is too shallow for the ADCP to operate. A message is flashed on the computer monitor display when low-pass filtered data values are being used so that a determination can be made as to the desirability of using a more suitable cross section.

### Estimating Bottom-Sediment Movement

The movement of sediment on the river bottom during high riverflow causes an unwanted bias in the determination of  $f$  values (as previously described). A simple method of determining bottom-sediment movement is to anchor the vessel and measure the bottom movement relative to the vessel with the ADDMS. Because the vessel is not moving, this velocity is the actual velocity of the bottom sediment. This method only provides bottom-sediment velocity data at one location in the river cross section; many such determinations at various points in the cross section would be needed to calculate a representative bottom-sediment velocity. The time needed to set and weigh the vessel's anchor for such a determination can be unduly prohibitive. A faster and more representative method was chosen that uses data provided by the heading gyroscope.

By use of directional information provided by the heading gyroscope as a reference, the average upstream velocity of the vessel during a round-trip transect can be determined. A round-trip transect consists of starting the vessel at a fixed reference point near the riverbank, steering the vessel across the river to the opposite bank, and returning the vessel to the starting reference point. The reference point preferably should be a buoy but could be a feature on the riverbank if the vessel operator is confident that the ending vessel position is nearly the same as the starting position.

The heading gyroscope and the ADDMS software are in operation during the entire round-trip transect. The apparent upstream movement of the vessel during a round-trip transect is actually an approximation of the downstream velocity of the bottom sediment layer. For each subsection measurement, the software, using the directional information provided by the heading gyroscope, aligns the ADCP water-velocity data with earth coordinates (North/South – East/West) and determines the mean direction of the water-velocity vector. Using this information,

an upstream/downstream-oriented coordinate system is calculated. The vessel-velocity vector (as determined by the ADDMS) then is aligned with the upstream/downstream coordinate system using simple trigonometry, and vessel velocity in the upstream direction is extracted. This value is averaged over the entire round-trip transect. At the same time, a mean downstream water velocity relative to the vessel is computed. These two values are used to compute a bottom-sediment movement correction coefficient:

$$C_b = \frac{V_w}{(V_b + V_w)}, \quad (18)$$

where

$C_b$  = bottom-sediment movement coefficient,

$V_w$  = mean downstream water velocity in the cross section relative to the vessel, and

$V_b$  = mean vessel velocity in the upstream direction.

When bottom-sediment movement is suspected, several round-trip transects can be executed and the results averaged. The average bottom-sediment movement coefficient can be used to correct the total discharge values of a subsequent series of discharge measurements by multiplying the measured discharge by  $C_b$ . After a series of discharge measurements are collected, several additional round-trip transects can be executed to verify the correction factors. This method works only when bottom movement is slight compared with downstream water velocity. Because the measurement of vessel velocity in the upstream direction is subject to an additive error that increases with distance, this method is only an approximation and should be used with caution. The most accurate method for measuring discharge during bottom-sediment movement could be accomplished by using an accurate, external navigation system (such as a microwave ranger) to determine vessel velocity.

#### Determination of Total River Discharge

Total river discharge ( $Q_t$ ) is provided by

$$Q_t = Q_m + Q_{e_l} + Q_{e_r}, \quad (19)$$

where

$Q_m$  = total channel discharge [the sum of all  $q_i$  values collected during the discharge measurements (eq. 13)],

$Q_{e_l}$  = near-shore discharge on the left side of the channel, and

$Q_{e_r}$  = near-shore discharge on the right side of the channel.

#### Software Display Features

The discharge-measurement software has been revised several times since 1986 and undoubtedly will be

further revised prior to the publication of this report. Additionally, the ADCP manufacturer has begun work on a version of the ADDMS software that will be compatible with the Microsoft disk operating system (MS-DOS). Therefore, the following description of software displays and output is prototypical and is intended as a pattern (or archetype) for the development of future ADDMS software.

The ADDMS software provides the ability to switch between a tabular or graphic display on the CRT screen. When using either form of display, the screen is updated after each subsection discharge computation. The tabular display (fig. 8) shows information about vessel heading and speed, distance traveled, depth, number of good bins, subsection discharge, and number of bad measurements. The graphic display (fig. 9) shows a two-dimensional velocity profile giving the 1/6-power curve fit, measured velocity points, synthetic velocity points calculated from the curve-fit equation, and velocity points estimated from low-pass filtered data. The data points are flagged according to the methods used to compute them (four-beam calculation, three-beam calculation, low-pass filter calculation, or 1/6-power curve-fit equation). The operator can switch between tabular and graphic displays without affecting discharge calculations. At the end of the measurement, a discharge summary is displayed and printed (fig. 10).

#### Discharge-Measurement Technique

A discharge measurement with the ADDMS is typically accomplished by first choosing a roughly trapezoidal channel cross section. This can be done using the depth sounder as a reconnaissance tool. Cross sections with shallow areas or "panhandles" are to be avoided (for reasons previously described). If there is bottom-sediment movement or such movement is suspected, a round-trip transect is needed. The measurement is started by positioning the vessel as close to one riverbank as possible. The distance between the vessel and the near shore is determined using an optical rangefinder. The ADDMS software is started and the vessel is steered across the channel (transect). During the transect, the results of each subsection discharge measurement are displayed sequentially on the computer monitor. At the end of the transect, the vessel is positioned as close to the bank as possible. The software is signaled by the operator that the measurement has ended, and the distance to shore is determined (again using the optical rangefinder). The software then prompts the operator to enter the starting and ending distances to shore, and a discharge-measurement summary is printed on the system printer. If the recording feature has been enabled, all the ADDMS velocity data, time tags, and error information are recorded on computer diskette for later playback and analysis. Another discharge measurement can be started immediately, if desired.

## Software Availability

The ADDMS software consists of about 5,000 lines of code written in the Pascal language. The software is presently designed to run on an HP-9816 microcomputer but could be translated into IBM-PC-compatible code with a moderate amount of reprogramming. The software can be obtained from the U.S. Geological Survey PRIME computer network by electronic mail request or from the authors at 2800 Cottage Way, Room W-2233, Sacramento, California 95825.

## ACCURACY OF THE ACOUSTIC DOPPLER DISCHARGE-MEASUREMENT SYSTEM AND SOURCES OF ERROR

An analysis was done of the effects of ADCP errors and discharge-measurement errors for a typical discharge measurement (using the ADDMS) of the Sacramento River near Freeport, California (fig. 11). This analysis is presented in detail in appendix B. The analysis shows that the random uncertainty in total measured discharge for the typical measurement is 1.17 percent. The systematic uncertainty falls between the boundaries of +2.11 percent and +0.49 percent. If corrections are made for known values of systematic uncertainty and operator error is assumed to be 0, total ADDMS uncertainty is between the bounds of  $\pm 1.47$  percent. This accuracy is nearly the same as that of a conventional, 30-subsection, current-meter discharge measurement made during steady-state flow condi-

tions. However, a conventional discharge measurement at the Freeport site can take 1 hour or more to accomplish; the ADDMS can be used to make 28 to 30 discharge measurements during that time.

In general, the error analysis indicates that the uncertainty of an ADDMS-measured discharge will increase or decrease as a function of the channel width and depth, the channel shape, the number of subsections collected during a discharge measurement, the number of subsection measurements containing bidirectional flow, and the mean water velocity in the channel. Until higher resolution ADCP systems become available, ADDMS measurements

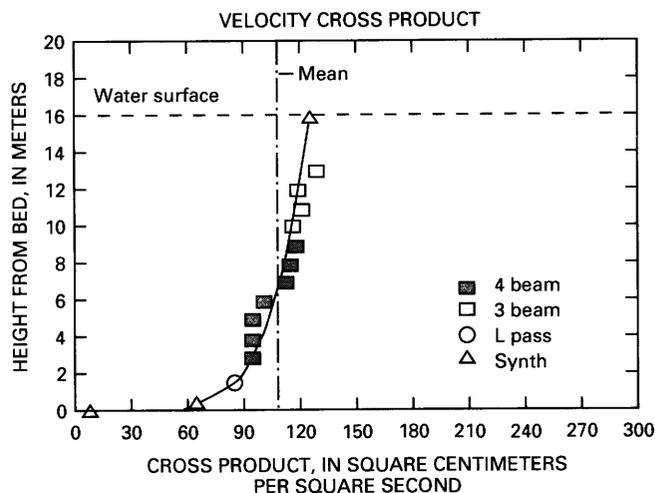


Figure 9. Graphic computer-monitor display.

```

CNTRL S= Start // CNTRL L= Last // Q= Quit
CNTRL A= Alpha screen // CNTRL G= Graphics // CNTRL V= Graph W. Speed
CNTRL N= Toggle averaging -- Averaging flg is TRUE
CNTRL B= Toggle bin 1 delete -- delete flg is FALSE

```

```

Heading (deg) = 120.02 Temperature (deg c.) = 16.484
Sound velocity (cm/s) 148166.929
Vessel speed (meters/second) = 4.37
1/6 Power curve fit
Cross section distance in meters = 35.91
Depth (meters)= 8.30
Profiler depth (meters) = 7.60
Bin 6 rejected (bad beam>2 or bindepth>.9 tot
Bin 7 rejected (bad beam>2 or bindepth>.9 tot
BOTTOM TRACK ERROR VELOCITY -9.164 cm/s
Badbin = 2
Totbin = 7
Unit discharge = -4095.12 ft3/s -115.96 m3/s
Sum discharge = -8568.72 ft3/s -242.64 m3/s
Badmeas = 0
Nmeas = 3

```

Figure 8. Tabular computer-monitor display.

(using the ADCP described in this report) should be avoided where the following conditions are present:

- Substantial wave action exists.
- Cross sections have average depths less than 4.5 m.
- Irregular cross sections exist (unless the vessel is slowed sufficiently to allow depth definition by the ADDMS).
- Mean river or estuarine velocity is extremely low (5 cm/s or less), unless a sufficient number of subsection measurements are made to reduce the instrument-caused random uncertainty that predominates at these water velocities (as described in appendix B).

Recent developments in signal-processing technology have made possible the design of high-resolution ADCP's with the ability to measure a greater part of the water column than previous ADCP's. The U.S. Geological Survey has purchased one version of a high-resolution ADCP called the broadband ADCP (BB-ADCP) that is scheduled for delivery in December 1991. Tests by the ADCP manufacturer indicate that the BB-ADCP has significantly less instrumental error than existing ADCP's, can resolve water velocities at bin widths of 20 cm or less, and can operate in depths as shallow as 1 m.

The software algorithms, measurement techniques, and error-analysis techniques described in this report can

be used to design discharge-measurement systems that use both existing and future ADCP technology.

## TESTS OF THE ACOUSTIC DOPPLER DISCHARGE-MEASUREMENT SYSTEM

Numerous measurements were made with the ADDMS on the Sacramento River near Freeport, California (fig. 11), and compared with data provided by an ultrasonic velocity meter (UVM) located at that site. (The UVM has been in successful operation since 1979.) More than 50 conventional current-meter discharge measurements and 4 area surveys were used to initially calibrate the UVM, and check measurements and area surveys are made quarterly to verify the calibration.

The discharge at Freeport is tide affected, and the discharge range during data collection was 85 to 1,400 m<sup>3</sup>/s. At this site, the river is approximately 200 m wide and from 6 to 9 m deep.

The ADDMS was used at the Freeport site to collect measurement data sets under various discharge conditions and using various discharge-measurement techniques. During data-collection transects, vessel traverse speeds were varied. Different ADCP averaging periods were tried; diagonal,

```

Date: 4/27/88
Time: 17:39
Start distance = 100.00 ft    30.48 m
End distance = 120.00 ft    36.58 m
First velocity = -1.24 ft/s  -0.38 m/s
Last velocity = -1.79 ft/s  -0.55 m/s

CHANNEL Q (Trapazoid/Power) = -225412.14 ft3/s    -6382.96 m3/s
EDGE Q = -6803.12 ft3/s    -192.64 m3/s
TOTAL Q (Trapazoid/Power) = -232215.25 ft3/s    -6575.60 m3/s

Number of Qi measurements = 30
Bad Qi measurements = 1
Qi measurements with bi-directional flow = 0
No of 3 beam solutions for veloc. = 113
Total area = 115263.35 ft2  10708.31 m2
Bottom 3 beam solutions = 0
Bottom LP values used = 0
Bin 1 delete flag is FALSE
Boatavn = -1.209
Boatave = -0.052
Mean bottom error velocity (cm/s) = 16.548
Bottom error velocity standard deviation (cm/s) = 19.789
Avg deltime (sec) = 19.2366
Avg depth = 42.32 ft  12.90 m
RECORDED AS #3:S4271730

```

Figure 10. Discharge-measurement summary.

s-curve, and figure-eight vessel traverse paths were used. The transducer mounting also was rotated through 360° during several data-collection transects.

Vessel traverse speeds and different ADCP averaging periods had a significant effect on the accuracy of dis-

charge measurements because they indirectly determine the number of subsection measurements collected during the cross-section traverse (as discussed in appendix B). It was determined that these parameters should be adjusted so that 45 or more subsection measurements are made dur-

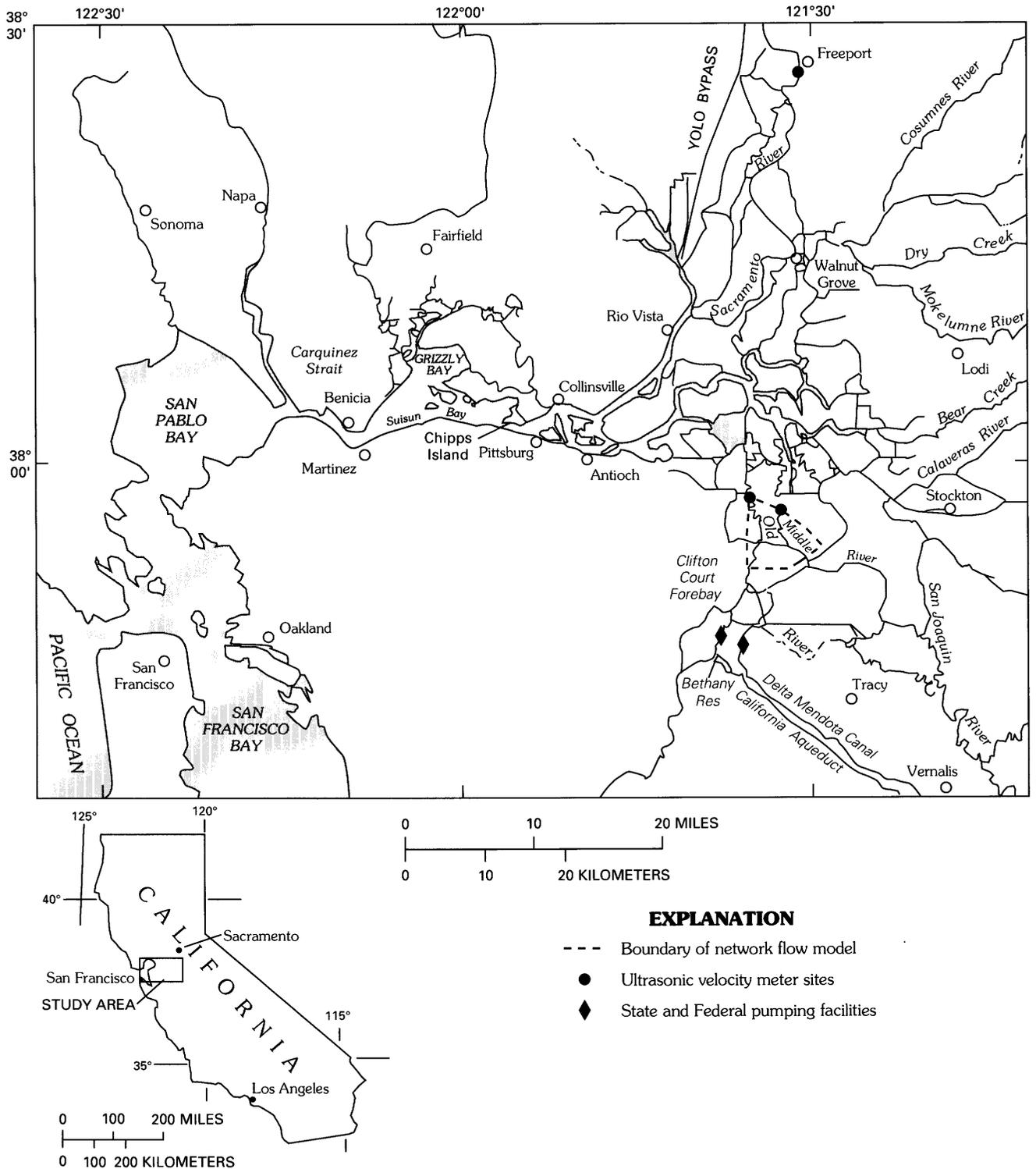


Figure 11. Location of the acoustic Doppler discharge-measurement-system test and application sites.

ing a transect. At Freeport, the slowest vessel speed attainable (1.1 m/s) was used with an ADDMS averaging period of 4 to 5 seconds. Vessel traverse path (diagonal, s-curve, or figure-eight path) had little effect (less than 2 percent) on the accuracy of the discharge measurement. Transducer rotation also had little effect on the accuracy of the discharge measurement; however, the sign ( $\pm$ ) of the subsection discharge values changed as the transducer was rotated through 180°.

Discharge-comparison results showed that the discharges provided by the ADDMS were within 2 percent of the UVM measured discharges. A typical comparison plot is shown in figure 12.

## FIELD APPLICATIONS

### Measurement of Freshwater Discharge into San Francisco Bay

To prevent saltwater from moving upstream from San Francisco Bay into the largely agricultural Sacramento–San Joaquin River Delta area, a sufficient net daily discharge of freshwater is required to flow into the bay from the delta. The magnitude of net daily discharge into the bay is greatly dependent upon the quantity of water withdrawn upstream from and within the delta for municipal and irrigation purposes and the quantity of water exported from the delta for irrigation in the southern San Joaquin Valley and for use in southern California.

Hydrologists have been attempting to quantify the magnitude of the daily discharge into the bay from the

delta for at least the last 35 years. Several previous attempts (Hoffard, 1980) to measure the discharge have been made just east of Suisun Bay and south of Chipps Island (fig. 11). This is the only location downstream from the confluence of the Sacramento and San Joaquin Rivers and upstream from the bay where the flow is sufficiently constricted to attempt a measurement.

Significant effects of tidal action on the flow at Chipps Island result in two large flood and ebb flows per day, with peak flows often exceeding 8,500 m<sup>3</sup>/s; however, the resulting net daily downstream discharge at times can be as low as 60 m<sup>3</sup>/s. Flow magnitude can change from 850 m<sup>3</sup>/s in one direction to 850 m<sup>3</sup>/s in the opposite direction in 15 minutes. The channel width is approximately 920 m, and average depth is approximately 12 m. These conditions exclude the use of conventional current-meter measuring techniques.

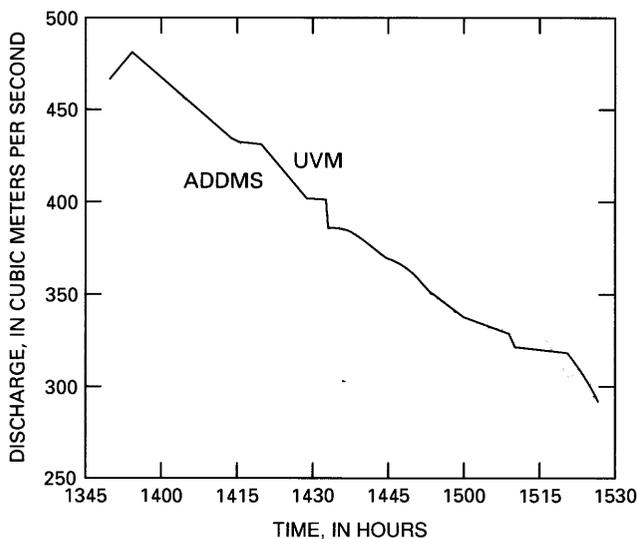
During April and May 1988, the ADDMS was used to measure the net daily discharge into the bay at Chipps Island. The approach consisted of making a discharge measurement every 15 minutes throughout a 24.8-hour tidal cycle and calculating the net flow by integration of the discharge hydrograph defined by the 15-minute-interval discharge measurements. Discharge measurements took 6 to 8 minutes, with the vessel traverse time dependent on wind and wave conditions. A crew of five persons, including vessel operators, was used to collect a set of measurements.

### Calibration of Ultrasonic Velocity Meters in the San Joaquin River Delta

In order to monitor river discharge, the U.S. Geological Survey in 1986 established two UVM sites on the Old and the Middle Rivers in the San Joaquin River Delta near Stockton, California (fig. 11). The riverflow at these locations is tide affected and also is significantly affected by the operation of the water-export facilities of the State Water Project and the Federal Central Valley Project. The export facilities transfer water from northern California through the San Joaquin River Delta to southern California. The pumps for these facilities are located about 18.5 km upstream of the UVM sites (fig. 11).

Both UVM's provide a horizontally averaged water velocity (line velocity) at the elevation of the acoustic path that must be related to mean cross-sectional velocity in order to provide a river-discharge record.

Several discharge measurements were needed throughout the flow range to determine the mean cross-sectional velocity. Tag lines and conventional current-meter discharge-measurement techniques could have been used at both sites, but because of heavy recreational boat traffic, measurement of the flow using a tag line would be extremely dangerous. In addition, flows at these sites during a



**Figure 12.** Relation of discharges measured with ultrasonic velocity meter (UVM) and acoustic Doppler discharge-measurement system (ADDMS), Sacramento River near Freeport, California.

typical day range from 430 m<sup>3</sup>/s in one direction to 230 m<sup>3</sup>/s in the other direction, and the flow frequently doubles in magnitude in 30 minutes. These flow characteristics would make the results of a discharge measurement using conventional techniques meaningless.

Beginning in May 1988, the ADDMS was used to make numerous discharge measurements at each site. Measurements averaged 2 to 3 minutes in duration and required a crew of three people. Short series of discharge measurements were collected alternately at each site over a period of 2 days. The frequent trips between the two sites were made to collect flow-measurement data during different flow conditions, which, as previously stated, were often changing rapidly with time.

Without the availability of the ADDMS, the task of calibrating and verifying the UVM's would have been extremely manpower intensive, would have taken much more time, and would have provided calibration data of questionable accuracy.

### Calibration of a Network Flow Model

After the above-described UVM's were installed and calibrated on the Old and the Middle Rivers in the San Joaquin River Delta, the U.S. Geological Survey's one-dimensional, unsteady-flow network model (BRANCH) (Schaffranek and others, 1981) was applied to a network of channels that included the two UVM locations (fig. 11). The model has 33 flow segments and 25 nodes and is driven by synchronized 15-minute-interval water-level data collected at five boundary locations. The area of the model is approximately 50 km<sup>2</sup>, and the lengths of the two primary channels, the Old and the Middle Rivers, are 11.4 and 8.7 km, respectively.

Preliminary sensitivity test runs of the model indicated that computed flows were sensitive to the hydraulic gradient (water-surface slope) between the five water-level boundary sites—so sensitive that the determination of the relative difference in elevation between the boundary sites by differential leveling was not done because the expected leveling error would be substantial relative to model output. Therefore, the approach used to calibrate the model combined collection of discharge-measurement data with adjustment of the water-surface slopes between the five boundary sites. Discharge measurements were collected throughout the flow range on several dates at 10 to 15 critical locations within the model area using the ADDMS. The model was then run for those data-collection periods, and the water-surface slopes were adjusted by applying elevation corrections to the water-level data provided by the boundary sites until acceptable agreement was obtained between model and measured discharges. Roughness coefficients also were adjusted but were not as sensitive to model output as water-surface slope.

The above approach would not have been attempted if it were not for the availability of the ADDMS. The system was used to collect four discharge-measurement data sets—three for use in calibration of the model and one for verification of model output after the model had been calibrated. Data sets were collected during a 2-day period, during which 130 to 160 discharge measurements were made at 11 to 13 locations throughout the area bounded by the model, using a crew of three people including the vessel operator. Measurement duration averaged 2 to 3 minutes, and three to five measurements were made at each location. Most locations were visited four to six times during the 2-day period.

### SUMMARY

A discharge-measurement system that uses a vessel-mounted acoustic Doppler current profiler was developed and tested by the U.S. Geological Survey. In addition to supplying vessel velocity, the ADDMS (acoustic Doppler discharge-measurement system) measures horizontal water velocity at 1-m vertical intervals in the water column by the use of an acoustic Doppler technique. Velocity and depth data are entered into the system software and processed with vector algebra to calculate the channel discharge as the vessel traverses the channel. The software contains algorithms for estimating the discharge in near-bank areas of the channel that are too shallow to be measured directly by the ADDMS.

The difference between a series of discharge measurements made using the ADDMS and discharges determined at an established UVM (ultrasonic velocity meter) discharge-measuring site on the Sacramento River near Freeport, California, averaged less than 2 percent. Error analysis indicates that a typical ADDMS-measured discharge made at the Freeport UVM site has both random and systematic uncertainty. The estimated random uncertainty is 1.17 percent, and the estimated systematic uncertainty lies somewhere between +2.11 percent and +0.49 percent. The ADDMS has the advantage of requiring less time than conventional current-meter discharge-measurement methods (2 minutes using ADDMS compared with 1 hour or longer using conventional methods) and does not require shore-based navigational aids or tag lines for positioning the vessel.

The system is particularly useful for measuring discharge in tidal estuaries where the flow is changing too rapidly for conventional discharge-measurement methods to be adequate. In the San Francisco Bay estuary near Chipps Island, California, the system has been used to measure discharge in a 920-m-wide cross section every 15 minutes over a 24.8-hour tidal cycle for the purpose of calculating net discharge. In the Sacramento-San Joaquin River Delta near Stockton, California, the system has been

used to collect discharge data for a numerical modeling study and to calibrate two UVM discharge-measuring sites.

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## APPENDIXES A AND B

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## APPENDIX A—DISCHARGE EQUATIONS

The following equations are taken from Christensen and Herrick (1982). Equation 1 (below) and equation 2 (after eq. 25) are reproduced here from preceding sections for purposes of continuity.

The general equation for determining river discharge through an arbitrary surface  $s$  is

$$Q_t = \int_s \bar{V}_f \cdot \bar{n} \, ds, \quad (1)$$

where

- $Q_t$  = total unknown river discharge,
- $\bar{V}_f$  = mean water-velocity vector,
- $\bar{n}$  = a unit vector normal to  $ds$  at a general point, and
- $ds$  = differential area.

For moving-boat discharge applications, the area  $s$  is defined by the vertical surface beneath the path along which the vessel travels. The dot product of  $\bar{V}_f \cdot \bar{n}$  will equal zero when the vessel is moving directly upstream or downstream and will equal  $|\bar{V}_f|$  when the vessel is moving normal to  $\bar{V}_f$ . (Both vectors are in the horizontal plane.)

The ADCP is capable of measuring  $\bar{V}_b$ , but to compute  $Q_t$  in equation 1, the differential area  $ds$  also must be calculated:

$$ds = |\bar{V}_b| dz \, dt, \quad (20)$$

where

- $\bar{V}_b$  = the magnitude of the vessel velocity,
- $dz$  = vertical differential depth, and
- $dt$  = differential time.

The ADDMS measures  $\bar{V}_b$  by measuring the bottom velocity relative to the vessel (as previously described). If

$\bar{k}$  is defined as a unit vertical vector, the cross product of  $\bar{V}_b \times \bar{k}$  results in a vector with a magnitude of  $|\bar{V}_b|$  and a direction normal to the vessel's path:

$$\bar{V}_b \times \bar{k} = |\bar{V}_b| \bar{n}, \quad (21)$$

where

$\bar{k}$  = a unit vertical vector.

Multiplying equation 21 by  $dz \, dt$  yields

$$\bar{V}_b \times \bar{k} \, dz \, dt = |\bar{V}_b| \bar{n} \, dz \, dt. \quad (22)$$

Multiplying equation 20 by  $\bar{n}$  yields

$$\bar{n} \, ds = |\bar{V}_b| \bar{n} \, dz \, dt. \quad (23)$$

The right-hand sides of equations 22 and 23 are the same; therefore,

$$\bar{n} \, ds = \bar{V}_b \times \bar{k} \, dz \, dt. \quad (24)$$

Substituting equation 24 into equation 1 yields

$$Q_t = \int_0^T \int_0^d (\bar{V}_f \cdot \bar{V}_b) \times \bar{k} \, dz \, dt, \quad (25)$$

where

$T$  = total cross-section traverse time and

$d$  = total depth.

By vector identity,

$$Q_t = \int_0^T \int_0^d (\bar{V}_f \times \bar{V}_b) \cdot \bar{k} \, dz \, dt. \quad (2)$$

Using this equation, river discharge can be computed from data provided by the ADDMS.

## APPENDIX B—ACCURACY OF THE ACOUSTIC DOPPLER DISCHARGE-MEASUREMENT SYSTEM AND SOURCES OF ERROR

Carter and Anderson (1963) concluded that the accuracy of conventional discharge measurements could be assessed by evaluation of the combined effects of instrument errors, errors due to velocity pulsations (short time-scale turbulence), errors due to variation in the velocity distribution in the vertical, and errors related to the number of individual  $q_i$  determinations (subsections) collected during a discharge measurement. This approach can also be used to assess the accuracy of discharge measurements collected with the ADDMS if it is extended to include errors related to the number of bins in each subsection and errors in the estimation of near-shore discharges.

Sources of ADCP instrument and discharge-measurement error and their effects on a typical ADDMS measured discharge of the Sacramento River near Freeport, California, are listed here. This typical measurement (made on March 1, 1989) is representative of over 1,500 discharge measurements made at the Freeport site and is referred to as "the Freeport measurement."

Errors introduced during the discharge-measurement procedure can be either random or systematic. Random errors can be reduced by averaging, whereas systematic errors cannot. Historical analyses of discharge-measurement errors, such as by Carter and Anderson (1963) and Herschy (1970), have lumped random and systematic errors together to produce a value for overall discharge-measurement error. However, the two types of errors are dissimilar and, in this analysis, are stated separately. Overall discharge-measurement uncertainty can be expressed by separately stating overall random uncertainty ( $X'_{RQ}$ ) and overall systematic uncertainty ( $X''_{RQ}$ ).

### EVALUATION OF RANDOM UNCERTAINTY

The random-error sources that form  $X'_{RQ}$  are

- (1) Random uncertainty in a discharge measurement due to uncertainties in subsection discharge ( $X'_{R_s}$ ), which is a function of uncertainty in an individual subsection discharge measurement ( $X'_{r_s}$ ) and the number of subsections ( $N_s$ ) collected during the discharge measurement.
- (2) Random uncertainty due to the inability of point sampling to adequately define the area and velocity distribution in a measured cross section ( $X'_{R_p}$ ), which is also a function of the number of subsections ( $N_s$ ) collected during the discharge measurement.
- (3) Random uncertainty in the estimation of unmeasured near-shore discharge ( $X'_{R_e}$ ).

These uncertainties, expressed as the standard deviation of error ratios, are summarized in table 1.

$X'_{RQ}$  can be calculated from the above-listed uncertainties using the root-sum-squares method:

$$X'_{RQ} = \sqrt{(X'_{R_s})^2 + (X'_{R_p})^2 + (X'_{R_e})^2}. \quad (26)$$

These sources of uncertainty are now evaluated in the order stated.

### Random Uncertainty in a Discharge Measurement Due to Uncertainties in the Measurement of Subsection Discharge

The total random uncertainty in the determination of subsection discharge is reduced by the square root of the total number of subsection measurements made during a discharge measurement:

$$X'_{R_s} = \frac{X'_{r_s}}{\sqrt{N_s}}, \quad (27)$$

where

$N_s$  = number of subsections measured during a discharge measurement, and

$X'_{r_s}$  = random uncertainty in the measurement of an individual subsection discharge.

This equation holds true if no correlation exists between adjacent subsections and the subsection discharges and variances are assumed to be nearly equal (Smith, 1971). In practice, some subsection-to-subsection correlation exists for certain sources discussed below, but the correlation is not considered significant and is not taken into account in this analysis. Subsection discharges are not always equal in practice; however, proper cross-section reconnaissance and adjustments of vessel speed enabled nearly equal subsection discharges for the Freeport measurement. Therefore, the above equation is applicable to this analysis.

Major random uncertainties in the measurement of an individual subsection discharge ( $X'_{r_s}$ ) are

- $x'_{r_b}$  = uncertainty in the instrument's ability to measure vessel velocity,
- $x'_{r_d}$  = uncertainty in the depth measurement of a subsection, and
- $x'_{r_f}$  = uncertainty in the determination of a depth-weighted mean velocity cross product ( $f$  value) in a subsection.

Each partial error ratio in table 2 is the percentage error in subsection discharge attributed to the specific source.

The random uncertainty in an individual subsection discharge measurement (due to the error sources listed above) can be calculated using the root-sum-squares method:

$$x'_{r_s} = \sqrt{(x'_{r_b})^2 + (x'_{r_d})^2 + (x'_{r_f})^2}. \quad (28)$$

**Table 1.** Statistics of principal random-error sources in computed instantaneous total discharge

[ $Q$  is actual discharge,  $Q_{\text{error}}$  is total discharge as affected by the error in question, and  $R_{\text{error}}$  is the partial error ratio in percent]

Source of error	Partial error ratio	Random uncertainty (standard deviation of ratio)
Subsection discharge	$R_s = \left( \frac{Q - Q_s}{Q} \right) 100$	$X'_{R_s}$
Point sampling	$R_p = \left( \frac{Q - Q_p}{Q} \right) 100$	$X'_{R_p}$
Near-shore discharge	$R_e = \left( \frac{Q - Q_e}{Q} \right) 100$	$X'_{R_e}$

These sources of uncertainty are now evaluated in the order stated.

#### Random Uncertainty in the Profiler's Ability to Measure Vessel Velocity

A river or channel bottom-track pulse, separate from the pulse used to measure water velocity, is used by the ADCP to measure vessel velocity relative to the bottom. This bottom-track pulse is normally set longer than the 1-m pulse used to measure water velocities. The bottom provides a much more efficient reflector than does particulate matter in the water column; therefore, the ADCP can measure the frequency of the backscattered signal with much greater precision. Results of ADCP bottom-track testing on a lake (Simpson, 1986) showed both a random and systematic error in the repeated measurement of a lake distance course. The systematic part of this error (due to beam misalignment and receiver chain effects) is discussed in the section "Evaluation of Systematic Uncertainty" in this appendix. The standard deviation of the percentage difference between the lake distance course and the ADCP measured distance was 0.89 percent and did not significantly vary with variation in vessel speed and direction. If all other factors remain constant, a 0.89 percent error in vessel speed will cause a 0.89 percent error in subsection discharge (see eqs. 3 and 4); thus, a value of 0.89 percent seems reasonable for  $x'_{r_b}$ . This 0.89

**Table 2.** Statistics of principal random-error sources in subsection discharges

[ $q$  is actual subsection discharge,  $q_{\text{error}}$  is the measured subsection discharge as affected by the error in question, and  $r_{\text{error}}$  is the partial error ratio in percent]

Source of error	Partial error ratio	Random uncertainty (standard deviation of ratio)
Vessel velocity	$r_b = \left( \frac{q - q_b}{q} \right) 100$	$x'_{r_b}$
Subsection depth	$r_d = \left( \frac{q - q_d}{q} \right) 100$	$x'_{r_d}$
Cross product	$r_f = \left( \frac{q - q_f}{q} \right) 100$	$x'_{r_f}$

percent value was determined using a ratio of one bottom-track ping to every two water-velocity measurements and is not valid for any other ratio.

#### Random Uncertainty in the Depth Measurement of a Subsection

Depths are measured using a depth sounder coupled to a high-resolution transducer. The accuracy of this depth sounder is claimed by the manufacturer to be  $\pm 0.5$  percent of the indicated depth. Systematic errors caused by misadjustment of operator controls, electronic bias, and salinity gradients are discussed later in the section "Evaluation of Systematic Uncertainty." Experience with this sounder has verified that the manufacturers' specifications are valid within the 0- to 29-m range of the ADCP if proper calibration procedures are performed. If all other factors remain constant, a 0.5 percent random error in depth measurement will cause a 0.5 percent random error in the measurement of subsection discharge (see eq. 4). Thus, a value of 0.5 percent is used for  $x'_{r_d}$ .

#### Random Uncertainty in the Determination of a Mean $f$ Value in a Subsection

Several factors affect the accuracy with which the ADDMS can measure mean water- and vessel-velocity cross products ( $f$  values) in a subsection. They are

- the short-term precision (instrumental) of a depth-averaged ADCP water-velocity measurement in a subsection ( $\sigma_i$ );
- the effects of short time-scale turbulence on the determination of depth-averaged water velocity in a subsection ( $\sigma_i$ ); and
- the errors caused by differences between the true water velocity in the unmeasured portions of the subsection and the estimated water velocity in the unmeasured portions. This error has both a random and systematic component. The random component ( $\sigma_f$ ) is discussed in this section.

The errors listed above are now discussed in the order stated; however, their magnitudes are not separately evaluated. A procedure is described that was used to quantify the random uncertainty in the determination of a mean  $f$  value in a subsection ( $x'_{rj}$ ), caused by the combined effects of  $\sigma_i$ ,  $\sigma_r$ , and  $\sigma_f$ .

The short-term precision of an ADCP water-velocity determination in a single bin can be approximated by the following equation (Gordon, 1989):

$$\sigma_{b_i} = \frac{1.6 \times 10^5}{F_t D \sqrt{j}}, \quad (29)$$

where

- $\sigma_{b_i}$  = standard deviation of the measured water velocity from a single bin, in meters per second;
- $F_t$  = transmit frequency, in Hertz;
- $D$  = bin length, in meters; and
- $j$  = number of pings averaged for the velocity estimate.

For example, if  $F_t = 1.2$  mHz,  $D = 1$  m, and  $j = 20$ , substitution of these values into equation 29 yields a value of 0.03 m/s for  $\sigma_{b_i}$ .

Although analysis of field test data collected during tests on a lake (Simpson, 1986) yielded a value of 0.034 m/s for  $\sigma_{b_i}$ , corrections were not made for random uncertainty in the vessel velocity, random uncertainty due to short time-scale turbulence in the lake water velocity, and systematic uncertainty due to ADCP beam misalignment and receiver nonlinearity. Therefore, the above error model proposed by Gordon (1989) seems reasonable.

If there were no correlation between  $f$  values from different bins in the subsection, the standard deviation due to instrumental error in a subsection ( $\sigma_i$ ) could be calculated by dividing  $\sigma_{b_i}$  by the square root of the number of bins in the subsection; however, the velocity-determination technique used in the ADCP is imperfect and some bin-to-bin correlation exists (approximately 15 percent). Therefore, the value of  $\sigma_i$  is a function of  $\sigma_{b_i}$ , the number of bins in a subsection, and the correlation between adjacent bins.

At short time scales (1–40 seconds), turbulence in the water-velocity field can become a significant source of ran-

dom uncertainty. Available measured data from the 1- to 10-second part of this range are extremely sparse because most velocity-measuring instruments have an overwhelming amount of random instrument-induced uncertainty at these time scales. Investigations (Pelletier, 1988) made in the United Kingdom, the U.S.S.R., and the United States have shown that the standard deviation of point velocity measurements made in natural rivers varies with the depth of the river, the magnitude of the mean river velocity, the position in the vertical velocity profile at which the measurement is made, the geometry and composition of the river bedform, and the length of time that the measurement data are averaged. Because of these factors, the development of a general rule for determining short time-scale turbulence in a subsection ( $\sigma_i$ ) has not been attempted; however, Bowden (1977) hypothesized that under normal stream conditions, the near-bottom value for  $\sigma_i$  of the up-down stream-velocity component was not much greater than 10 percent, and that values for the vertical and cross-stream components were somewhat less than 10 percent ( $\sigma_i$  is generally greater near the bottom).

The  $f$  values in a subsection vertical are the cross product of the water-velocity vector in each bin and the vessel-velocity vector converted to a scalar using the dot product of a unit vertical vector. Because the vessel-velocity vector is constant for each bin in the profile, the distribution of  $f$  values in the water column can be examined in the same manner as a typical vertical water-velocity distribution.

The curve-fitting method used in the ADDMS software fits the measured velocity data ( $f$  values) to a 1/6-power curve and uses the resulting equation to estimate the  $f$  values that cannot be collected by the ADDMS (as previously discussed). Errors arise when the curve-fitting scheme does not accurately estimate the unmeasured  $f$  values. The errors can be both systematic and random. Systematic errors arise when there is a constant bias between the vertical velocity profile as depicted by the 1/6-power curve-fit equation and the true vertical velocity profile. The systematic component of this error is discussed in the section "Evaluation of Systematic Uncertainty."

The random component of this error ( $\sigma_f$ ) can be caused by a multitude of phenomena: winds affecting the surface boundary layer, changing bottom topography and composition, random disturbances in the velocity profile caused by turbulent eddies, and the number of bins collected by the ADCP and used to compute the 1/6-power curve. Like  $\sigma_r$ ,  $\sigma_f$  is not easily determined by a generalized rule, and if empirically determined, will only apply to a specific set of circumstances.

A procedure was devised to approximate the combined effects of  $\sigma_i$ ,  $\sigma_r$ , and  $\sigma_f$  on a typical ADDMS mean velocity determination, thus providing an estimate of the uncertainty in the determination of a mean  $f$  value for a subsection ( $x'_{rj}$ ). Investigation of these combined errors

ideally requires the collection of two depth-averaged, water-velocity time series using the following scenario:

One time series is collected that approximates the true mean velocity in the subsection vertical profile. This can be accomplished by measuring point velocities at numerous, representative points in the vertical profile and calculating "true" mean velocity by integrating these velocities over the profile depth using a trapezoidal rule. This is done for each velocity-profile measurement in the time series. Simultaneously, another depth-averaged velocity time series is calculated from ADDMS measured velocity profiles and velocities estimated using the 1/6-power curve-fitting scheme (also integrated over the depth using a trapezoidal rule for each profile). If the "true" mean velocity time series is filtered to remove the effects of random instrumental error ( $\sigma_i$ ) and short time-scale turbulence ( $\sigma_t$ ), the standard deviation of the difference (in percent) between the filtered "true" mean velocity time series and the ADDMS calculated mean velocity time series will approximate the combined uncertainty due to  $x'_{rf}$ .

In practice, a rough approximation of  $x'_{rf}$  was obtained by using the ADDMS to collect both a "true" mean water-speed and calculated mean water-speed time series. (A distinction between speed and velocity is intended here because Price AA meters provide speed but not direction.) In addition to water-speed profiles collected from the ADDMS, two Price AA current meters were deployed to collect data from the unmeasured areas at the top and bottom of the ADCP-collected profile. These additional data were used for calculating "true" mean water speed.

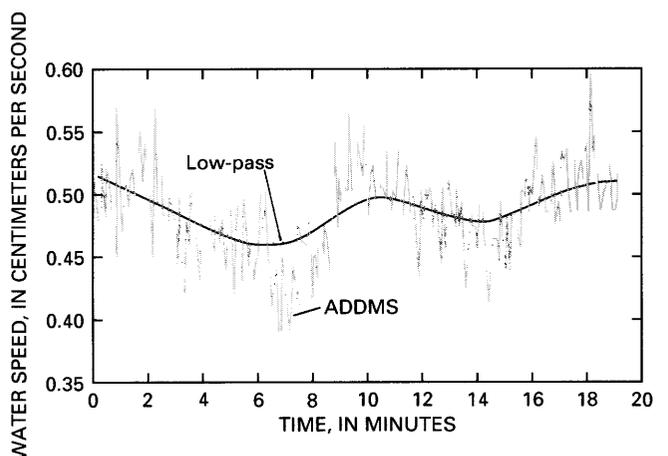
During the data-collection procedure, the ADDMS test vessel was anchored (to minimize the effects of  $x'_{rb}$ ) two separate times, at two locations in the same river cross section used for the Freeport measurement. Two Price AA current meters were suspended from the vessel, one 0.5 m below the water surface and the other 0.3 m above the river bed. Simultaneous water-speed measurements were made with the ADCP system and the current meters. The current-meter-measured water speeds were averaged over 15 seconds, and the ADCP-measured water speeds were averaged using the same averaging period used for the Freeport measurement (4.7 seconds). The elapsed time for collection of each of the four water-speed time-series profile measurements averaged 14 minutes. One of the measurement locations was in the deepest part of the cross section, where maximum river velocities exist. The positions of the current meters were reversed during the course of the measurements to minimize systematic error associated with the current meters. River flow and meteorological conditions were similar to those that existed during the Freeport measurement.

Two depth-averaged time series were constructed from the profile data collected during each measurement. In order to compute the first time series ("true" mean water speed), the 15-second, current-meter-measured water

speeds were synchronized with the 4.7-second, ADCP-measured water-speed profiles using a spline interpolation technique, and a depth-averaged water speed for each 4.7-second measurement was calculated using a trapezoidal integration method applied to the current-meter-measured water speeds and ADCP-measured water-speed profiles. For the other time series (ADDMS mean water speed), the mean water speed was computed using the trapezoidal integration method applied to only the ADCP-collected water-speed profiles and speeds estimated using the 1/6-power curve-fit equation (the same method used by the ADDMS and discussed previously). Spectral analysis of the "true" mean water-speed data was performed, and the results revealed that a 7-minute low-pass filter would remove all of the random instrumental error and short time-scale turbulence present in the measured speeds but preserve most of the long time-scale phenomena. The use of a filter was required because the long time-scale data were oscillatory in character and not easily defined using linear regression methods.

To calculate the filtered "true" mean water speed, a 7-minute, low-pass, butterworth-squared filter was applied to each "true" mean water-speed time series. Conditioning at both ends of the time series was needed because of filter "startup" effects and was accomplished by copying a "mirror image" portion of the time series onto each end of the series, applying the filter in both directions, and then removing the artificial ends. Applying the filter in both directions had the advantage of removing nonlinear phase lag caused by this type of filter. The resulting filtered time series approximated the long-term "true" mean water speed (for the purposes of this investigation), and a typical plot of an overlay of ADDMS calculated water speed with filtered "true" mean water speed is shown in figure 13.

The standard deviation of the differences (in percent) between the individual values in the ADDMS water-speed



**Figure 13.** Overlay of low-pass filtered "true" mean water speed with acoustic Doppler discharge-measurement system (ADDMS) calculated mean water speed.

time series and the filtered “true” mean water-speed time series was computed for each measurement and the results arithmetically averaged. An average value of 5.55 percent was obtained, with the lowest value being 4.84 percent and the highest being 5.95 percent. If all other factors remain constant, a 5.55 percent error in the determination of a depth-integrated cross product ( $f$  value) will cause a 5.55 percent error in subsection discharge (see eq. 5). Because the average number of bins per subsection during the Freeport measurement was six and the average number of bins used in this analysis was four, it seems reasonable and conservative to use a value of 5.55 percent for  $x'_{rf}$  if it is realized that the determination of long-term “true” mean water speed is only an approximation, and that  $x'_{rf}$  is only valid for the Freeport measurement.

Wind-driven and gravitational (density-induced) circulation in estuaries and tide-affected rivers can have considerable effect on the shape of the vertical water-velocity distribution, especially in the parts of the velocity profile that cannot be measured by the ADCP. Results of discharge measurements made under these conditions should be interpreted with caution.

Substituting the values for a typical subsection discharge measurement from the Freeport measurement into equation 28 yields

$$X'_{r_s} = \sqrt{(0.89)^2 + (0.5)^2 + (5.5)^2} = 5.59 \text{ percent.}$$

The Freeport measurement had 45 subsections. Therefore, substituting 5.59 percent and 45 into equation 27 yields a value of 0.83 percent for the total random uncertainty of the measurement of subsection discharge ( $X'_{R_s}$ ).

### Random Uncertainty Due to the Inability of Point Sampling to Adequately Define the Area and Velocity Distribution in a Cross Section

In computing a conventional discharge measurement, the depth and the velocity are assumed to vary linearly with distance between subsection measurements in a cross section. The error in a discharge measurement due to this assumption is related to the number of subsections ( $N_s$ ) at which depth and velocity are measured. The ADDMS continually samples velocity during the traverse of a cross section; therefore, error due to inadequate sampling of the velocity field within a subsection is probably not significant. Depth, however, is only sampled at the end of each data ensemble; therefore, error in the definition of cross-section area is dependent on the number of subsection measurements collected during a cross-section traverse.

Error in the definition of cross-section area can vary greatly, depending on the geometry of the cross section. For example, the area of a smooth rectangular channel can be accurately defined by a few depth measurements,

whereas accurate definition of the area of a boulder-strewn, panhandle-shaped cross section can require 100 or more depth measurements.

Studies by Carter and Anderson (1963) of discharge measurements using conventional current-meter measurement techniques made at more than 127 different discharge-monitoring sites indicate that the standard deviation of the measured discharge (due to nonlinear changes in velocity and depth across the width of the cross section) of a typical stream averages 1.6 percent if 30 subsections are collected. This error decreases nonlinearly with an increase in the number of subsections and does not improve significantly when more than 30 subsections are collected. The 1.6 percent error also includes error due to inadequate sampling of the velocity field; therefore, it is expected that this value would be significantly less for discharges measured with the ADDMS.

The Freeport measurement had 45 subsection discharge measurements. Analysis of variance of repetitive area calculations made using varying numbers of equally spaced subsections for a typical cross section on the Sacramento River near Freeport (near the site of the Freeport measurement) indicates that uncertainty in the definition of cross-section area is 0.8 percent when 45 subsections are collected during a cross-section traverse.

The ADDMS indirectly integrates subsection area using values of depth, vessel velocity, and time (see eqs. 3 and 4). Because vessel velocity remains relatively constant during a cross-section traverse, and the incremental time and depth measurements are a function of ADDMS parameters and occur at equally spaced increments, the variance in cross-section area becomes a function of the number of subsection measurements made during a cross-section traverse (as seen in the previous paragraph). Both the time of each depth measurement and the velocity of the vessel will vary slightly with each successive discharge measurement; therefore, the error is not systematic. For the Freeport measurement, it seems reasonable to use a value of 0.8 percent for  $X'_{R_p}$ .

### Random Uncertainty in the Estimation of Unmeasured Near-Shore Discharge

The technique used by the ADDMS to estimate near-shore discharges assumes a triangular discharge area between the first or last measured subsection and the channel bank. The significance of this error as it relates to total discharge depends on the ratio of near-shore discharge to total discharge. For example, the Freeport measurement has a measured channel discharge of 345 m<sup>3</sup>/s and an estimated near-shore discharge of 3.6 m<sup>3</sup>/s. If the near-shore discharge is in error by 20 percent, the random uncertainty in total discharge due to near-shore discharge estimation error ( $X'_{R_e}$ ) is 0.2 percent. This error could have both a

random and systematic component. For example, if the optical rangefinder constantly underregistered distance by 10 percent, the near-shore discharge would be underestimated consistently by 10 percent. The random component of this error could be caused by variable near-shore bottom topography, mistakes by the operator in selecting and focusing on proper edge targets using the optical rangefinder, random error in the first or last mean velocity measurement, and disagreement between the interpolated velocities and actual velocities at a point halfway between the vessel and the riverbank.

The systematic component of this error is discussed in the section "Evaluation of Systematic Uncertainty." Analysis of discharge-measurement data collected at the Freeport location indicates that the standard deviation of near-shore estimated discharge does not exceed 20 percent. It therefore seems reasonable to use a value of 0.2 percent (as calculated above) for the value of  $X'_{R_c}$ .

### Total Random Uncertainty in a Typical Discharge Measurement

Substituting the values determined above for the Freeport measurement into equation 26 yields

$$X'_{R_Q} = \sqrt{(0.83)^2 + (0.8)^2 + (0.2)^2} = 1.17 \text{ percent.}$$

### EVALUATION OF SYSTEMATIC UNCERTAINTY

The impacts of systematic (bias) errors are significant because errors of this type cannot be reduced by data averaging. Systematic errors do not fall into distribution categories and therefore cannot be expressed as standard deviations of ratios (as can random errors). Systematic errors also have direction and can add to or subtract from the overall systematic uncertainty. The systematic errors listed in this section are all expressed as partial error ratios of the following form:

$$x''_{r_{\text{systematic error}}} = \left[ \frac{Q - Q_{\text{systematic error}}}{Q} \right] 100 \quad (30)$$

where

$Q$  = actual river discharge, and

$Q_{\text{systematic error}}$  = measured discharge as affected by systematic error.

Total ADDMS systematic uncertainty ( $X''_{R_Q}$ ) is a function of the following systematic error sources:

$x''_{r_a}$  = systematic uncertainty of ADCP measured velocities due to uncompensated ADDMS vessel-attitude changes,

$x''_{r_f}$  = systematic uncertainty due to the inability of the 1/6-power curve-fitting scheme used by the

ADDMS to accurately estimate unmeasured parts of the vertical velocity profile,

$x''_{r_\theta}$  = systematic uncertainty due to improper ADCP beam geometry,

$x''_{r_r}$  = systematic uncertainty due to several related error sources that can be loosely categorized as ADCP "receiver-chain effects,"

$x''_{r_\Delta}$  = dynamic bias uncertainty due to the mispositioning of ADCP receiver low-pass tracking filters,

$x''_{r_\lambda}$  = systematic uncertainty due to ADCP transmit-filter skew, and

$x''_{r_o}$  = miscellaneous operator-caused systematic uncertainty due to improper calibration of ancillary devices (tide and draft settings for depth sounder, speed-of-sound determination for depth sounder, and optical rangefinder calibration) and improper setup values for ADCP measurement parameters.

Total systematic uncertainty in an ADCP-measured discharge ( $X''_{R_Q}$ ) can be determined by the following equation (James R. Slack, 1990, USGS, written commun.):

$$X''_{R_Q} = (1 \pm x''_{r_a}) (1 \pm x''_{r_f}) (1 \pm x''_{r_\theta}) (1 \pm x''_{r_r}) (1 \pm x''_{r_\Delta}) (1 \pm x''_{r_\lambda}) (1 \pm x''_{r_o}) - 1 \quad (31)$$

A comprehensive analysis of ADCP systematic uncertainty is beyond the scope of this report. For a detailed discussion of these and other ADCP error sources, see Regier (1982), Hansen (1986), Theriault (1986), Appel and others (1988), and Chereskin and others (1989). The exact magnitude of these errors can only be approximated in most cases, so we have chosen to discuss the "worst-case" impact of these errors on a typical ADDMS discharge measurement (the Freeport measurement). These sources of uncertainty are discussed in the order stated.

### Systematic Uncertainty Due to Uncompensated Vessel-Attitude Changes

Errors due to uncompensated pitch and roll of the data-collection vessel probably have little effect on the accuracy of a typical discharge measurement made under normal conditions (pitch and roll less than 5°). Pitch-and-roll data are not used in the ADDMS because the small amount of pitch and roll encountered during the course of a discharge measurement introduces only a small positive systematic error that is not considered significant.

Systematic error due to uncompensated transducer attitude can result if the center of the vertical transducer assembly axis is not vertical. This occurs on the ADDMS test vessel (research vessel *Saul E. Rantz*) because of weight distribution, which causes a list or trim bias that differs from the vessel's unloaded trim. Because of this effect, the forward transducer is constantly pitched above the aft transducer by 3°. This condition causes a systemat-

ic error in the measurement of water and vessel velocity from the fore/aft direction of about -0.14 percent (RD Instruments, 1989). Because discharge is calculated using the cross product of water and vessel velocity, the propagation of this error must be examined using the cross-product formula.

If the error is expressed as a coefficient in percent, then equation 3 can be redefined to inspect the effects of the error:

$$f_{er}f = (a_{1_{er}} a_1) (b_{2_{er}} b_2) - (a_{2_{er}} a_2) (b_{1_{er}} b_1) \quad (32)$$

where

- $f_{er}$  = total error affecting the cross product ( $f$  value),
- $a_{1_{er}}$  = error affecting the cross component of the mean water-velocity vector,
- $a_{2_{er}}$  = error affecting the fore/aft component of the mean water-velocity vector,
- $b_{1_{er}}$  = error affecting the cross component of the mean vessel-velocity vector, and
- $b_{2_{er}}$  = error affecting the fore/aft component of the mean vessel-velocity vector.

The transducer attitude error only affects the fore/aft velocity components, and if no error is assumed on the cross-velocity components, values for each error can be substituted into equation 32:

$$f_{er}f = a_1 (0.9986b_2) - b_1 (0.9986a_2) \quad (33)$$

and, simplifying,

$$f_{er} = \frac{0.9986 (a_1 b_2 - a_2 b_1)}{f} \quad (34)$$

Equation 3 shows that  $f$  is defined as  $a_1 b_2 - a_2 b_1$  and therefore  $f_{er} = 0.9986$  or -0.14 percent.

If all other values remain constant, a -0.14 percent error in the cross product ( $f$  value) will equal a -0.14 percent error in the measurement of total discharge (see eqs. 5 and 13).

Errors in the heading information generally will not affect the accuracy of an ADDMS measured discharge unless the gyroscope is used to provide earth-based velocity information for use in determining sediment bottom movement. Even this measurement will not be in error unless the heading gyroscope drifts or precesses during the measurement traverse. If the heading gyroscope is checked regularly and is refurbished at regular intervals, this error is negligible.

The systematic error due to uncompensated pitch and roll is the only significant uncertainty attributed to  $x''_{ra}$  and is probably not greater than -0.14 percent.

### Systematic Uncertainty Due to the Use of the 1/6-Power Curve-Fitting Method for Estimating Unmeasured $f$ Values

Systematic errors can arise when the 1/6-power curve-fitting scheme used by the ADDMS does not accu-

rately depict the actual river vertical velocity profile in a long-term sense. This can happen when, for various reasons, the shape of the actual velocity profile is not congruent with that of a 1/6-power curve for a significant length of time.

The curve-fitting method used in the ADDMS software fits the measured velocity data ( $f$  values) to a 1/6-power curve and then uses the resulting equation to estimate the  $f$  values that cannot be collected by the ADDMS (as previously discussed). As a sensitivity test, ADDMS-recorded velocities were used to recompute discharges using different power-curve fits to assess the effect of these slope changes on a typical discharge measurement. The measured discharge varied from the 1/6-power-law computed discharge by only 2.1 percent when recomputed using a 1/2-power curve and by only 2.0 percent when recomputed using a 1/12-power curve.

Hulsing and others (1966, p. C7) described a vertical velocity distribution based on ratios of point velocities to mean velocities from multiple-point velocity measurements of 48 different nonestuarine rivers. Smith (1971) calculated the ratios of point to mean velocities in a tide-affected reach of Suisun Bay near Chipps Island and found that his estuarine ratios were almost identical with the non-estuarine ratios described by Hulsing and others. These results are of interest because the ratios described by Hulsing and others were based on observations of steady-state flow in natural streams, and the ratios described by Smith were based on observations in a tide-affected channel having two-directional flow. Smith hypothesized that the dynamic effects related to rapid changes in discharge rate possibly have, on the average, little effect on the velocity-distribution relations (except near slack-tide periods).

Analysis of differences between the vertical velocity distribution described by Hulsing and others (1966, p. C7) and the curve-fitting method used by the ADDMS indicate that a 1.1 percent systematic error exists between the two systems for the worst case of using ADCP velocity data from only one bin. This systematic error, which drops below 1.0 percent when two or more velocity bins are used for the comparison, is of the same magnitude as that of a conventional, dual-point, current-meter measurement made at points corresponding to 20 percent and 80 percent of the total depth (Hulsing and others, 1966).

As described in the section "Random Uncertainty in the Determination of a Mean  $f$  Value in a Subsection," a procedure was designed to evaluate the combined effects of  $\sigma_i$ ,  $\sigma_t$  and  $\sigma_f$  on an ADDMS determination of mean velocity. The products of this procedure were a set of time-series data that approximated the mean water speed ("true" mean water speed) and a simultaneously collected set of time-series data that were mean water speeds calculated from ADDMS-measured water speeds and water speeds estimated using the 1/6-power curve-fitting scheme.

The difference (in percent) of the mean of each time series was calculated and arithmetically averaged, yielding a value of 0.45 percent. The values from each time series ranged from a minimum of -0.08 percent to a maximum of +0.90 percent and were predominantly positive. (The ADDMS overestimated the mean water speed.) A +0.45 error in the determination of a depth-weighted cross product will produce an error in total discharge of +0.45 percent if all other factors remain constant (see eqs. 5 and 13); therefore, a value of +0.45 percent was used for  $x''_{r_f}$  for the Freeport measurement.

### Systematic Uncertainty Due to Improper Profiler Beam Geometry

Errors can be introduced into the computation of horizontal velocities due to incorrect transducer-beam axis angles. For example, if an ADCP (similar to the one used in this study) is manufactured with a 31.0° pointing angle on all transducers instead of 30.0° and the conversion algorithms are not corrected, measured horizontal water and vessel velocities would be in error by +3.0 percent. Errors in the included angles between opposing and adjacent beams can cause direction-dependent errors. Transducer pointing angles can be measured in the laboratory and those data used to apply corrections to ADCP-measured horizontal velocities, but the ADCP used in this study was manufactured before beam-angle calibration procedures were instituted by the manufacturer.

Lake tests performed on the ADCP used in this study, although less accurate than laboratory measurements, indicate that velocity measurement error due to beam pointing angles is a significant source of systematic error and causes the ADCP to overestimate vessel and water velocities by approximately 0.72 percent. Data for this analysis were taken from four different lake distance courses. This result did not vary significantly with different transducer azimuths and vessel speeds. Because discharge is computed using the cross product of water and vessel velocity, the propagation of this error is examined using equation 32. Because of the test method, delineation of error between the various transducer beams is not possible; therefore, the +0.72 percent error must be applied to each direction, and equation 32 becomes

$$f_{er}f = (1.0072a_1)(1.0072b_2) - (1.0072a_2)(1.0072b_1), \quad (35)$$

which simplifies to

$$f_{er} = \frac{1.01445(a_1b_2 - a_2b_1)}{f}. \quad (36)$$

Equation 3 shows that  $f = a_1b_2 - a_2b_1$  and therefore  $f_{er} = 1.01445$  or +1.45 percent.

Thus, overestimation of vessel and water velocities by 0.72 percent causes an overestimation of velocity cross products by 1.45 percent. Assuming all other values remain constant, a +1.45 percent error in velocity cross-product calculations causes a +1.45 percent error in calculated total discharge (see eqs. 5 and 13); therefore, a value of +1.45 percent is used for  $x''_{r_\theta}$ .

### Systematic Uncertainty Due to Receiver-Chain Effects

Hansen (1986) discusses a category of hardware errors that affect reverberation spectra of the measured velocity field. Among the most important of these are

1. nonlinearities caused by mismatched transducers, uneven or defective transducer coatings, misaligned receiver electronics, and "ringing" due to various sources;
2. spectral-windowing effects caused by the response of fixed-receiver input bandpass filters;
3. noise-induced errors;
4. magnitude-transfer function coloring caused by a non-"white" or nonlinear magnitude-transfer function of the receiver bandpass filters and their interaction with the spectral-moment estimation technique used in the ADCP; and
5. quadrature channel amplitude and phase imbalances.

These and other miscellaneous receiver-caused errors are termed by Hansen (1986) as receiver-chain effects. The magnitude of errors introduced by receiver-chain effects is dependent, to a certain extent, on the algorithm used to calculate the center of power (in the frequency domain) of the water-parcel reverberation spectra. These errors can be extremely hard to quantify individually; prior to 1989, not many attempts were made to do so.

Based on in-house research, the manufacturer doubts that the combined error in the measurement of horizontal velocity due to receiver-chain effects (excluding noise-induced error) exceeds -0.5 percent of the actual velocity; however, they agree that more tests are needed to confirm this value (Joel Gast, RD Instruments, oral commun., 1989). Laboratory tests done by Appel and others (1988) that compute error from lumped sources (of which receiver-chain effects are only one) indicate that this value is not unreasonable. Many of the errors due to receiver-chain effects can be minimized by optimized circuit design, proper quality control during the ADCP manufacture, and stringent calibration procedures. It should be noted, however, that because of the properties of fixed bandpass filters, two important error sources discussed by Hansen (1986) (errors 2 and 3 listed above) are always present in ADCP systems of the type used in this study and tend to bias the computed horizontal velocities toward the center of the fixed bandpass filters (zero velocity). Thus, these errors most often cause an ADCP to underestimate horizontal velocities. This

hypothesis was partly confirmed by laboratory tests (Appel and others, 1988).

In the case of skew errors, the vessel-velocity vectors are largely unaffected because of the shape and much narrower spectral width of the returned bottom-track signal (Joel Gast, RD Instruments, written commun., 1989). At vessel speeds used for discharge measurement, skew errors only affect the measured water-velocity vectors. Because discharge is computed from the cross product of water and vessel velocity, an error in the measurement of water velocity of -0.5 percent will cause an error of -0.5 percent in the calculation of total discharge if all other factors remain constant (see eqs. 5, 13, 32, 33, and 34). In the absence of conclusive test results, the manufacturer's estimated value of -0.5 percent will be used for  $x''_{r_f}$ .

### Dynamic Bias Uncertainty Due to the Mispositioning of Receiver Tracking Filters

Most ADCP's use broad bandpass filters at the receiver "front end." These filters are the source of some error due to receiver-chain effects (as previously discussed). Also implemented in most ADCP's are signal-tracking low-pass filters just ahead of the analog-to-digital conversion section of the receiver. These filters have a much narrower bandwidth than the input bandpass filters to improve signal-to-noise ratio (which increases the ADCP's profiling range). The filters are centered at a fixed frequency, and the input signal is shifted toward that frequency by being heterodyned with a variable reference signal. Because these filters can be thought of as movable in the frequency domain, they are called tracking filters. The errors caused by mispositioning these tracking filters could be classed as receiver-chain effects and are the same type of errors that affect receiver-input bandpass filters (skew errors). However, because the culprits here are moving filters with narrower bandwidths than the receiver-input bandpass filters, the errors produced are dynamic and deserve a separate discussion.

Chereskin and others (1989) describe two sources of error due to mispositioning of low-pass tracking filters:

1. Skew error ( $V_{b_e}$ ) caused when the center frequency of the received signal is located either outside of or in the nonsymmetrical part of the tracking-filter bandwidth. The magnitude of this error is a nonlinear function of the difference between the center frequency of the acquired signal and the center frequency of the filter.
2. Noise-induced error ( $V_{b_n}$ ) due to the tendency of the complex covariance estimator to bias the estimated center of power toward the mean of the filter frequency when the signal-to-noise ratio is low and "white" noise dominates the filter envelope.

The error due to noise bias ( $V_{b_n}$ ) is not usually significant in shallow water (29 m or less). Signal levels in shal-

low riverine environments are usually well above the noise threshold for the entire measured profile; therefore, the value of  $x''_{r_d}$  is equal to that of  $V_{b_e}$  integrated over the entire profile.

The starting center frequency of the low-pass tracking filter is computed by an algorithm that uses the information from initial ADCP pings, along with setup parameters in the ADCP memory. Using the ADCP parameters used for the Freeport measurement, the error in horizontal water-velocity measurement in an individual bin due to tracking-filter skew error can be approximated using the following equation (Joel Gast, RD Instruments, oral commun. 1989):

$$V_{b_e} = 0.019\Delta V + 0.0009\Delta V^2, \quad (37)$$

where

$V_{b_e}$  = error in horizontal velocity, in centimeters per second; and

$\Delta V$  = difference between the filter center frequency (velocity) and the actual velocity, in centimeters per second.

This equation was developed for a relatively narrow set of 1,200-kHz ADCP operating parameters, which are used when the ADCP is employed for the measurement of discharge in shallow water; it does not apply in other cases. It is important to note that the value of  $V_{b_e}$  applies to horizontal velocity measurements in a single bin and depends on the position of the filter center frequency relative to the center frequency of the returned reverberation spectra at the time of the velocity calculation for that bin. After the initial filter position is determined, a bin-to-bin positioning algorithm is employed by the ADCP in an attempt to center the filter near the frequency of the next expected return signal (the next successive bin). The degree of slew in the filter center frequency is controlled by the tracking-loop time constant. If, during conditions of current shear, the tracking-loop time constant is improperly set, the filter-positioning algorithm will not be capable of matching the slew (bin to bin) of the true horizontal water velocity. This means that the magnitude of  $V_{b_e}$  is a function of the magnitude of current shear contained in the velocity profile and the value of the time constant that controls the movement of the filter center position. Proper adjustment of the ADCP bin-to-bin tracking parameter (tracking-loop time constant) can help minimize the impact of this error.

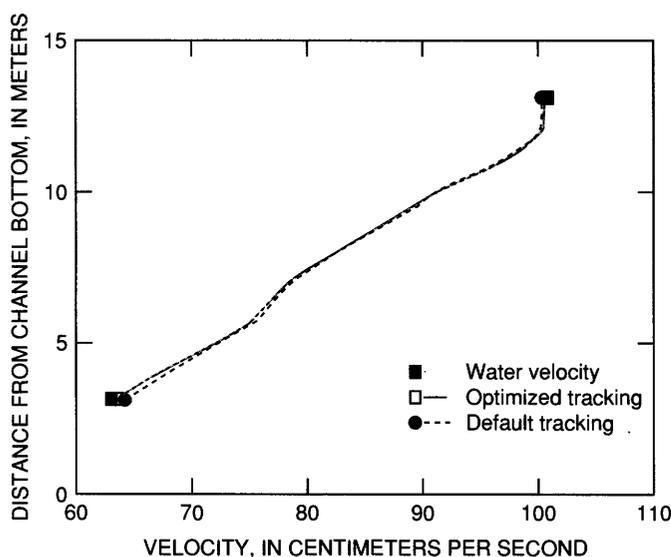
Because  $V_{b_e}$  is a dynamic error that can increase with increased current shear, a small computerized error model was developed to assess its impact on a typical ADCP-measured, riverine velocity profile. The computer error model integrates  $V_{b_e}$  over the entire profile and therefore provides a value for  $x''_{r_d}$ . Results indicated that the magnitude of  $x''_{r_d}$  becomes insignificant if the proper ADCP parameters are chosen. However, if "open ocean" ADCP memory default values or incorrect tracking-loop parameters

are used, the error can become significant. A typical ADCP-measured water-velocity profile for Suisun Bay near Chipps Island is shown in figure 14. The dotted line represents water velocities as output by the ADCP. The solid line represents the actual velocity. The dashed line represents the uncorrected ADCP-measured velocity using "open ocean" ADCP default tracking-loop parameters. As revealed in figure 14, if filter tracking-loop parameters are not properly set, the velocity in near-surface bins is underestimated by 0.3 percent and overestimated in the bottommost bins by 1.9 percent.

Values for  $V_{be}$  were determined from a typical water-velocity profile taken from the Freeport measurement (with optimized ADCP filter tracking-loop parameters), using equation 37. Integrating those errors over the entire profile yields a mean uncertainty in the measurement of water velocity of +0.04 percent. As previously discussed, skew errors do not affect the vessel-velocity vectors. An error of +0.04 percent in the measurement of water velocity will cause an error of +0.04 percent in the calculation of total discharge if all other factors remain constant (see eqs. 5, 13, 32, 33, and 34); therefore, a value of +0.04 is used for  $x''_{r_A}$ .

### Systematic Uncertainty Due to Profiler Transmit-Filter Skew

The ADCP manufacturer has reported an error in ADCP units fabricated prior to autumn 1989 (which includes the ADCP used in this study). The error is primarily due to slight mismatches between the transmit-filter's bandpass frequency and the physical resonant frequency of the transducer ceramics on each beam. This error causes a



**Figure 14.** Bias due to mispositioning of acoustic Doppler current-profiler tracking filters.

skew in the transmit frequency envelope. Because internal ADCP reference signals are offsets of the true transmitted frequency and not the biased transmitted frequency and because the reverberation spectrum is Doppler shifted based on the biased transmitted frequency, computations of horizontal velocity are biased. The measured horizontal velocity (using the ADCP parameters previously described) is biased approximately  $-0.7$  cm/s from the actual horizontal velocity. This error estimate is only a rough "conservative" guess based on the manufacturer's experience (Joel Gast, RD Instruments, oral commun., 1989). This error consists of both slope and offset components; however, the slope error (error as a percentage of velocity) is not significant because of the large bandwidth of the transmit filters compared with the bandwidth of the tracking filters (four times the bandwidth of the tracking filters). ADCP units purchased after autumn 1989 or that have recently been sent to the manufacturer for upgrade have undergone a rigorous tuning procedure that virtually eliminates this error. However, with time, the transducers and associated electronics age and can become detuned. The manufacturer estimates that bias error attributed to  $x''_{r_A}$ , introduced because of the aging process, probably does not exceed  $\pm 0.20$  cm/s. The ADCP system used in this report was returned to the manufacturer for upgrade after the new tuning procedures were implemented; therefore, the expected systematic uncertainty due to transmit-filter mistuning has been reduced to approximately  $\pm 0.2$  cm/s.

The Freeport measurement had a mean cross-sectional velocity of 60 cm/s. If a skew error of  $\pm 0.2$  cm/s due to transmit-filter mistuning is assumed, the calculation of water velocity will be in error by  $\pm 0.3$  percent. As previously discussed, skew errors do not significantly affect the vessel-velocity vectors. If all other factors remain constant, a  $\pm 0.3$  percent error in the measurement of water velocity will cause an error of  $\pm 0.3$  percent in the measurement of total measured discharge (see eqs. 5, 13, 32, 33, and 34); therefore, the value for  $x''_{r_A}$  will be  $\pm 0.3$  percent.

### Systematic Uncertainty Due to Operator-Caused Errors

Errors by the operator of the ADDMS can have a significant effect on the accuracy of an ADDMS-measured discharge. These errors can be categorized into two classes: operator-caused errors not involving the ADCP system, and operator-caused errors due to improper ADCP parameter settings.

Operator-caused errors that do not involve the ADCP system are (1) failure to properly calibrate the auxiliary depth sounder, (2) improper calibration of the optical rangefinder used in measuring the distance from vessel to riverbank, (3) poor choice of measurement cross sections,

and (4) too rapid cross-section traverse speeds. Proper calibration practices and adequate cross-section reconnaissance can minimize these errors.

Most ADCP parameters can affect the accuracy of the measured discharge if improperly set, and many (particularly the bottom-track parameters) must be selected based on stream conditions. The most common mistakes in the selection of ADCP parameters can be traced to the following sources:

- An incorrect bin-length parameter will confuse the ADCP discharge-measurement software. (The software assumes a 1-m bin length.)
- Incorrect bottom-track parameters will prevent the ADCP from properly acquiring the bottom echo and, in so doing, will cause the ADCP to provide incorrect or incomplete vessel-velocity data. Proper adjustment of these parameters becomes critical when sediment is moving along the river bottom. These parameters are unique to the ADCP described in this report and are best described in the manufacturer's manual.
- If ADCP timing parameters are adjusted near their critical limits, errors in the measured velocities can occur. The minimum ADCP transmit-blanking distance is 0.3 m. This parameter should be set somewhat longer (0.4–0.5 m) to prevent corruption of the first measured bin velocity. The maximum ADCP acquisition rate is one ping every 0.1 second. This parameter should probably be set somewhat slower (0.12–0.15 second) to prevent possible loss of the bottommost bins when profiling in deep water.
- The ADCP tracking-filter loop parameters must be properly set to prevent low-pass filter skew bias of the measured velocity. The ping-to-ping loop parameter should be set to center the filter frequency as close as possible to the average initial return frequency from bins 2 and 3. The bin-to-bin tracking-loop time constant should be set as short as possible to enable the filter to track properly in conditions of current shear. The filters should be set for broadband mode (when using a 1,200-kHz system in 29 m of water or less).
- The pings-per-ensemble parameter (number of pings averaged) should probably not be set below 18. This can cause an unacceptable variability in the measured velocity profile, which invalidates the curve-fitting scheme used in the ADDMS software. This parameter, along with the vessel channel-traverse speed, should be adjusted to obtain 45 or more subsection measurements during a discharge measurement (as previously discussed).

Proper calibration of ADCP ancillary devices, adequate cross-section reconnaissance, and proper ADCP parameter setup can reduce errors due to  $x''_{r_0}$  below significant levels. However, it is probable that at least some of these errors will be present in a typical discharge measurement even under the best of conditions. Therefore,

an arbitrary value of  $\pm 0.5$  percent error in total calculated discharge will be used for the value of  $x''_{r_0}$  for the Freeport measurement.

### Total Systematic Uncertainty in a Typical Discharge Measurement

Substituting the systematic uncertainty incurred during the Freeport measurement into equation 31 yields

$$X''_{R_Q} = (0.9986) (1.0045) (1.0145) (0.995)$$

$$(1.0004) \left[ \begin{array}{c} 1.003 \\ \text{or} \\ 0.997 \end{array} \right] \left[ \begin{array}{c} 1005 \\ \text{or} \\ 0.995 \end{array} \right] - 1,$$

giving  $X''_{R_Q}$  a value between +2.11 percent and +0.49 percent.

### TOTAL UNCERTAINTY IN A TYPICAL DISCHARGE MEASUREMENT

It has been shown in the above analysis that the total random uncertainty in the Freeport measurement was 1.17 percent and the total systematic uncertainty was between +2.11 and +0.49 percent. Random uncertainty and systematic uncertainty cannot be combined directly to form total uncertainty because of differences in the properties of the two types of uncertainty, but their limits may be examined to determine the maximum amount of error that can be expected in a typical discharge measurement. For example, if the Freeport measurement had a total systematic uncertainty of +2.11 percent, and the random uncertainty is assumed to be normally distributed about the value of the systematic uncertainty for a typical series of discharge measurements at that location, the probable limit for overestimation of discharge would occur if the instantaneous value of the random uncertainty were +1.17 percent. Total uncertainty could then be calculated by multiplication: (1+1.17 percent) (1+2.11 percent) – 1 or +3.30 percent. Conversely, the probable limit for underestimation of discharge would occur if the total systematic uncertainty were +0.49 percent and the instantaneous value of random uncertainty were –1.17 percent. The total uncertainty would then be (1–1.17 percent) (1+0.49 percent) – 1 or –0.68 percent.

Thus, the total uncertainty ( $X_{R_Q}$ ) of a typical discharge measurement made on the Sacramento River at Freeport, California (the Freeport measurement), has a probable value somewhere between +3.30 and –0.68 percent. If the direction and magnitude of the transmit-filter skew could be obtained, and the operator error were assumed to be zero, the above limits could be narrowed

somewhat. For example, if the transmit-filter skew bias were +0.05 cm/s and the operator-caused systematic error were zero, the total uncertainty would most likely be between the bounds of +2.57 and +0.19 percent.

This method of error presentation is cumbersome compared with the presentation of results of historical error analyses (Carter and Anderson, 1963; Herschy, 1970). However, historical analysts typically defined only a few systematic uncertainties and treated them differently than is done in the above analysis. Carter and Anderson (1963) made the assumption of no systematic uncertainty (presumably to simplify the error analysis) but acknowledged that a different current meter must be used for each discharge measurement for this assumption to be valid. Herschy (1970) identified three sources of systematic uncertainty (depth, width, and current-meter calibration errors) but treated them as random, summing them with the random error sources using the root-sum-squares method to compute a total uncertainty. Presumably Herschy assumed that the current meters would be rotated (traded with other hydrographers between discharge measurements) and tag-line and depth calibration errors would change with each discharge measurement, causing the errors produced to be randomlike. The above assumptions may be reasonable for conventional discharge measurements if systematic uncertainties are small and hydrographers use current-meter rotation procedures. However, the significance of ADDMS systematic uncertainty, ADDMS cost, and the semipermanent nature of ADDMS transducer installation preclude the use of the above-mentioned techniques.

ADDMS systematic uncertainty is likely to be constant or change only slowly with time and will be apparent as both a scale and offset error; that is, it will have a multiplicative component that can be expressed as a percentage and will have an offset component that can be expressed as a velocity. If the values and direction of these systematic errors are known, they can be used to correct ADDMS errors by applying coefficients to the ADDMS-measured velocities using the form

$$y = mx + b, \quad (38)$$

where

- $y$  = the corrected ADDMS-measured velocity,
- $m$  = a coefficient,
- $x$  = the uncorrected ADDMS-measured velocity, and
- $b$  = an offset in centimeters per second.

If, as in the above analysis, systematic uncertainty values have been obtained for all but  $x''_{r\lambda}$  and  $x''_{r_o}$ , a partial correction can be used to center the error boundaries about zero. For example, a partial, lumped, systematic-uncertainty value can be calculated using equation 31 for the values of  $x''_{r_o}$  through  $x''_{r\Delta}$ :

$$(0.9986) (1.0045) (1.0145) (0.995) (1.0004) - 1 = +1.30 \text{ percent.}$$

If ADDMS-measured velocities are corrected by substituting 1–1.30 percent into equation 38 ( $y = 0.9871x + 0$ ) and operator error ( $x''_{r_o}$ ) is assumed to be zero, the resulting discharges will have a constant total systematic uncertainty that exists between the bounds of  $(1 \pm x''_{r\lambda}) - 1$  or +0.30 percent and –0.30 percent. The probable limits can then be calculated (assuming that the random uncertainty is normally distributed about the systematic uncertainty) and will equal  $(1 \pm 0.30 \text{ percent}) (1 \pm 1.17 \text{ percent}) - 1$  or  $\pm 1.47 \text{ percent}$ . Note that this is using a value of  $x''_{r\lambda}$  computed from the manufacturer's estimate of a  $\pm 0.2 \text{ cm/s}$  bias for transmit-filter skew and a mean river velocity during the Freeport measurement of 60 cm/s. The ratio  $((Q - Q_\lambda)/Q)100$  (and therefore the boundaries) will vary with changes in mean river velocity. If the value of  $x''_{r\lambda}$  can be quantified and its direction established, it can be substituted into the offset term of equation 37 to further narrow or eliminate the effects of systematic uncertainty.

Appel and others (1988) developed a calibration method using a tow-tank facility that may identify the error (in lumped form) of many of the error sources previously discussed. The validity of this laboratory test procedure is still being scrutinized, but preliminary results look promising. These and other test procedures, when implemented, will be extremely valuable in identifying and quantifying ADCP errors, thereby reducing the errors in an ADDMS-measured river or estuarine discharge.