In cooperation with the Sacramento Regional Wastewater Treatment Plant and the California Department of Water Resources

Investigation of Hydroacoustic Flow-Monitoring Alternatives at the Sacramento River at Freeport, California: Results of the 2002–2004 Pilot Study

Scientific Investigations Report 2004-5172

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

Cover. Sacramento River at Freeport Bridge, Freeport, California. (*Photograph by Cathy Munday, U.S. Geological Survey*)

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Conversion Factors, Abbreviations, and Acronyms

Multiply	By	To obtain
acre	0.4047	hectare (ha)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
foot (ft)	0.3048	meter (m)

Abbreviations

hrs	hours
kHz	kilohertz
sec	seconds

Acronyms

ADVM	acoustic Doppler velocity meter
AVM	acoustic velocity meter
CADWR	California Department of Water Resources
CDMA	code division multiple access
CDPD	cellular digital packet data
LR-ADVM	long-range acoustic Doppler velocity meter
MPD	median percent difference
RMS	root-mean-squared
SR-ADVM	short-range acoustic Doppler velocity meter
SRWTP	Sacramento Regional Wastewater Treatment Plant
USGS	U.S. Geological Survey

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Executive Summary

The Sacramento River at Freeport (Freeport) is a tidally affected channel approximately 620 feet wide located at the northern boundary of the Sacramento—San Joaquin River Delta, California. In 1978, an acoustic velocity meter (AVM) was installed at Freeport to monitor the flow. The AVM was calibrated successfully and has been used continuously since that time. Although the calibration has been stable, an increasing number of maintenance problems prompted a search for alternatives to monitor discharge at this location. Two sideward-looking acoustic Doppler velocity meters (ADVMs) were tested in a pilot study from 2002–2004: a short-range SonTek SL-1500 (SR-ADVM) and a long-range SonTek SL-500 (LR-ADVM). The pilot study was conducted over a wide range of hydrologic conditions, and both sideward-looking ADVMs performed well at this location and have been calibrated successfully.

The SR-ADVM and the LR-ADVM have good calibrations and data-recovery rates. Based on data collected through February 2004, the SR-ADVM had an r^2=0.997 and a data-recovery rate of 97 percent; the LR-ADVM had an r^2=0.996 and a data-recovery rate of 91 percent. The discharge data from the SR-ADVM have been selected as the primary record because this instrument has a robust calibration and a higher data-recovery rate. The discharge data from the LR-ADVM are the secondary record and provide real-time data redundancy, thereby minimizing data loss.

Two issues require further attention: (1) although the SR-ADVM data have been selected as the primary record, there appears to be some problems with the discharge records, as compared to the discharge records from the other systems; and (2) there are problems with the radio-transmission system between the ADVM systems on the Freeport Bridge and the datalogger in the Outfall Building.

To confirm the stability of all the calibrations, additional discharge measurements should be collected, particularly in flow conditions below 30,000 cubic feet per second. These additional measurements should help resolve the discrepancies between the SR-ADVM discharge data and that from the other two systems. Based on the analysis of the new discharge measurements, there may be changes to the ADVM calibrations and in the determination of which ADVM system will provide the primary record.

Reliability of the radio-transmission signal between the ADVM systems on the Freeport Bridge and the datalogger in the Outfall Building continue to be problematic. A comparison of the 15-minute time series telemetered directly to the U.S. Geological Survey (USGS) offices by a cellular digital packet data system, and the 1-minute data transmitted by radio to the Outfall Building, show that there are data-transmission problems between the Freeport Bridge and the Outfall Building. The datalogger at the Outfall Building records the “selected discharge”. The selected discharge is determined through automated error-checking protocols to confirm that the incoming data meet quality-control criteria. In the event that the primary record (SR-ADVM) data fail to meet the criteria, the secondary record (LR-ADVM) data are selected automatically. In the event that both records fail to meet the quality-control criteria, then the last data value is retained. During January and February 2004, 56 percent of the selected discharge record was the primary record, 27 percent of the selected discharge record was the secondary record, and the remaining 17 percent was the retained value. However, the USGS record shows that the time series was complete and in no instance was the criteria met for rejecting the primary record, indicating that the radio transmission was not working between the Freeport Bridge and the Outfall Building.

To provide additional time to identify and test a robust data-transmission system between the ADVM systems on the Freeport Bridge and the datalogger in the Outfall Building, the AVM can continue to be operated. However, in the event that problems arise with the AVM, the ADVM systems are available to provide backup data. During this time, additional calibration data should be collected as part of the standard operation and maintenance protocol of the station. In the event of complete AVM failure prior to the resolution of the data-transmission problems, the ADVM system with the strongest calibration and best data-recovery rate should be selected as the primary replacement system and the other should be used as the secondary system.

Abstract

The Sacramento River at Freeport is a tidally affected channel approximately 620 feet wide located at the northern boundary of the Sacramento—San Joaquin River Delta, California. In 1978, an acoustic velocity meter was installed at Freeport to monitor the flow. The acoustic velocity meter was calibrated successfully and has been used continuously since that time. Although the calibration has been extremely stable, an increasing number of maintenance problems prompted a search for alternatives to monitor discharge at this location. Two sideward-looking acoustic Doppler velocity meters were tested in a pilot study from 2002–2004: a short-range system and a long-range system. The pilot study was conducted over a wide range of hydrologic conditions and both sideward-looking acoustic Doppler velocity meters have performed well at this location and have been calibrated successfully. As of February 2004, the short-range system had a robust calibration and a higher data-recovery rate, therefore, it was selected as the primary replacement of the acoustic velocity meter, with the long-range system providing real-time data redundancy to minimize data loss.

Introduction

The Sacramento—San Joaquin Delta (Delta) is a complex network of tidally influenced channels located in the heart of California's Central Valley (*fig. 1*). More than 20 million people depend on the Delta for drinking water, 4.5 million acres of cropland are irrigated with Delta water, and several endangered fish species reside in or migrate through the Delta. Approximately 80 percent of the water entering the Delta is conveyed by way of the Sacramento River past Freeport. During the study period, daily averaged river flows on the Sacramento River at Freeport ranged from approximately 9,000 cubic feet per second (ft^3/s) to 75,000 ft^3/s, and tidal flows ranged from 300 ft^3/s to 77,000 ft^3/s.

The U.S. Geological Survey (USGS) has been using acoustic technology to monitor flow in tidally affected areas since the late 1970s. Use of acoustic flow meters has expanded since that time and the USGS and the California Department of Water Resources (CADWR) currently operate more than 20 stations in the Delta. The use of acoustic technology in stream gaging across the United States has been growing, and an increasing number of stream-gaging stations are employing these approaches (Morlock and others, 2002). Standard "stage-discharge" stream-gaging techniques are not appropriate for tidally affected locations because the relationship between stage and discharge is variable over time (Laenen, 1985).

Purpose and Scope

The purpose of this report is to present general information regarding acoustic velocity meter (AVM) technology and to document the results of a pilot study from September 2002 to February 2004 investigating flow-monitoring alternatives at the Sacramento River at Freeport. The objective of the pilot study, done in cooperation with the Sacramento Regional Wastewater Treatment Plant (SRWTP) and CADWR, was to find a viable alternative to the existing AVM flow-monitoring system at Freeport. The study entailed installation of two sideward-looking acoustic Doppler velocity meters (ADVMs) and the calibration and maintenance of these systems during 2002–2004. It is unusual to have three independent systems to measure discharge at a single station. The data collected from all three systems during the pilot study were analyzed and compared to identify the best alternative for monitoring discharge at Freeport. In addition, data-transmission equipment and a program to conduct preliminary error checking were tested as a part of the study. The resulting discharge data are transferred or will be transferred electronically in near-real time to three agencies: USGS, CADWR, and SRWTP. On-going operation and maintenance of the ADVM systems are scheduled to become part of the continuing monitoring program.

Acknowledgments

We sincerely thank the cooperators who funded this study: SRWTP and CADWR. In addition, there were many participants who made this study possible. The field staff, who have worked many long hours installing, calibrating, and troubleshooting the station: Jon Yokomizo, Jim George, Curt Battenfeld, Mike Simpson, Bill Brazelton, Laureen Fong-Frydendal, Rob Hilditch, and Greg Smith from the USGS, and Larry Bezanson from SRWTP. Additional thanks to Mike Simpson from the USGS for contributing his thorough knowledge of acoustics; he was involved with the installation and calibration of the original AVM system and his participation in this project has been invaluable both for understanding the history of the station and for his technical expertise. Cathy Munday at the USGS took the cover photograph of the Freeport Bridge. Finally, many thanks to the reviewers and production staff who have helped with this report: John Kemp, Mike Simpson, Robert Meyer, Carmen Lee, Mitchell Maidrand, Bill Hendrix, Stephen Ito, Art Hinohosa, Carol Sanchez, Phil Contreras, Jeremy Woods, Charlie Kaehler, and Kimberly Engelking

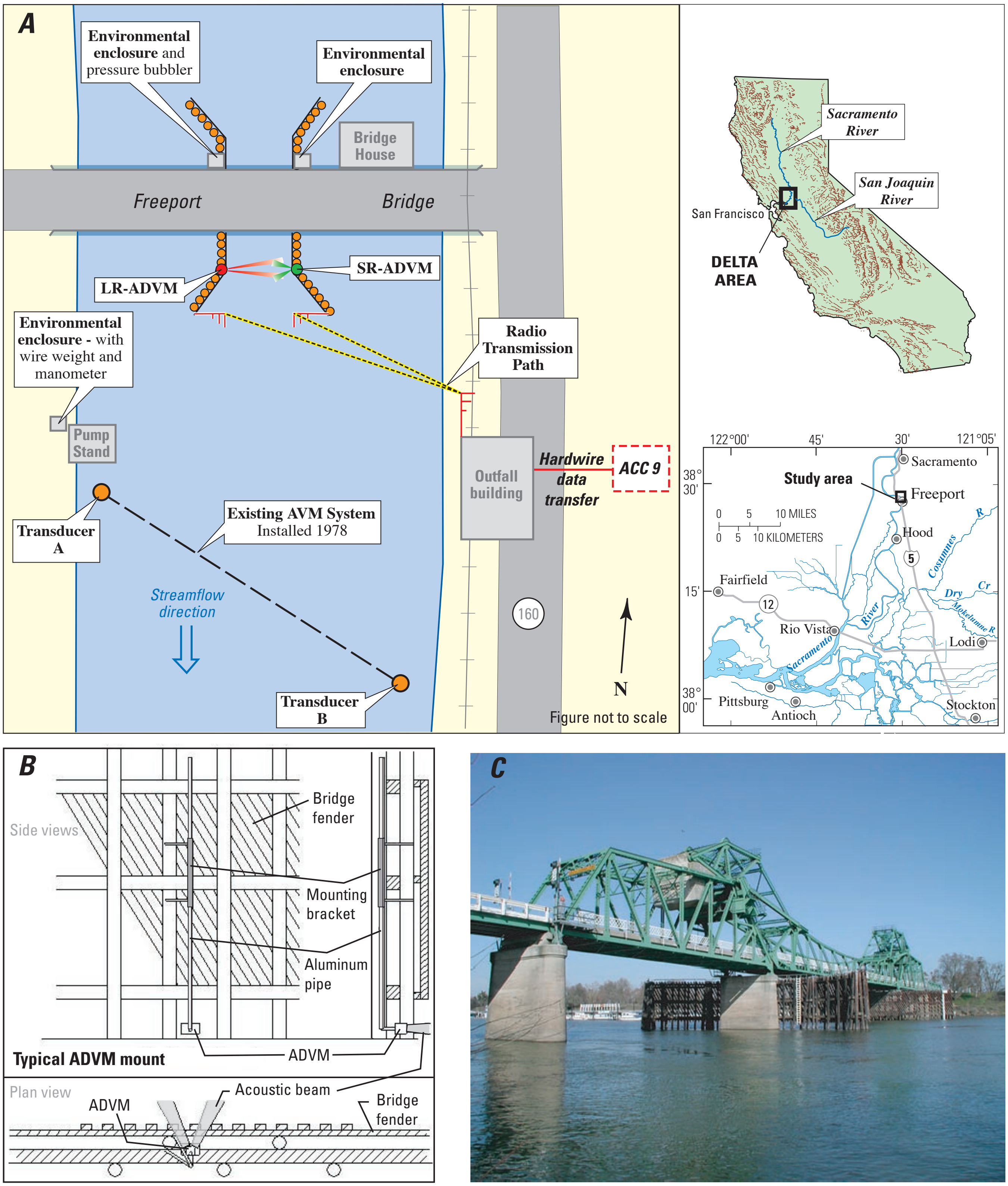


Figure 1. Study location, Sacramento River at Freeport, California. (*A*) station location map, (*B*) acoustic Doppler velocity meter mounting system, (*C*) photo of Freeport Bridge (photo by C. Munday). ADVM, acoustic Doppler velocity meter; LR-ADVM, long-range acoustic Doppler velocity meter; SR-ADVM, short-range acoustic Doppler velocity meter; AVM, acoustic velocity meter; ACC9, building name.

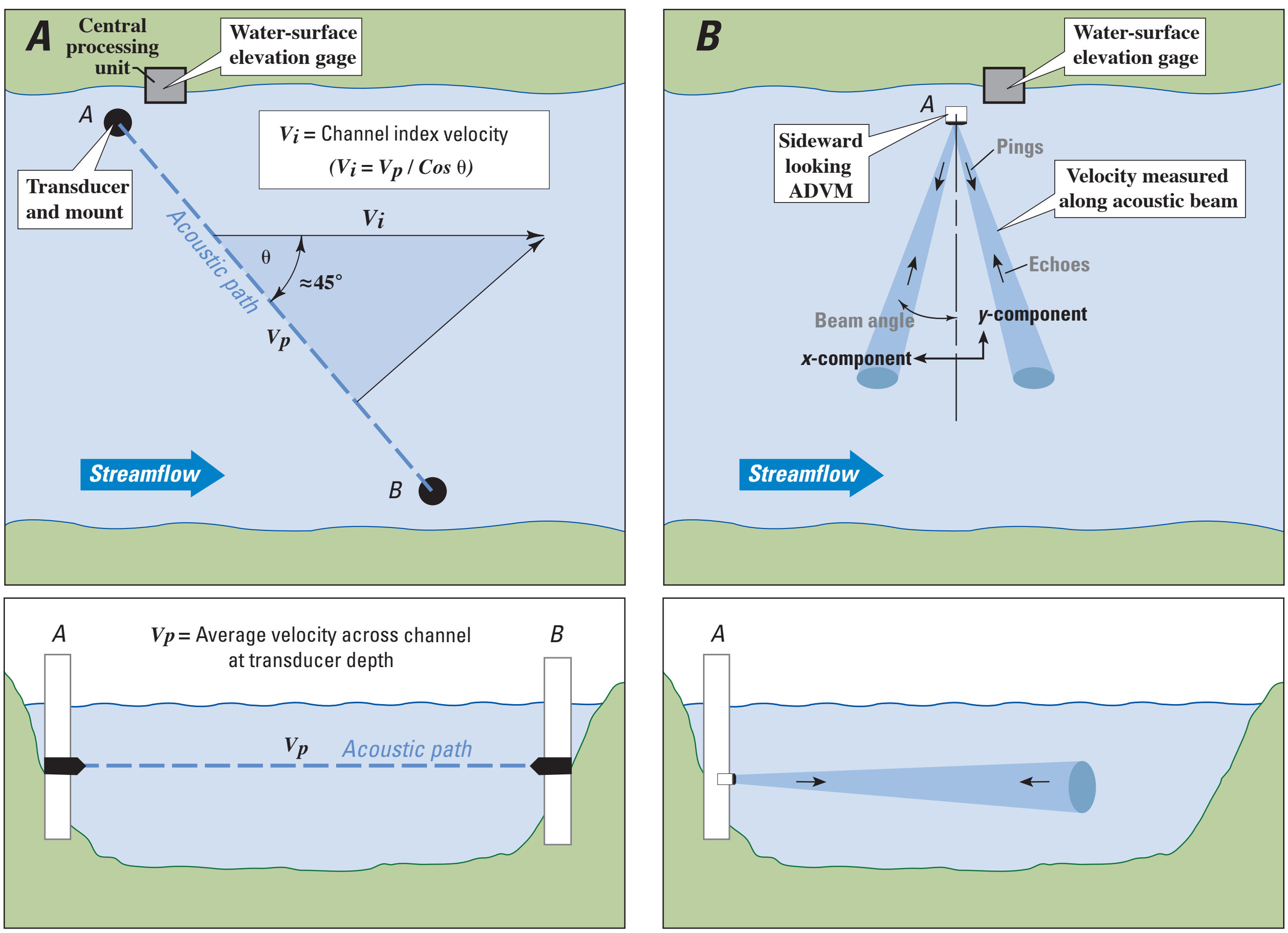
Principles of Operation of Acoustic Flow-Monitoring Systems

Acoustic Velocity Meter

AVMs work on a "time of travel" principle. The AVM system is comprised of two transducers that are mounted diagonally across a channel and connected to a central processing system by cables. An acoustic signal that has a component travelling in-line with the water velocity (from transducer A to B) will move faster than an acoustic signal that has a component travelling against the water velocity (from transducer B to A). The water velocity along the acoustic path (V_p) is proportional to the difference, in time, required for the acoustic signal to travel between the transducers in each direction (Accusonic Technologies, 2003). Index velocity (V_i) is determined by measuring the difference in the time required for an acoustic signal to travel between the two transducers and a knowledge of the transducer geometry (specifically the distance between the transducers and the angle of the acoustic path with respect to the principal flow direction) (*fig. 2A*).

Acoustic Doppler Velocity Meter

ADVMs utilize a pair of monostatic transducers–transducers that both send and receive an acoustic pulse. An acoustic pulse of a known frequency is sent out into the water column along the acoustic beam. A fraction of that acoustic pulse then is reflected by small particles in the water back to the transducer at a different frequency. The water velocity within the acoustic beam (V_i) can be determined based on the change in the acoustic frequency and the geometric configuration of the transducers (SonTek Corporation, 2000) (*fig. 2B*).



(Modified from Accusonic Technologies, 2003)

(Modified from Morlock and others, 2002)

Figure 2. Schematics of standard acoustic stream-gaging stations. (*A*) acoustic velocity meter installation and (*B*) acoustic Doppler velocity meter installation. ADVM, acoustic Doppler velocity meter.

Calculation of Discharge

River discharge is a function of the cross-sectional area and the cross-sectionally averaged velocity. However, because these parameters cannot be directly measured on a real-time basis, surrogate parameters that can be measured easily in the field are used and then calibrated to calculate the discharge. In tidally affected channels, stage and index velocity are measured directly in the field. Stage is calibrated to determine the cross-sectional area. Index velocity is calibrated to determine the cross-sectionally averaged velocity. These two values are used to calculate discharge as:

$$Q = A\overline{V} \tag{1}$$

where Q is discharge,
A is cross-sectional area, and

$\overline{V}$ is cross-sectionally averaged velocity.

Equipment Configuration

During the pilot study, a total of three independent equipment configurations were used to monitor the discharge at Freeport: an AVM, a short-range ADVM (SR-ADVM), and a long-range ADVM (LR-ADVM). *Table 1* compares the configuration settings for the two ADVMs. In addition, a profiling ADVM is mounted in a downward looking position to a boat-and is used periodically to directly measure the discharge, and these data are used to calibrate the equipment (Simpson and Oltmann, 1993; Simpson and Bland, 1999; and Simpson, 2001).

Table 1. Comparison of acoustic Doppler velocity meter configuration settings used during the 2002–2004 pilot study at the Sacramento River at Freeport, California

[kHz, kilohertz; sec, seconds; ft, feet; m, meter, n/a, not applicable]

Parameter	Short-range acoustic Doppler velocity meter	Long-range acoustic Doppler velocity meter
System configuration		
System type	Sideward looking	Sideward looking
Serial number	E600	C420
Sensor frequency	1,500 kHz	500 kHz
Number of beams	2	2
Vertical beam (stage)	Yes	No
Program configuration		
Average interval	40 sec	40 sec
Sample interval	900 sec	900 sec
Cell begin	16.4 ft (5 m)	49.2 ft (15 m)
Cell end	65.6 ft (2 m)	147.6 ft (45 m)
Profiling mode	n/a	Yes
Number of cells	n/a	5
Cell size	n/a	16.4 ft (5 m)
Blanking distance	n/a	49.2 ft (15 m)

Acoustic Velocity Meter

The AVM system at Freeport is an Ocean Research equipment model 7410 Accusonic flowmeter. This AVM system measures index velocity and a Stevens manometer measures water level. The AVM is located approximately 630 feet (ft) downstream of the Freeport Bridge. The transducers are mounted to aluminum “H” beams driven into the channel bottom and must be serviced by divers. Average hourly data are recorded; however, the SRWTP receives high-frequency (every minute or less) real-time data from this station to manage their effluent stream.

Short-Range Acoustic Doppler Velocity Meter

The SR-ADVM system at Freeport is a SonTek SL-1500. This system has an integrated upward-looking stage beam. The SR-ADVM is installed on a sliding aluminum pipe mount that is bolted to the eastern Freeport Bridge fender (*fig. 1*) as near to the center of the channel as possible to best characterize the flow. This system is programmed to provide 15-minute time series; however, to provide higher-frequency data to the SRWTP, data are transferred to the Outfall Building as a rolling 5-minute average at 1-minute intervals. In addition, the datalogger at the Outfall Building is programmed to check for errors. The error-checking protocols are discussed in the Outfall Building Datalogger Programming and Error-Checking Algorithm section of this report.

Long-Range Acoustic Doppler Velocity Meter

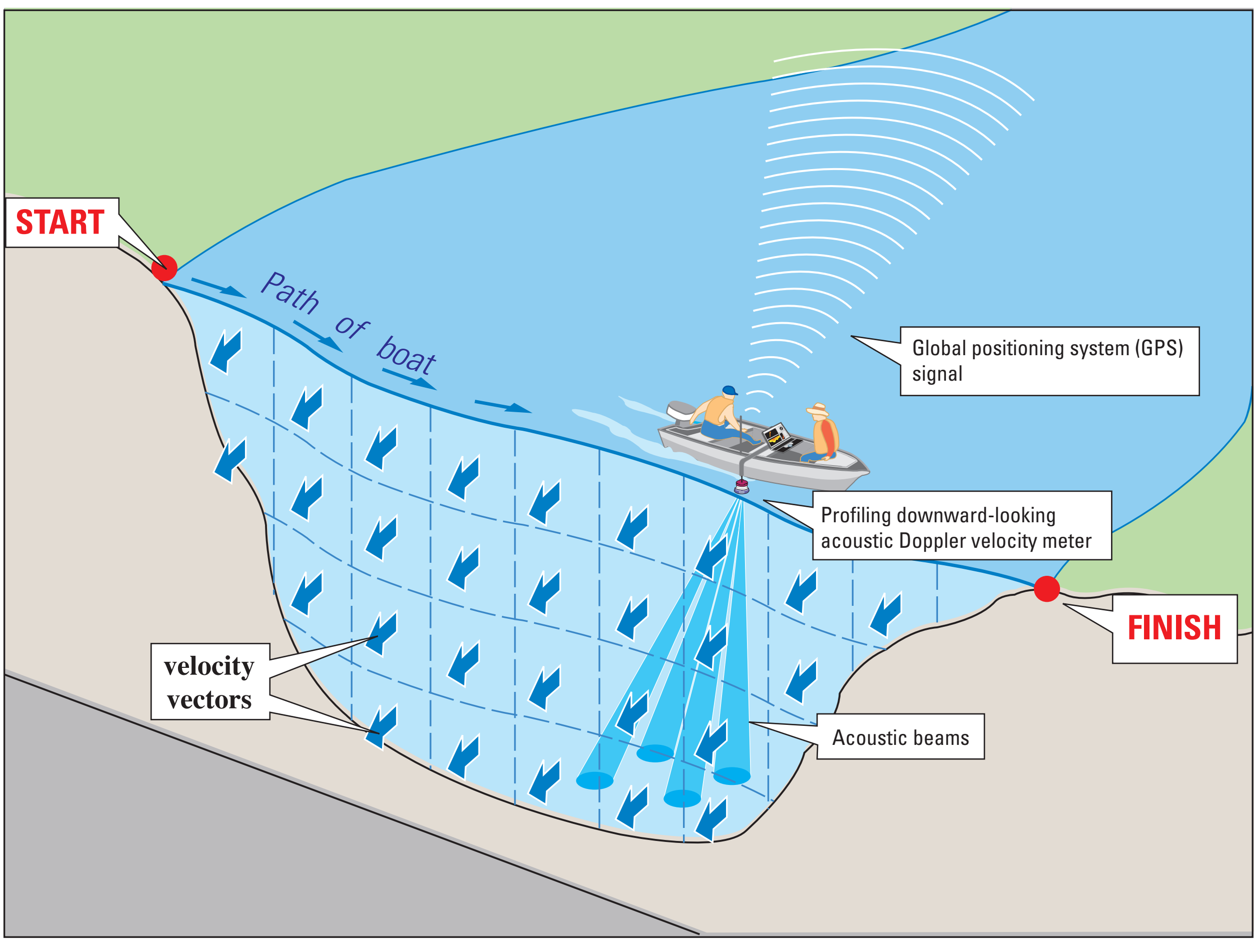
The LR-ADVM system at the Freeport Bridge is a SonTek SL-500. Stage is measured with a pressure bubbler system. The LR-ADVM is installed with a similar mount as the SR-ADVM and is bolted to the western Freeport Bridge fender. The LR-ADVM was programmed to sample the velocities between 50 ft and 150 ft from the face of the instrument. Although this system is capable of measuring velocities approximately 400 ft away from the face of the instrument, the sample volume was reduced because of obstructions with the Freeport Bridge fender. This system is capable of reporting profile data (or lateral variability in the velocity structure); however, for the purposes of calibration and reporting discharge, a bulk average of the entire sample volume is used. This system is programmed to provide 15-minute time series; however, to provide higher-frequency data to the SRWTP, data are transferred to the Outfall Building as a rolling 5-minute average at 1-minute intervals. In addition, the datalogger at the Outfall Building is programmed to check for errors. The error-checking protocols are discussed in the Outfall Building Datalogger Programming and Error-Checking Algorithm section of this report.

Downward-Looking Acoustic Doppler Current Profiler

Periodically discharge at Freeport was directly measured using a boat-mounted downward-looking ADVM profiler (*fig. 3*). Discharge measurements were collected over the full range of expected flows to fully characterize the index velocity relationship (Simpson, 2001). In addition, full-tidal cycle measurements were collected in September and October 2002 to ensure proper characterization of flood-ebb asymmetry.

Proof-of-Concept Study

In January 2002, the USGS installed the SR-ADVM on the Sacramento River at Freeport (*fig. 1*) as part of a month-long proof-of-concept study. The results of this preliminary study indicate that sideward-looking ADVM technology would be a feasible replacement for the existing AVM. Although no calibration measurements were collected during the proof-of-concept study, a direct comparison of the measured index velocities (*fig. 4*) indicates that the SR-ADVM successfully monitors velocities in a large, tidally influenced channel. The existing AVM has a consistent rating, and discharge measurements have been consistently within 5 percent of the calculated flows from the AVM (water year 2001 Sacramento River at Freeport station analysis). Because the AVM rating is stable, the index-velocity data collected by the AVM were compared directly to the index-velocity data collected by the SR-ADVM, and a strong correlation ($r^2 = 0.990$) exists. Moreover, ebb-flood asymmetries were not observed on the Sacramento River at Freeport.



(Modified from Simpson, 2001)

Figure 3. Discharge measurement from a boat using a profiling downward-looking acoustic Doppler velocity meter.

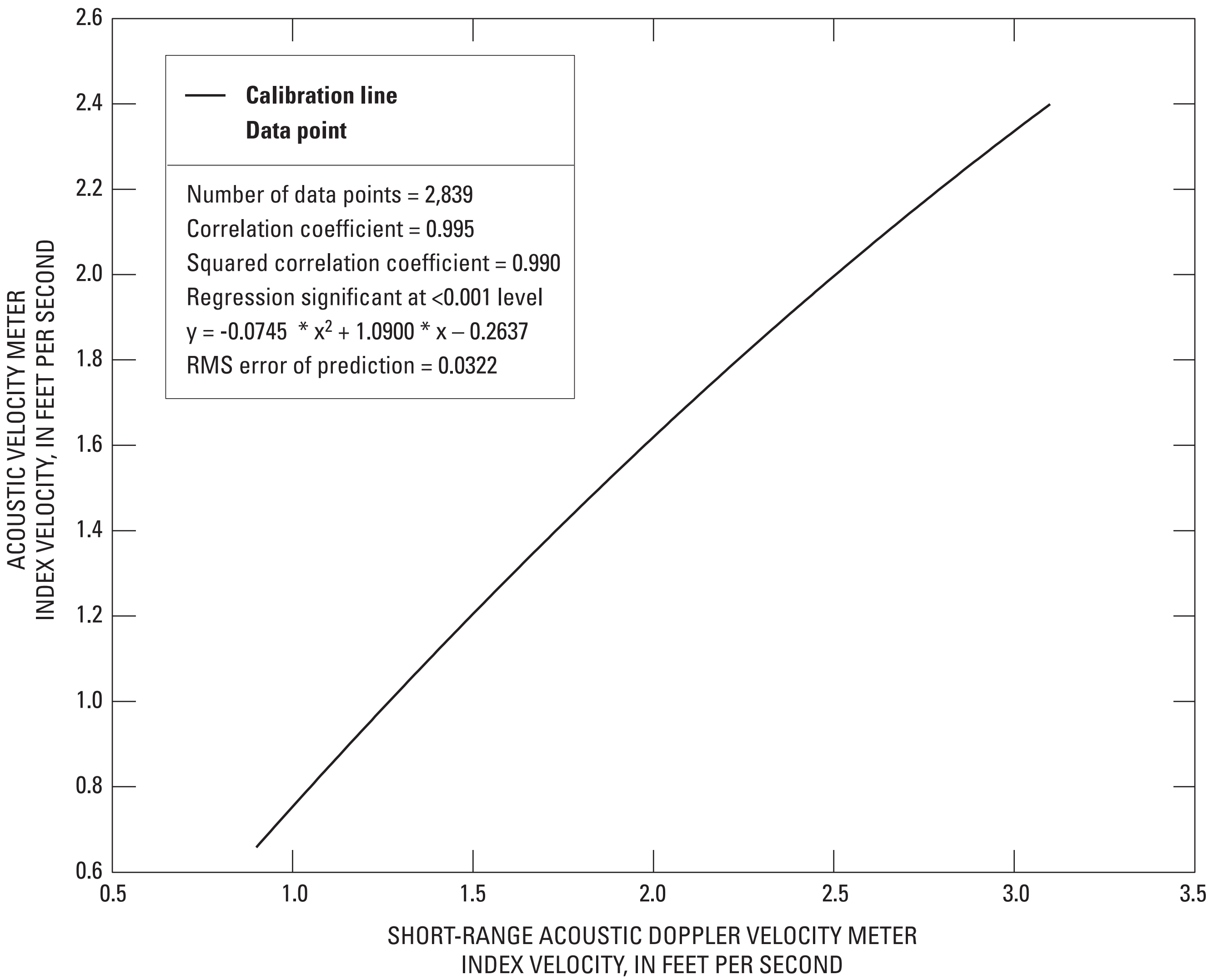


Figure 4. Relationship between index velocity measurements collected using a short-range acoustic Doppler velocity meter and an acoustic velocity meter. RMS, root-mean-squared.

There were two periods of deviation between the AVM and the SR-ADVM relation: January 18 at 2245 through January 19 at 1315 (14.5 hrs) and February 9 from 0745 through 0945 (2 hrs). Although the exact cause of these discrepancies is unknown, it was likely a transient obstruction of the acoustic beams such as floating debris in the channel.

In August 2002, the LR-ADVM was installed on the western Freeport Bridge fender. Stage and index-velocity data collection by both ADVM systems began in September 2002. Calibration measurements have been collected periodically since October 2002.

Calibrations

Area Calibration

The original area calibration was not adjusted during this pilot study. Periodic comparisons between the original calibration and subsequent cross-sections suggest that this section of the channel is stable and that no calibration is needed. The equation describing the relationship is:

$$A = 2.269499 * H^2 + 131.0353 * H - 25761.21 \quad (2)$$

where A is the cross-sectional area, and

H is the water-surface elevation.

Velocity Calibration

In all cases, least-squares regression analysis was used to develop the calibration relationships.

Acoustic Velocity Meter

This system was calibrated in 1978 using a “k-curve” relationship (Laenen, 1985) based on direct measurements of the river flow. No modifications to the calibration relationship have been made since that time. Directly measured check measurements are collected regularly and are consistently within 5 percent of the calculated discharge time-series (water year 2001 Sacramento River at Freeport station analysis). To ensure that the site has been stable over time, a recalibration effort using the index velocity method was undertaken in 2003 using discharge measurements collected from March 2000 to February 2003; a difference of approximately 1 percent between the existing and the new calibrations for tidal and daily discharge was found. This suggests that the Freeport station has been stable over time. The results of the recalibration effort, which included data collected over a wide range of hydrologic conditions, show a strong calibration ($r^2 = 0.998$) (*fig. 5*).

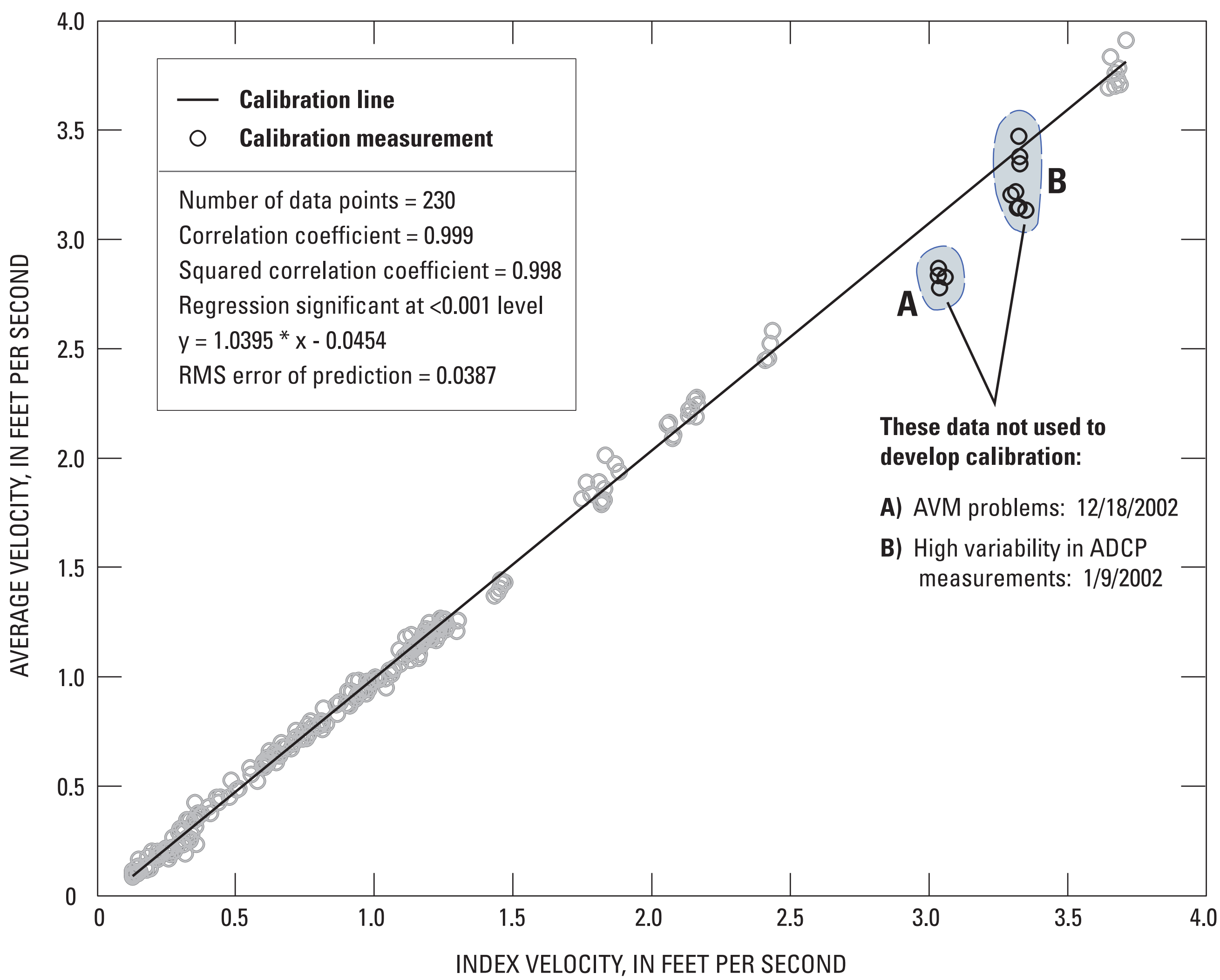


Figure 5. Acoustic velocity meter (AVM) calibration relationship. RMS, root-mean-squared.

Short-Range Acoustic Doppler Velocity Meter

The calibration of the SonTek SL-1500 SR-ADVM changed slightly since the beginning of the pilot study as additional calibration measurements were collected. The latest calibration was developed in June 2003 when additional high-flow measurements were incorporated into the calibration (*fig. 6*). Periodic check measurements have been collected since that time. This system has a strong calibration (r^2 = 0.997) with data being collected in flow conditions ranging from 1,100 ft^3/s to 72,500 ft^3/s. The check measurements suggest that the calibration has been stable in the lower and middle range and can be extrapolated for high-flow conditions. The calculated discharge values were within 5 percent of the measured low-to-moderate flows and within 2 percent of the measured high-flow data.

Long-Range Acoustic Doppler Velocity Meter

The calibration of the SonTek SL-500 LR-ADVM changed slightly since the beginning of the pilot study as additional calibration measurements were collected. The latest calibration was developed in June 2003 when additional high-flow measurements were incorporated into the calibration (*fig. 7*). Periodic check measurements have been collected since that time. This system has a strong calibration (r^2 = 0.996) with data being collected in flow conditions ranging from 1,100 ft^3/s to 72,500 ft^3/s. The check measurements suggest that the calibration has been stable in the lower and middle range and can be extrapolated for high-flow conditions. The calculated discharge values were within 7 percent of the measured low-to-moderate flows and within 2 percent of the measured high-flow data.

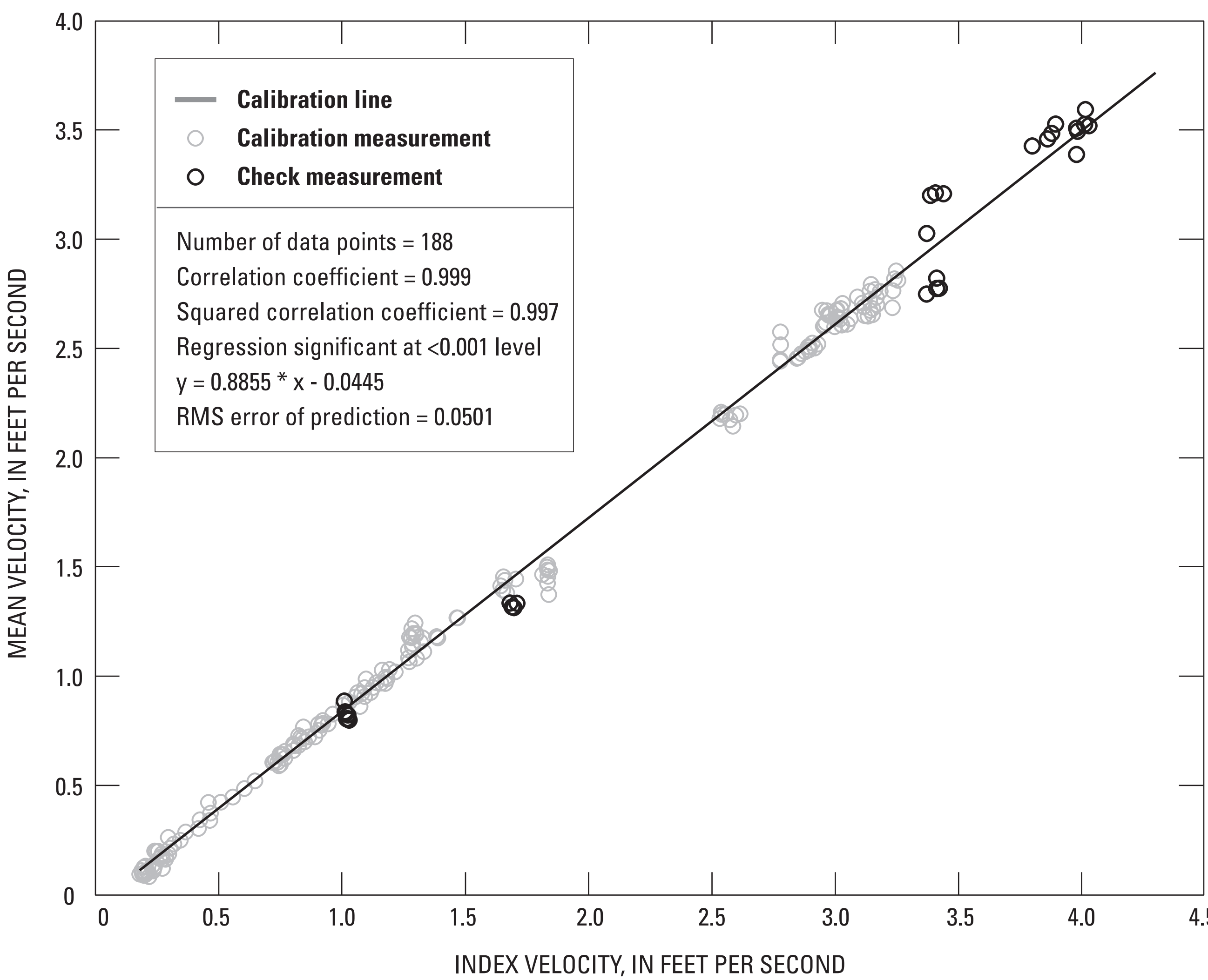


Figure 6. Short-range acoustic Doppler velocity-meter calibration relationship. RMS, root-mean-squared.

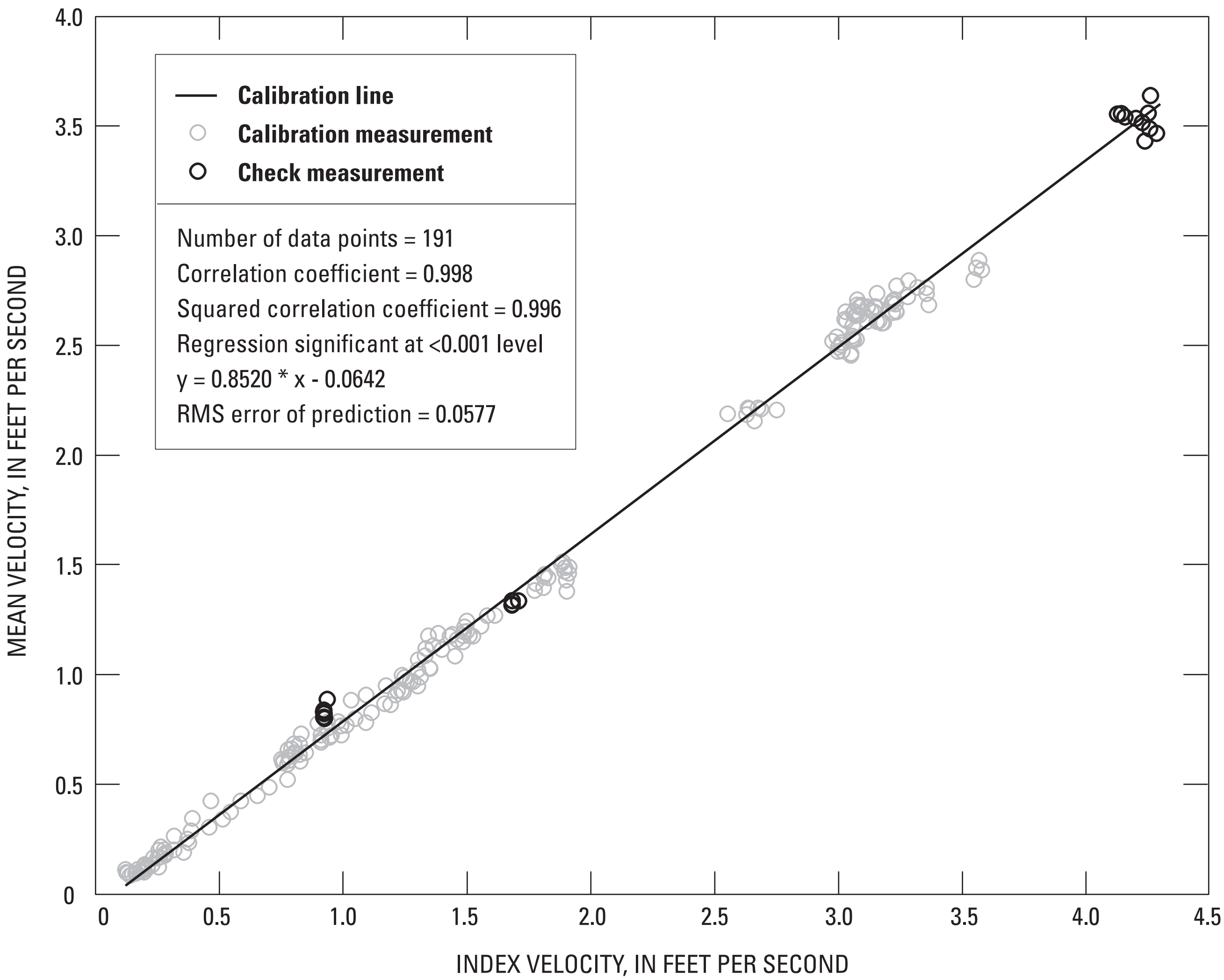


Figure 7. Long-range acoustic Doppler velocity-meter calibration relationship. RMS, root-mean-squared.

Outfall Building Datalogger Programming and Error-Checking Algorithm

The Outfall Building datalogger is programmed to provide a rolling 5-minute average every minute. These 1-minute data at the Outfall Building are converted to analog data and transferred to the SRWTP through a 4–20 milliamp converter.

Error-checking and programmatic decision-making algorithms are used to determine which system is providing the best possible data. Because two ADVM flow-monitoring systems were installed as part of the pilot study, a datalogger was installed at the Outfall Building to perform automated error checking. Based on the strong data-recovery rate and the calibration relationship, the SR-ADVM has been selected as the system providing the “primary record”; the LR-ADVM provides the “secondary record”. The purpose of the third datalogger programmed with data-quality and error-checking algorithms is to minimize data loss and to fully utilize the redundancy of the independent stream-gaging instrumentation.

Two approaches to check for errors are used: percent difference and absolute difference. Under most conditions the percent difference approach is used; however, in low-flow conditions (less than 1,000 ft^3/s), the absolute difference approach is used because high-percent differences may result from small denominator values, even though the absolute difference between subsequent measurements is small. If the discharge is greater than 1,000 ft^3/s and the percent difference between subsequent measurements is greater than 15 percent, then the program automatically selects the discharge value from the secondary record (*fig. 8*, open circles). The program also calculates the magnitude of the difference between the current measurement and the previously recorded measurement. If the discharge is less than 1,000 ft^3/s and the absolute difference

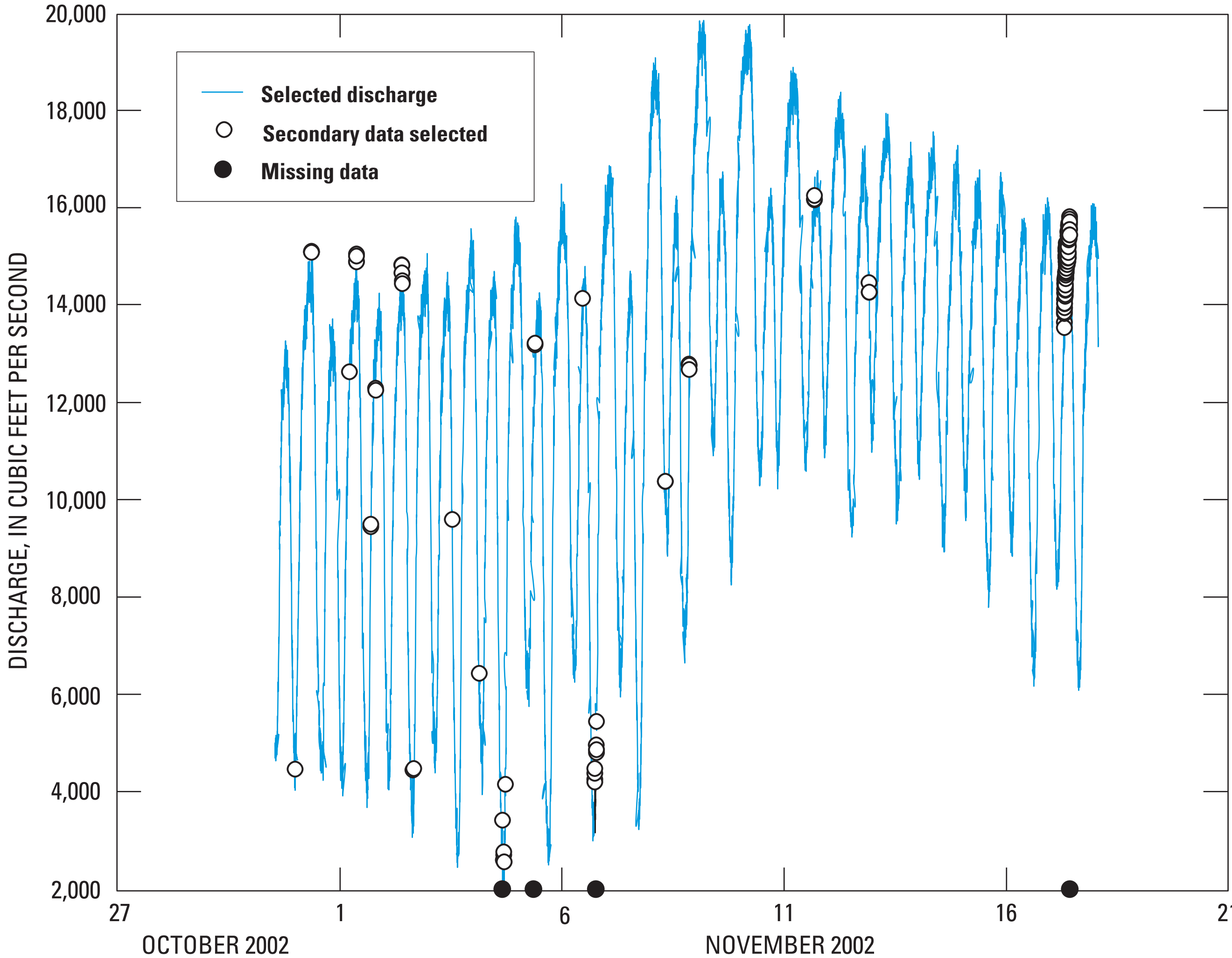


Figure 8. Discharge record recorded at the Outfall Building showing results from the error-checking program.

between the two measurements is greater than 500 ft^3/s, then the program will reject the new value and select the discharge value from the secondary record.

In the event that both the primary and secondary record values are rejected as "poor-quality data", the selected discharge value is held constant until a good data point is received from one of the two ADVM systems. The program parameters of 1,000 ft^3/s, 500 ft^3/s, and 15 percent were selected from an analysis of the data. These parameters have proven to be conservative enough to not cause large erroneous shifts, while allowing for the use of the secondary record when the primary record is in question.

Analysis of the data reported to the datalogger at the Outfall Building shows that the error-checking protocols are working as expected and provide a continuous data record. Based on the error-checking algorithm, the program selected the secondary discharge a total of 232 times during a 3-week period (*fig. 8*, open circles). There were a total of 11 instances that a missing-data indicator was recorded in the final discharge record (*fig. 8*, solid circles). A closer look at a 2-day period shows that the error-checking algorithm is working as expected (*fig. 9*). When the primary record is not available, the program switches automatically to the secondary record and provides a complete record.

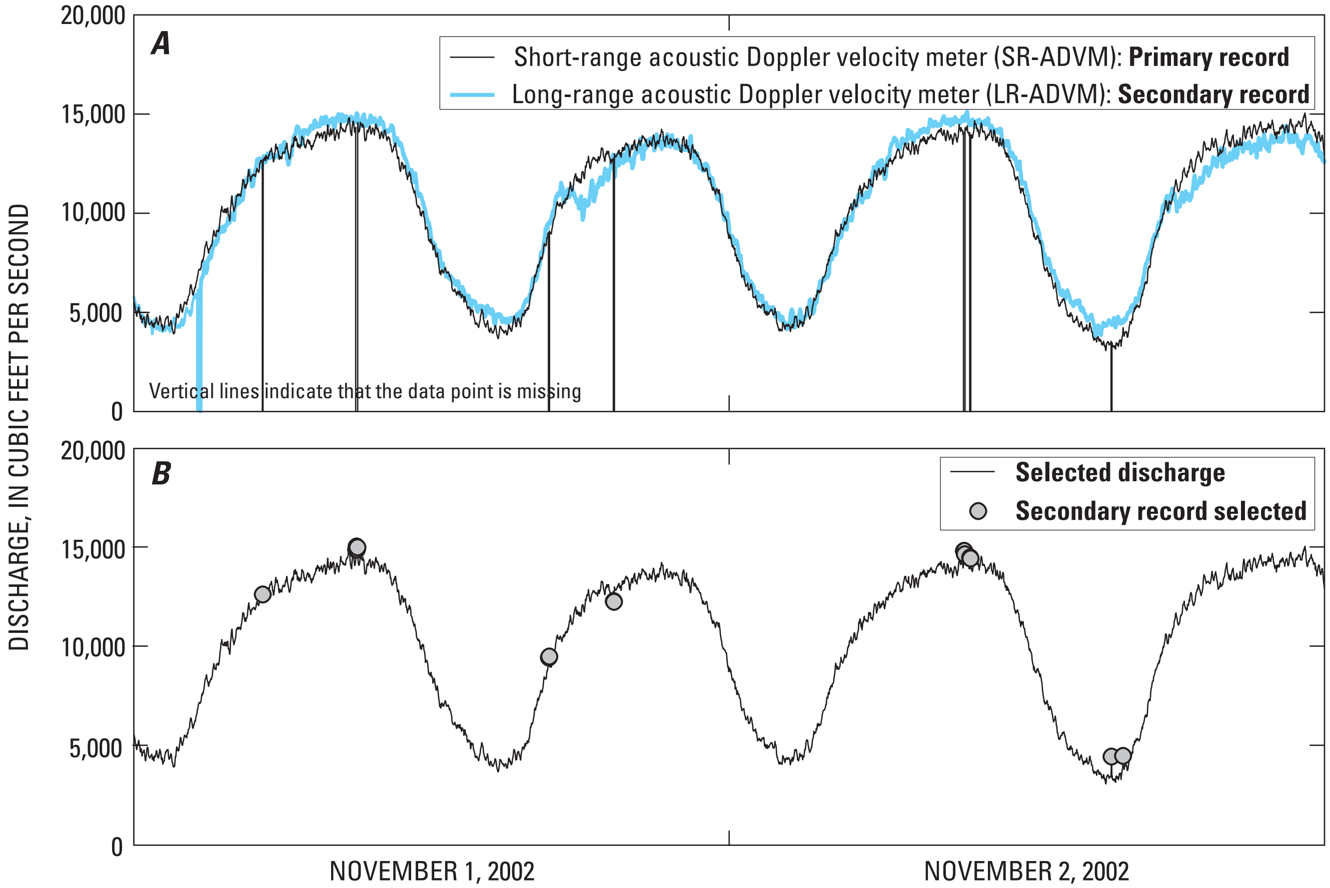


Figure 9. (*A*) Comparison of primary and secondary discharge records and (*B*) selected discharge record recorded at the Outfall Building, based on an error-checking program.

Data Transmission

The data-collection system at Freeport transmits data in two ways: (1) cellular digital packet data (CDPD) transmission from the two ADVM systems mounted on the Freeport Bridge to the USGS; and (2) radio-signal transmission from the two ADVM systems mounted on Freeport Bridge to the datalogger at the Outfall Building.

Cellular Digital Packet Data

This telemetry system has been utilized elsewhere in the USGS Delta Flows Network and has proven to be reliable. No problems have been identified in this application and the USGS continues to receive reliable real-time data from the ADVMs mounted on the Freeport Bridge. Although the vendor is phasing out the CDPD system, the USGS is testing another digital data transmission system elsewhere in the Delta Flows Network: code division multiple access (CDMA) Digital Cellular. We do not anticipate significant problems launching the CDMA system.

Radio Signal

Radios have been used under different conditions elsewhere in the USGS Delta Flows Network without substantial problems; however, with the SRWTP's requirement of data transfer to the Outfall Building every minute have proven radio data transmission to be unreliable. Numerous attempts at improving the data-recovery rate at the Outfall Building have been unsuccessful and currently it is unclear if interference is from the Freeport Bridge structure, is electromagnetic, or if other problems are degrading the performance of this system. The problems associated with this approach suggest the need for a different communication system for the long-term implementation of a flow-monitoring station on the Freeport Bridge.

A comparison of the 15-minute time series received through the CDPD system at the USGS and the 1-minute data recorded as “selected discharge” at the SRWTP Outfall Building show that there are substantial data-transmission problems between the Freeport Bridge and the Outfall Building (*fig. 10*). During January and February 2004, 56 percent of the “selected discharge” record was from the primary system (SR-ADVM), 27 percent of the selected discharge record was from the

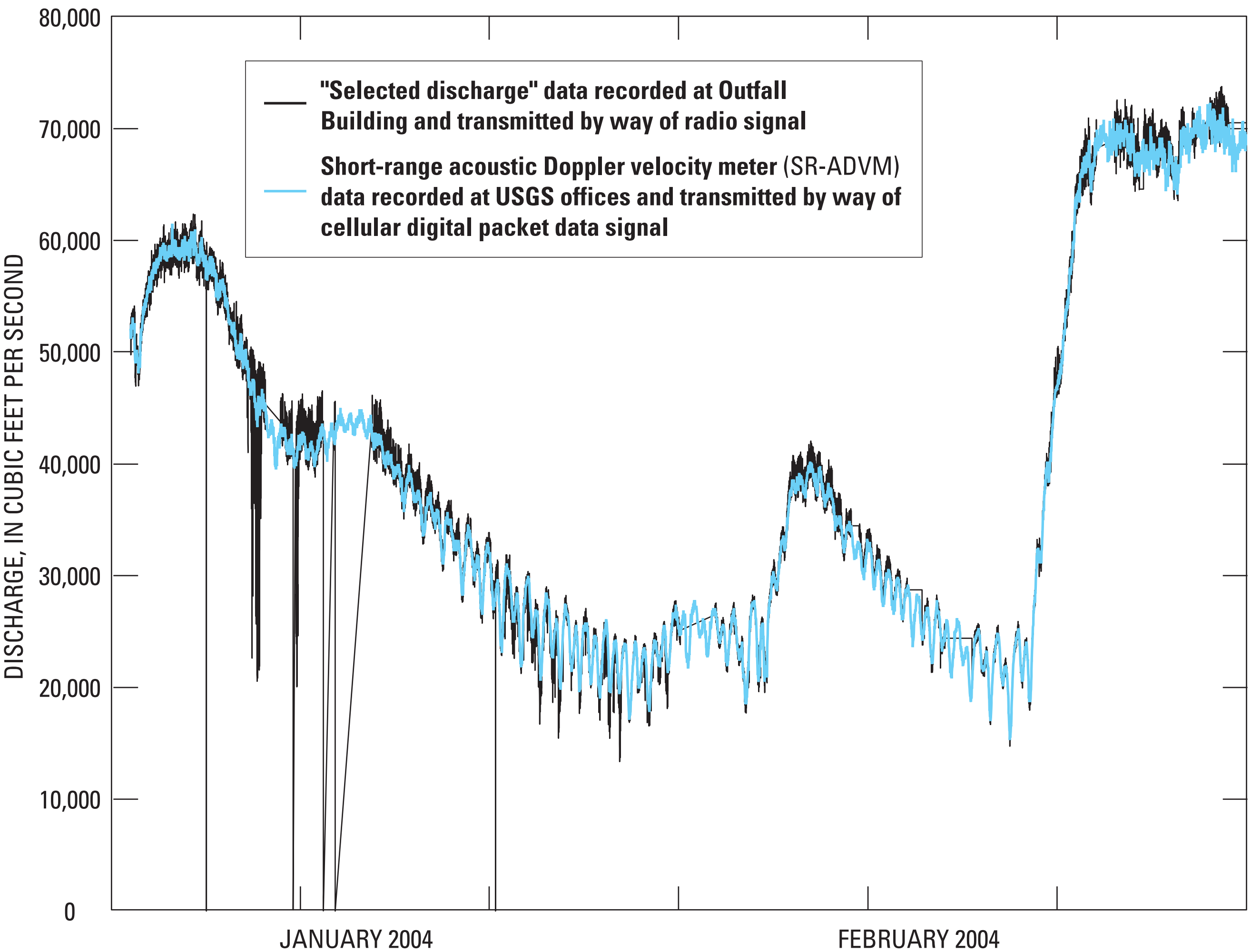


Figure 10. Comparison of short-range acoustic Doppler velocity-meter record received at the U.S. Geological Survey office and selected discharge record recorded at the Outfall Building.

secondary system (LR-ADVM), and the remaining 17 percent was the retained value. However, the USGS record shows that the primary-record time-series is complete and in no instance is the criteria for rejecting the primary record (discharge below 1,000 ft^3/s with a change of more than 500 ft^3/s between subsequent discharge measurements or a change of more than 15 percent between subsequent discharge measurements) met. This result indicates that the radio transmission between the Freeport Bridge and the Outfall Building was not working. The high-frequency variability in the 1-minute time-series record at the Outfall Building is due to the shorter averaging time; transitions between the primary and secondary records; and data-transmission problems.

Results

It is unusual to have three, independent flow-monitoring systems at a single location. Inevitably, even small differences among the results lead to questions about the overall performance of each of the instrumentation configurations. Each system has a strong calibration (r^2 values ranging from 0.996 to 0.998), and all three systems performed well during the 17-month period of the pilot study (*fig. 11*). A comparison of the resulting discharge calculations shows that the difference between the discharge time-series datasets is less than 5 percent overall (*table 2*).

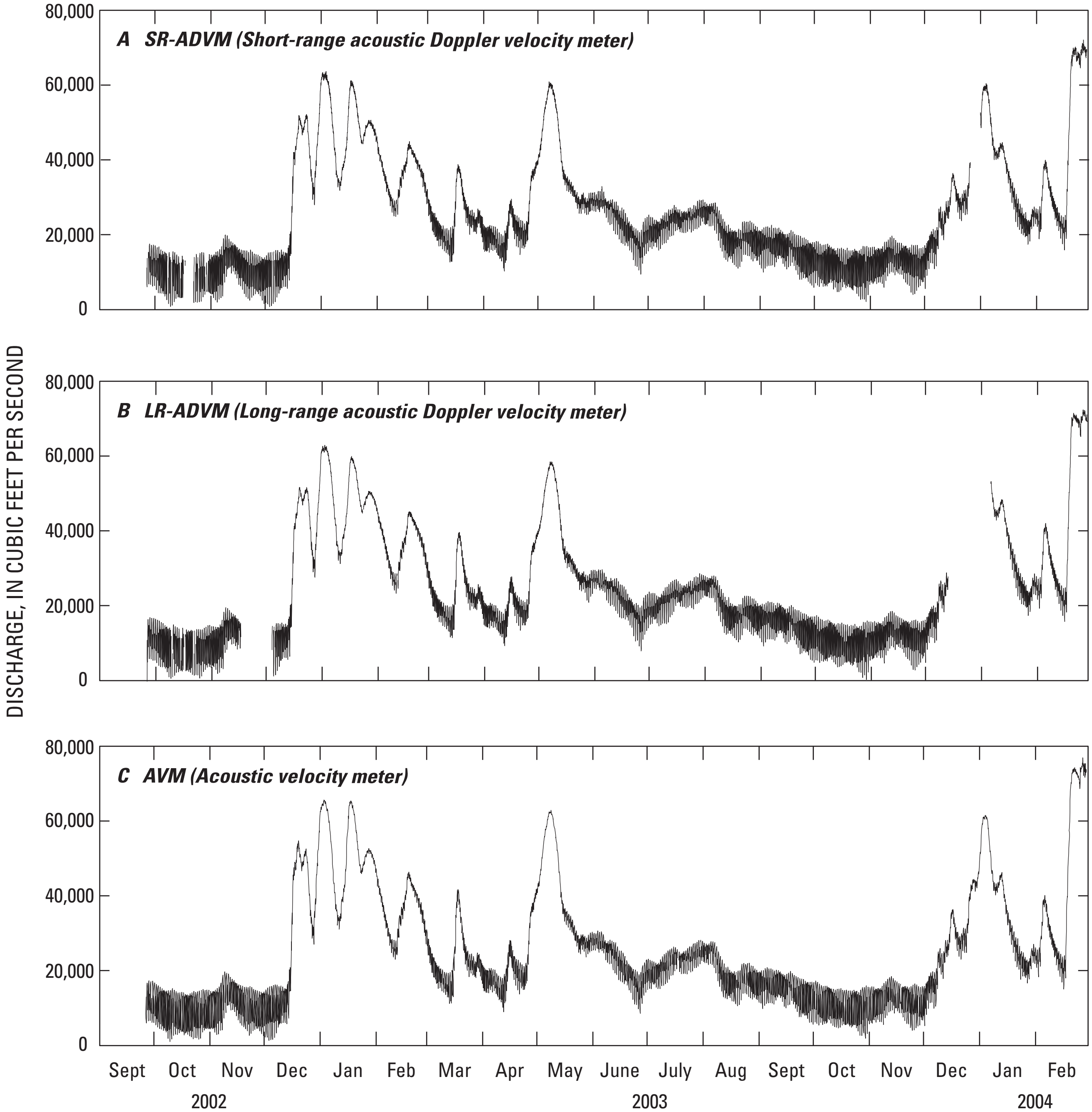


Figure 11. Tidal discharge data collected from the three hydroacoustic systems during the 2002–2004 pilot study. (*A*) short-range acoustic Doppler velocity meter; (*B*) long-range acoustic Doppler velocity meter; and (*C*) acoustic velocity meter.

The median percent difference (MPD) was determined as the median of the absolute value of the difference between the two time-series records divided by the first time-series record. For example, for the comparison of the AVM and the SR-ADVM, the MPD was calculated as follows:

$$\text{MPD} = \text{median [abs } (100 * \frac{Q_{AVM} - Q_{SR-ADVM}}{Q_{AVM}})]; \quad (3)$$

where MPD is the median percent difference,

Q is the discharge,

and the subscript describes the equipment used to collect the data. The median difference was determined as the median of the absolute value of the difference between the two time-series records.

Overall, each independent stream-gaging system compares well with the others (*table 3*). The largest discrepancies are between the daily flows measured by the SR-ADVM system and the other two systems, with 61 percent of the data being reported within 5 percent. The best correlation is between the tidal flows measured by the two ADVM systems, with 96 percent of the data being reported within 5 percent. The USGS has the following standards for categorizing discharge records: A record is classified as “excellent” when 95 percent of the daily discharge data are within 5 percent of the real value; “good” when 95 percent of the data are within 10 percent of the real value; “fair” when 95 percent of the data are within 15 percent of the real value; and “poor” if the data do not meet these criteria (Kennedy, 1983).

Based on the initial calibration results and data-recovery rates, the data collected by the SR-ADVM were selected as the primary record and the LR-ADVM data were classified as the secondary record. Comparisons between the daily-flow data from the two ADVM systems show that, in general, the data from the SR-ADVM and the LR-ADVM compared very well until March 2003 when a shift occurred and the SR-ADVM tended to report higher discharge values than the LR-ADVM and the AVM (*fig. 12*). After March 2003, the SR-ADVM reported daily discharge values approximately 800 ft^3/s, or 4.6 percent higher than the AVM and the LR-ADVM when flows were less than 30,000 ft^3/s (*fig. 12B, C*). These higher discharge values reported by the SR-ADVM may have been caused by a slight change in the SR-ADVM alignment. The SR-ADVM was found to be rotated approximately 5 degrees from the original position and was repositioned in June 2004. In December 2003, the LR-ADVM reported higher discharge values than the SR-ADVM. It is unclear what caused this change in the relationship between these two instruments; it may be due to the high flows recorded at the end of the study period. A similar, though less dramatic, change in the relationship occurred during high flows in early 2003.

Similar comparisons between the SR-ADVM and the AVM and the LR-ADVM and the AVM show greater differences between the instruments during periods of high flow

Table 2. Differences among calculated discharge records from three hydroacoustic stream-gaging systems during the 2002–2004 pilot study at the Sacramento River at Freeport, California

[ft^3/s, cubic feet per second; AVM, acoustic velocity meter; SR-ADVM, short-range acoustic Doppler velocity meter; LR-ADVM, long-range acoustic Doppler velocity meter]

Systems compared	Tidal flows		Daily flows	
	Median percent difference	Median difference (ft^3/s)	Median percent difference	Median difference (ft^3/s)
AVM and SR-ADVM	4.77	1120	4.41	780
AVM and LR-ADVM	3.52	740	2.70	460
SR-ADVM and LR-ADVM	3.98	830	4.17	840

Table 3. Record comparisons of hydroacoustic stream-gaging systems used during the 2002–2004 pilot study at the Sacramento River at Freeport, California

[AVM, acoustic velocity meter; SR-ADVM, short-range acoustic Doppler velocity meter; LR-ADVM, long-range acoustic Doppler velocity meter; >, greater than]

Systems compared	Tidal flows, in percent			Daily flows, in percent		
	Within 5 percent	Within 10 percent	Within 15 percent	Within 5 percent	Within 10 percent	Within 15 percent
AVM and SR-ADVM	62	87	96	61	99	>99
AVM and LR-ADVM	82	96	99	73	99	>99
SR-ADVM and LR-ADVM	96	>99	>99	61	97	>99

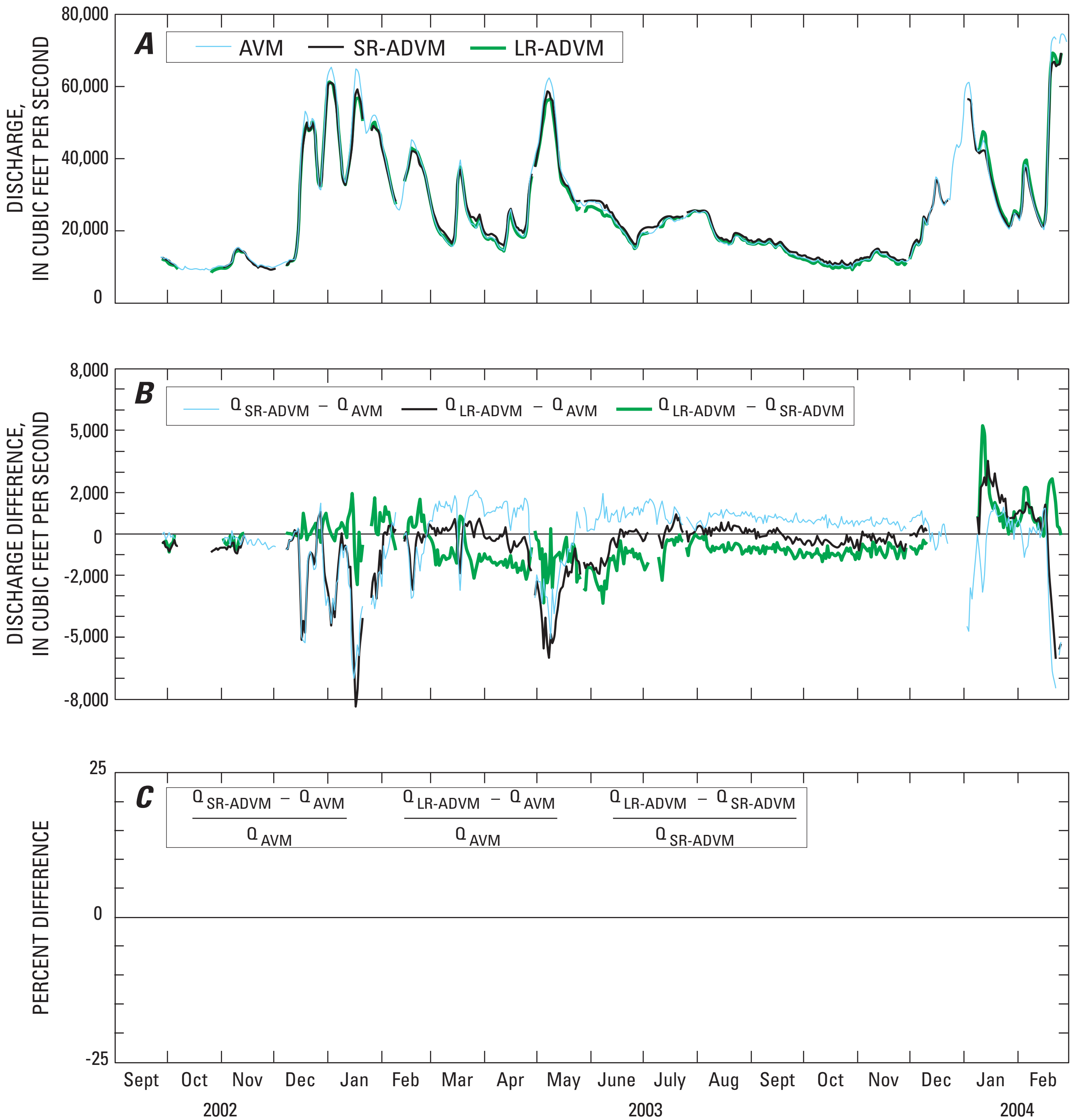


Figure 12. Comparison of tidally averaged discharge data collected from the three hydroacoustic systems during the 2002–2004 pilot study. (*A*) discharge records, (*B*) difference between discharge records, and (*C*) percent difference between discharge records. AVM, acoustic velocity meter; SR-ADVM, short-range acoustic Doppler velocity meter; LR-ADVM, long-range acoustic Doppler velocity meter; Q, discharge.

(*fig. 12*). Both of the ADVM instruments measured lower discharge during the periods of high flow suggesting that the AVM is overestimating discharges above 60,000 ft^3/s by 3,000–4,000 ft^3/s (*fig. 12B*); comparison of the percent differences over the entire period of record shows that the percent difference is relatively consistent between periods of low flow (fall 2003) and high flow (spring 2003) (*fig. 12C*).

The best method to assess the accuracy of the various instrumentation systems is to compare the calculated discharge results from the three hydroacoustic instruments with the direct discharge measurements collected with a downward-looking ADVM profiler (*table 4*). The SR-ADVM showed the least difference between the measured and calculated discharge values, as measured by the mean and median differences, and had the lowest variability, as measured by the standard deviation. The LR-ADVM tends to be slightly biased towards underestimating the discharge and the AVM tends to be biased towards overestimating the discharge. The standard deviations for the LR-ADVM and the AVM are higher than those for the SR-ADVM.

The higher discharge values that are apparent when comparing the time-series data of the SR-ADVM with that of the AVM and LR-ADVM (*fig. 12*) are not apparent when comparing the SR-ADVM results with measured data (*fig. 6*). The low-flow period in 2002, when most of the low-flow calibration measurements were collected, shows good agreement among all three systems. However, beginning in March 2003, the SR-ADVM consistently reported higher discharge results than the other two systems. The cause of this offset is unclear; however, the check measurements do not indicate that there are any substantial problems with the SR-ADVM calibration.

All three stations have high data-recovery rates. During the period of study, the SR-ADVM had a 97-percent complete record, the LR-ADVM had a 91-percent complete record, and the AVM system had a 99-percent complete record. Most of the missing data associated with the ADVM systems were lost during the first 2 months of the pilot study when programming problems caused several periods of data to be lost. The programming problems have been addressed and data loss has declined significantly. Since November 2002, the SR-ADVM has a 99-percent complete record and the LR-ADVM has a 95-percent complete record.

Table 4. Statistical comparison of measured and calculated discharge values during the 2002–2004 pilot study at the Sacramento River at Freeport, California

[ft^3/s, cubic feet per second; SR-ADVM, short-range acoustic Doppler velocity meter; LR-ADVM, long-range acoustic Doppler velocity meter; AVM, acoustic velocity meter]

Hydroacoustic system	Mean difference (ft^3/s)	Median difference (ft^3/s)	Standard deviation (ft^3/s)
SR-ADVM	95	100	890
LR-ADVM	–559	–169	1,179
AVM	805	611	1,268

Conclusions

The acoustic velocity meter (AVM), the short-range acoustic Doppler velocity meter (SR-ADVM), and long-range acoustic Doppler velocity meter (LR-ADVM) configurations have been calibrated successfully, with strong relationships with the measured data. Although the AVM system provides high-quality data and has a strong calibration (r^2=0.998) and a high data-recovery rate (99 percent during the 2002–2004 pilot study), the system is more than 25 years old and operation and maintenance costs are increasing substantially. It is becoming more difficult to obtain replacement parts and, in some cases, the parts are no longer manufactured. In addition, data recovery had been a problem prior to the pilot study, with several periods of missing data in fall 2000.

Both sideward-looking ADVM systems are viable alternatives to the existing AVM system. Moreover, maintenance of the ADVM equipment is easier because the equipment can be reached without diver assistance and replacement parts are readily obtainable. The SR-ADVM is the best replacement system based on its calibration (r^2=0.997) and data-recovery rate (97 percent). However, check measurements collected in flow conditions below 30,000 ft^3/s should be conducted to confirm the stability of the calibration and to resolve the apparent discrepancy between the SR-ADVM and the other two systems. In addition, there continue to be significant problems with data transmission between the ADVM systems on the Freeport Bridge and the datalogger in the Outfall Building.

To provide time to identify and test a robust data-transmission system, the AVM can continue to be operated as the primary system. However, in the event that problems arise with the AVM, the ADVM systems are available to provide backup data. During this time, additional calibration data should be collected as part of the standard operation and maintenance protocol of the station. In the event of complete AVM failure prior to the resolution of the data-transmission problems, the ADVM system with the strongest calibration and best data recovery rate should be selected as the primary replacement system.

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