COMPARISON OF RECORDING CURRENT METERS IN SHALLOW WATERS OF SAN FRANCISCO BAY, CALIFORNIA

By *Jeffrey W. Gartner* and *Richard N. Oltmann*

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 90-4018

Prepared in cooperation with the

CALIFORNIA STATE WATER RESOURCES CONTROL BOARD

Sacramento, California
1990

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., ***Secretary***

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, ***Director***

For sale by:
Books and Open-File Reports Section
U.S. Geological Survey
Federal Center, Box 25425
Denver, CO 80225

For additional information write to:
District Chief
U.S. Geological Survey
Federal Building, Room W-2234
2800 Cottage Way
Sacramento, CA 95825

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS

Metric (International System) units are used in this report. For readers who prefer inch-pound units, the conversion factors for terms used in this report are listed below:

Multiply metric unit	By	To obtain inch-pound unit
meter (m)	3.281	foot
meter per second (m/s)	3.281	foot per second
millimeter (mm)	0.03937	inch
centimeter (cm)	0.3937	inch
centimeter per second (cm/s)	0.3937	inch per second
kilometer (km)	0.6214	mile
kilogram (kg)	2.204	pound
kilogram per square centimeter (kg/cm^2)	14.22	pound per square inch

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows:

Temp. °F = 1.8 temp. °C + 32

In this report, time is given in hours and minutes (as 19:30, for example) of 24-hour time.

Specific electrical conductance is given in millisiemens per centimeter (mS/cm). Millisiemens per centimeter is numerically equal to millimhos per centimeter.

Abbreviations used:

CMOS	complementary metal-oxide semiconductor
M_2	in this report an M_2 cycle is equal to 12.42 hours
Pst	Pacific standard time
RAM	random-access memory
RMS	root-mean-square
s/d	seconds per day
‰	parts per thousand

COMPARISON OF RECORDING CURRENT METERS IN SHALLOW WATERS OF SAN FRANCISCO BAY, CALIFORNIA

By *Jeffrey W. Gartner* and *Richard N. Oltmann*

ABSTRACT

Four recording current meters with different types of speed sensors were field tested to determine their ability and accuracy in collecting velocity data in shallow, tidally affected waters under the influence of wind-generated waves. The speed sensors were: horizontal-axis ducted impeller, vertical-axis Savonius rotor, inclinometer, and electromagnetic. The meters were deployed during June to September 1984 in south San Francisco Bay, California, in an area where the water depth ranged from 2.0 to 5.1 meters, and windspeeds generally were 5 to 10 meters per second. All current meters were positioned approximately 1.2 meters above the bottom of the bay using either bottom platforms or taut-wire moorings.

Overlaid time-series plots of 30-minute vector-averaged velocity data showed that, when the magnitude of the wind was about 5 meters per second or greater and the water depth above the current meter was about 2.3 meters or less, the vertical-axis rotor meter and inclinometer recorded higher current speeds than did the horizontal-axis ducted impeller meter and electromagnetic meter. The higher current speeds were especially apparent during slack-water periods when current speed approaches or equals zero. When windspeeds were greater than 10 meters per second, the vertical-axis rotor meter and inclinometer recorded speeds higher than the horizontal-axis ducted impeller meter and electromagnetic meter regardless of water depth. For windspeeds between 5 and 10 meters per second, the inclinometer tended to record speeds higher than the other meters, even at high tide. These findings indicate that both the vertical-axis rotor meter and inclinometer are sensitive to orbital wave motion induced by wind. (A shallow water version of the vertical-axis rotor meter was not tested in this study.) Speed intercomparison plots of the 30-minute, vector-averaged speed values confirm this conclusion.

The horizontal-axis ducted impeller and electromagnetic meters recorded speed values that approached zero during slack water regardless of windspeed and water depth. However, as current speed increased during tidal flood and ebb, the speed values recorded by the electromagnetic meter were 20 to 50 percent higher than those recorded by the horizontal-axis ducted impeller meter. Price AA current-meter readings indicated that the horizontal-axis ducted impeller current-meter values were low, although the data were not sufficient to be conclusive. In the absence of wind (or during periods of very light winds when wave motion was slight), current-speed readings determined by horizontal-axis ducted impeller and vertical-axis rotor meters were in close agreement, as were readings determined by electromagnetic and inclinometer meters. However, the latter two meters recorded higher speed values during maximum-flood and maximum-ebb periods than did the horizontal-axis ducted impeller and vertical-axis rotor meters. Multiple deployments of the horizontal-axis ducted impeller and vertical-axis rotor meters were made; comparison of records collected using the same type of meter showed variations as much as 20 percent. Whereas the horizontal-axis ducted impeller and electromagnetic meters seem to have the ability to measure accurately low velocities in the wind-wave zone, further testing is required to determine which meter types record accurately at higher current speeds.

INTRODUCTION

Population growth and agricultural development have changed the quality and quantity of freshwater entering the San Francisco Bay estuarine system (fig. 1). These changes have altered the chemical and physical characteristics of the bay, and thus are perceived to be responsible for observed changes in the aquatic ecosystem. Aquatic studies have been and are being done by State and Federal agencies to understand the complicated relations among physical, chemical, and biological processes, and to estimate how changes in freshwater quality and quantity affect these relations. This study, done by the U.S. Geological Survey in cooperation with the California State Water Resources Control Board, addresses a facet of these complicated relations.

Because hydrodynamic processes generally are recognized as inseparable from ecological processes, achievement of the above goals will depend in part on understanding the bay's hydrodynamics--a complicated

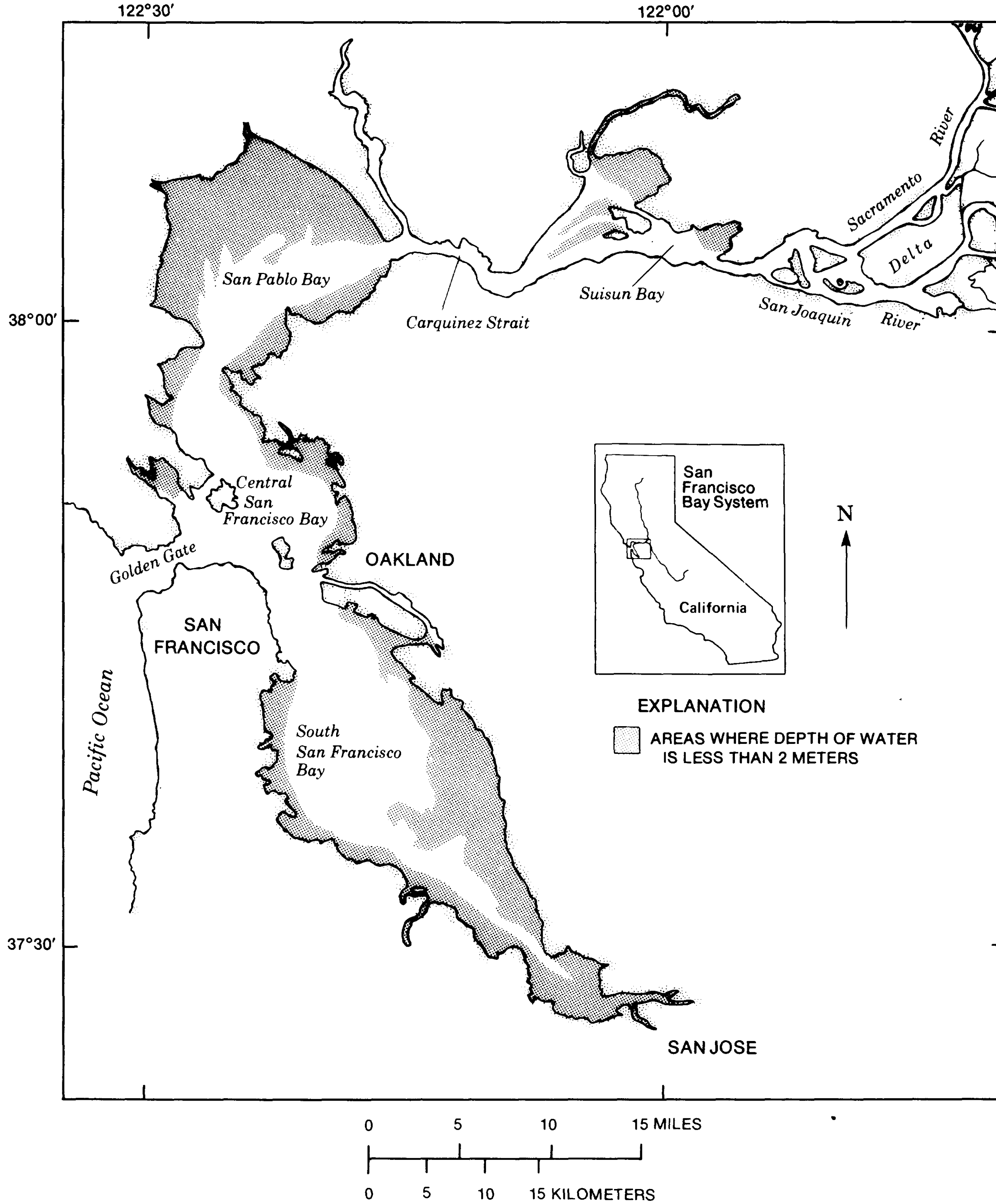


Figure 1. San Francisco Bay estuarine system.

interaction of tides, winds, salinity, freshwater inflows, and bottom configuration. A clearer understanding of the hydrodynamic processes depends on the collection of field data and the use of these data in calibration and verification of mathematical models. Although field data are too sparse in space and time to obtain an adequate understanding of the bay, field data can be used in conjunction with hydrodynamic models to provide a greater understanding of the estuarine system.

A considerable amount of water-level and velocity data were collected in San Francisco Bay in 1979 and 1980 (Cheng and Gartner, 1984), but nearly all of the velocity data are from regions where the water depth is 6 m (meters) or greater. (All depths are referenced to mean lower low water [see glossary] unless otherwise stated.) National Oceanic and Atmospheric Administration (NOAA) bathymetric data indicate that approximately 44 percent of the San Francisco Bay system (south San Francisco, central San Francisco, San Pablo, and Suisun Bays) is less than 2 m in depth (fig. 1). Collection of velocity data in the shallow regions of the bay is of particular importance to enable determination of tidal exchange rates of biological, chemical, and physical constituents between shallow tidal flats and deep channels. Velocity data in shallow regions also are needed to calibrate mathematical models and to verify model results so that the models can be used to investigate declines in the fishery resources, dispersion of wastewater discharges, and tidal "trapping" of pollutants in the shallows. Velocity data generally are not available for shallow-water regions of the bay because of the difficulty associated with collecting reliable data in shallow regions under the influence of wind-generated waves. The limited amount of data that do exist are suspect. This problem is not unique to San Francisco Bay, but is common to shallow regions of all bays and estuaries.

The action of wind on a body of water produces oscillatory (orbital) waves. As these waves pass a point at the water surface, water particles rise as the wave approaches and fall as the wave passes, producing nearly circular (deep water) or elliptical (shallow water) particle paths. Current-meter studies by Saunders (1976), Halpern and Pillsbury (1976), Beardsley and others (1977), Cheng (1978), and Fuyo Ocean Development Company and Institute of Central Electric Research (1982) indicated that when a current meter is subjected to circular or elliptical wave motion and is not attached to a fixed mooring, the current meter detects not only the desired horizontal water velocity, but also mooring-line motion and the orbital motion of the water produced by the surface waves. The studies also indicated that measured velocity data were unreliable because of wave-motion effects to a lesser or greater extent depending on the type of current-meter design. These studies were done in laboratories or in waters about 10 m or more in depth. Few studies have been done in water depths approaching the shallow conditions of interest in this study. A further complicating factor in this study was changing depths; at times during the study, water depth doubled during a tidal cycle.

PURPOSE AND SCOPE

This report describes a study by the U.S. Geological Survey to determine whether reliable current-meter data can be collected in shallow, tidally affected waters under the influence of wind-generated waves. Four types of recording current meters with different speed sensors were tested, and the accuracy of data recorded by the meters under different conditions (slack water and maximum-flood and maximum-ebb periods during calm and windy conditions) was compared. It is important to note that the four meters tested are not necessarily representative of all available designs. This report describes the various current meters and mooring configurations used in the study, the procedures used to deploy and retrieve the meters and moorings, the methods for data translation and analysis, and the results of the comparison of current-meter records.

ACKNOWLEDGMENTS

This study was financed in part with Federal funds from the U.S. Environmental Protection Agency under grant number C060000-21. The contents do not necessarily reflect the views and policies of the Environmental Protection Agency.

The authors wish to acknowledge the assistance of the National Ocean Service, National Oceanic and Atmospheric Administration (NOS/NOAA) (especially, members of the NOAA ship *McArthur* of Seattle, Washington), and of InterOcean Systems Inc., and General Oceanics for loan of current meters and mooring platforms used during the study. We also thank the captain and crew of the U.S. Geological Survey research vessel RV *Polaris* for their invaluable assistance in the deployment and retrieval of the instrumentation used during the study.

DESCRIPTION OF RECORDING CURRENT METERS USED IN THIS STUDY

TYPE AND SPEED SENSOR

Four types of recording current meters, each with a different kind of speed sensor, were used to measure current velocity (a vector quantity consisting of speed and direction). The speed sensors were:

1. Horizontal-axis ducted impeller,
2. Vertical-axis rotor (Savonius type),
3. Inclinometer (tilt sensing), and
4. Electromagnetic.

Specifications for each of the meters used in the comparison are given in table 1. Each meter's speed and direction sensors, and sampling and recording methods, are described in the following sections. The results of other comparison studies involving these current meters also are included in the following discussions.

Horizontal-Axis Ducted Impeller

The horizontal-axis ducted impeller current meter (fig. 2) records the number of impeller revolutions during the specified sampling interval to determine current speed. The current meter's external housing is designed to align the meter with the direction of current, which is measured using an internal magnetic compass. The meter also records water temperature and electrical conductivity. Data are recorded on eight-track cartridge magnetic tape at a selected sampling interval (refer to "Data-Sampling Characteristics" section). Sampling intervals can be changed by replacing an internal selection plug. Current speed is integrated over the sampling interval, whereas current direction, temperature, and electrical conductivity are instantaneous values recorded at the time of each sample. The horizontal-axis ducted impeller meter is documented in a 16-page service manual (Environmental Devices Corporation, 1978) containing meter description and specifications, instrument operation, and service and deployment procedures.

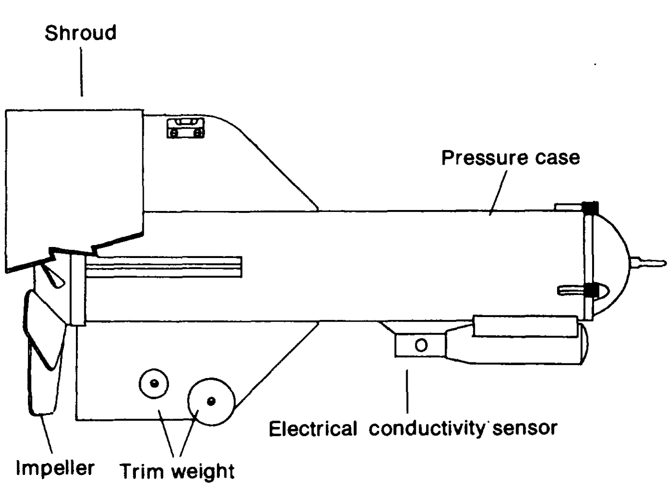


Figure 2. Horizontal-axis ducted impeller current meter (length 85.1 cm; diameter of shroud 40.6 cm).

Horizontal-axis ducted impeller meters, in use since 1971, were used by the U.S. Geological Survey in deep regions of San Francisco Bay in 1979 and 1980 (Cheng and Gartner, 1984). Horizontal-axis ducted impeller meters have been evaluated in several current-meter performance studies (Beardsley and others, 1977; Cheng, 1978; Fuyo Ocean Development Company and Institute of Central Electric Research, 1982). The findings of these studies indicate that the horizontal-axis ducted impeller meter is not significantly affected by wave motion. One reason is that the impeller is able to sense reverse-flow pulses by turning backwards even though the meter has not reversed direction, and thus it does not erroneously record reverse-flow pulses as positive flow.

The horizontal-axis ducted impeller meter is neutrally buoyant and is designed to be tethered from a taut-wire mooring. Directional response of the meter at slack water has been a problem experienced by the authors and others in the past. If the meter is not trimmed properly (a difficult task when a range of density occurs over a tidal cycle), the compass can lock when the meter's tilt (due to positive or negative buoyancy) exceeds the limit of the compass gimbal. This situation prevails until the flow speed is high enough, about 10 cm/s (centimeters per second), to cause the tethered meter to extend downstream and again become horizontal and parallel to the flow. This problem can result in incorrect current-direction readings for a period as great as 1 hour.

Vertical-Axis Rotor

The vertical-axis rotor current meter is of the Savonius type and uses the number of rotor revolutions during the selected sampling interval to determine current speed (fig. 3). Current direction is determined using a magnetic compass and a vane that aligns the meter with the current. The

Table 1.--Current-meter manufacturer specifications

[Table compiled from Environmental Devices Corp. (1978), InterOcean Systems, Inc. (1984), General Oceanics, Inc. (1982), Aanderaa Instruments Ltd. (1983), and Appell and Crump (1977). m, meter; m/s, meter per second; cm, centimeter; cm/s, centimeter per second; kg, kilogram; kg/cm^2, kilogram per square centimeter; mS/cm, millisiemens per centimeter; s/d, seconds per day]

	Specification			
	Endeco 174[1]	Aanderaa RCM-4	General Oceanics 6011 MKII	InterOcean S4
Date first manufactured	1977	[2]1967	1983	1984
Speed sensor	Ducted impeller	Vertical-axis rotor	Inclinometer	Electromagnetic
Direction sensor	Impeller shroud	Vane	Wing	2-axis E/M sensor
Magnetic heading	Magnetic compass, gray code	Magnetic compass, potentiometric	3 Hall-effect devices	Flux-gate magnetic
Speed				
Range	0-223 cm/s	2.5-250 cm/s	0-300 cm/s	0-350 cm/s
Resolution	0.89 cm/s (0.4 percent full scale)	0.1 percent of range	(@ 5 cm/s) ±3.1 cm/s (@ 20 cm/s) ±1.0 cm/s (@ 60 cm/s) ±0.5 cm/s	0.2 cm/s
Accuracy	±3 percent of full scale	±1 cm/s or 2 percent of reading	±1 cm/s	±1 cm/s or 2 percent of reading
Threshold	2.5 cm/s	2 cm/s	2 cm/s	0 cm/s
Reading	Average over interval	Average over interval	Discrete	Discrete
Direction				
Range	0-360°	0-360°	0-360°	0-360°
Resolution	1.4°	0.35°	1°	0.5°
Accuracy	±7.2	±7.5° at 2.5 to 5 or 100 to 200 cm/s; ±5° at 5 to 100 cm/s	±2°	±2°
Temperature				
Range	-5 to 45 °C	-2.46 to 21.4; or 10.08 to 36.0; or -0.34 to 32.17 °C	-5 to 45 °C	-2.5 to 36 °C
Resolution	0.098 °C	0.1 percent of range	0.016 °C	0.05 °C
Accuracy	±0.2 °C	±0.05 °C	±0.25 °C	±0.1 °C

See footnotes at end of table.

Table 1.--Current-meter manufacturer specifications--Continued

	Specification			
	Endeco 174[1]	Aanderaa RCM-4	General Oceanics 6011 MKII	InterOcean S4
		Electrical conductivity		
Range	5-55 mS/cm	25-72, 25-38, or 0-77 mS/cm	0-75 mS/cm	1-70 mS/cm
Resolution	0.098 mS/cm	0.1 percent of range	[3]1 mS/cm	0.1 mS/cm
Accuracy	±0.55 mS/cm	±0.025 mS/cm	[3]±2.5 mS/cm	±0.2 mS/cm
		Pressure		
Range	Pressure sensor not available	0-7.0, 14.1, 35.2, 70.3, or 210.9 kg/cm^2	0-21.1 kg/cm^2 0-210.9 kg/cm^2	0-102 kg/cm^2; others available
Resolution	Pressure sensor not available	0.1 percent of range	0.1 percent of range	0.1 percent of range
Accuracy	Pressure sensor not available	1 percent of range	0.5 percent of range	0.5 percent of range
Allowable tilt	27° with compass gimbal	27° mooring tilt; 12° compass tilt	0-90°	25°
Depth capability	152 m high-pressure case available	2,000 m	6,000 m	1,000 m
Manufacturer recommended use	All	Below wave zone	All	All
Recorder type	0.64 cm 8-track	7.6 cm reel-to-reel	Digital cassette	CMOS static RAM (64K)
Sampling interval	2-minute; others optional (3,4, 5,6, and 10 minute)	1/2,1,2,5,10,15, 30,60,180 minute interval	1,2,4,8,16,32,64,128,256, 512 readings per hour. 1,2,4,8,16,32 vector-averaged samples per reading	Duty cycle 1 minute to 225 days. On/off cycle selectable
Output data	Two 4-bit or gray-code words for each parameter	Digital-serial 10-bit binary	Serial binary	RS232 ASCII code
Real-time information	Crystal controlled; elapsed time ±1.5 s/d	Quartz clock; elapsed time ±2 s/d	Real time recorded ±0.1 s/d	Quartz clock factory set to Greenwich Mean Time (5-yr life) ±12 min/yr

See footnotes at end of table.

Table 1.--Current-meter manufacturer specifications--Continued

	Specification			
	Endeco 174[1]	Aanderaa RCM-4	General Oceanics 6011 MKII	InterOcean S4
Limit	40 days at 2-minute interval	10,000 samples on 183 m of tape	1 year at 2 samples/ hour (battery limit)	64K bytes; speed saved as 3 bytes. Each analog channel takes 2 bytes
Power source	8 D-size (12V) batteries	Eveready 276 batteries (NEDA 1603) (9V)	Lithium battery (6.5 V)	6 D-size alkaline batteries (9V)
Dimensions	76 cm long 40 cm diameter	51 cm long, 12.8 cm diameter, 37x100 cm vane	51.4 cm long 10.5 cm diameter	25 cm diameter
Material	Polyvinyl chloride plastic with stainless hardware	Copper/nickel/ silicon alloy	Plastic and anodized aluminum	Glass filled cyclo-aliphatic epoxy with titanium mooring rod
Weight	12.3 kg	13.7 kg, vane 12.9 kg	9 kg	8 kg
Buoyancy	Neutral	-9.3 kg	-2.7 kg	Neutral
Galvanic corrosion protection	Not applicable	Zinc anodes	None	None
Price	Standard $7,000 Conductivity added, $1,000 Data interface, $7,500	Standard $5,400 Pressure added, $574 Conductivity added, $640 Data interface, $2,650	Standard $5,250 Conductivity added, $6,745 Pressure added, $6,145 Conductivity and pressure added, $7,600 Data interface, $5,065	Standard $6,400 Temperature added[4], $800 Pressure added, $1,200 Conductivity added, $1,800 Tilt added[5], $965 Data interface, $589

[1]Endeco-174 upgrade (174SSM) to include solid-state memory, real-time clock, selectable sampling interval, and vector averaging. Data transfer via RS-232 interface. Production mid-1985. Model 174 replaced hydrodynamically similar model 105.

[2]Instrument was first introduced in 1967. Numerous technological improvements incorporated subsequently but model name (RCM-4) retained.

[3]6011 MKII conductivity resolution and accuracy were determined under field conditions, in which fouling occurred. Specifications under lab conditions should be better by factor of 10 (similar to Aanderaa specifications for conductivity).

[4]All standard units have temperature sensor except InterOcean S4.

[5]S4 tilt option compensates for tilt up to 45 degrees.

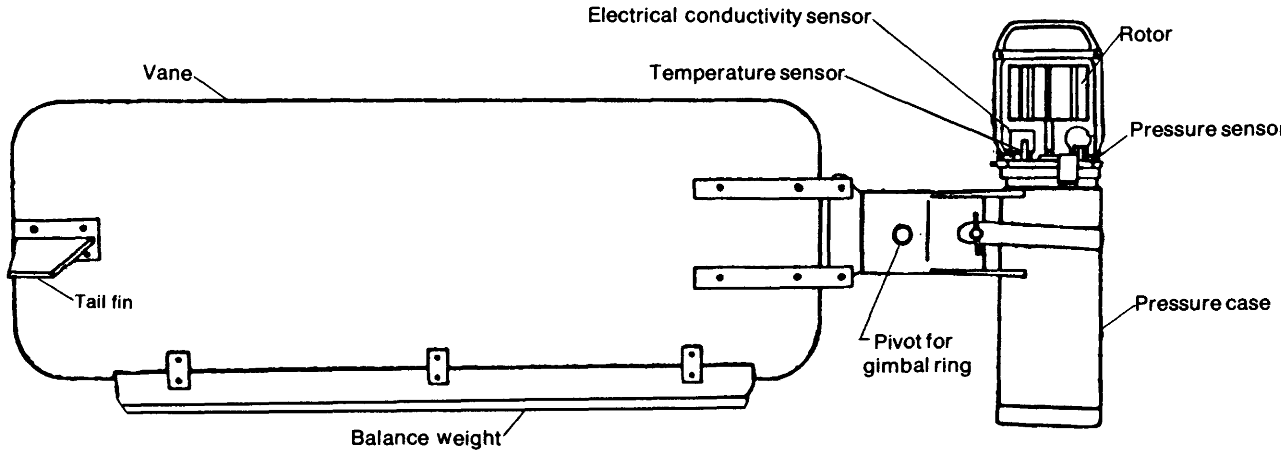


Figure 3. Vertical-axis rotor current meter (length of pressure case/rotor assembly 51 cm).

meter also records water temperature, electrical conductivity, and pressure (used to measure water depth) when optional sensors are installed. The data are recorded on 64-mm (millimeter) magnetic tape using 76-mm-diameter reels. The sampling interval is user selectable by an internal switch. Current speed is integrated over the sampling interval, whereas current direction, water temperature, electrical conductivity, and pressure are instantaneous values recorded at the time of each sample. Documentation for this meter is an 84-page service manual (Aanderaa Instruments Ltd., 1983) containing meter description and specifications, theory of operation, operating instructions, and tape-reading, data-processing, calibration, and maintenance procedures.

Vertical-axis rotor meters have been marketed since 1967, and were previously used in the deep regions of San Francisco Bay by NOS/NOAA and the Geological Survey in 1979 and 1980 (Cheng and Gartner, 1984). Vertical-axis rotor meters have been evaluated in numerous performance studies, including Saunders (1976), Halpern and Pillsbury (1976), Beardsley and others (1977), Cheng (1978), McCullough (1978), and Fuyo Ocean Development Company and Institute of Central Electric Research (1982). These studies show that the rotor speed sensor is extremely sensitive to orbital wave motion and to mooring-line motion. The Fuyo Ocean Development Company study showed that the rotor rotated when the meter was slowly hoisted in water with no horizontal current or waves present. Cheng (1978) concluded that although the vertical-axis rotor meter is susceptible to inaccurate speed readings because of mooring-line motion, orbital motion from wind-fetched short-period waves does not have a substantial influence on current-meter records if the meter is rigidly mounted (meter deployed 3 m below surface). All the studies concluded that mooring-line motion is a problem with the vertical-axis rotor meter because of its Savonius-type rotor, and that the meter is not recommended for use in wave zones. The manufacturer also recommends that this meter be used only below the wave zone (Aanderaa Instruments Ltd., 1983). Nevertheless, vertical-axis rotor meters were used in this study to evaluate whether rigid mounting of the meter reduces its sensitivity to orbital wave motion, and, if the rigid mounting does not diminish the meter's sensitivity to orbital wave motion, whether the speed records from the meter could serve to indicate the presence of orbital wave motion during periods of high windspeed.

The manufacturer in late 1983 announced the availability of a new, ducted paddle-wheel rotor for use with its current meters. Meters with this new type of sensor were not tested in this study.

Inclinometer

The inclinometer is a current deflection meter (fig. 4) that has no external moving parts. The meter hangs vertically in the absence of a current, and is tilted downstream in the presence of a current. The angle of tilt varies with the speed of the current. The instrument utilizes an inclinometer to determine the tilt angle, which is converted to current speed. Three orthogonally mounted Hall-effect sensors are used to determine current direction. Water-temperature, electrical conductivity, and pressure sensors are available. Data are recorded on a magnetic-tape cassette. Various combinations of vector averaging,

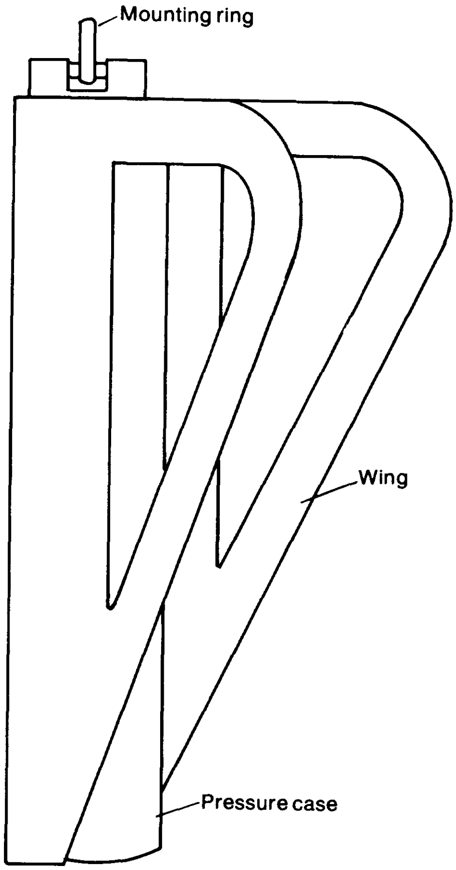


Figure 4. Inclinometer current meter (length 51.4 cm).

burst sampling, and sampling intervals are selectable by internal switches (General Oceanics, Inc., 1982). Documentation for the meter is a 20-page service manual (preliminary) containing meter description and specifications, principles of operation, guides to data translation, and operating instructions.

Cheng (1978) determined that the inclinometer recorded accurate speed readings at slack water for both calm and windy periods. However, it also was determined that the nonlinearity of the speed-and-tilt relation was a problem in certain speed ranges. The meter used in the study that is the subject of this report was equipped with the standard wing for intermediate flow rates; the manufacturer also provides a "low speed" wing that can be used for speeds up to about 70 cm/s. The maximum speed recorded during this study was about 40 cm/s; therefore, the use of the low-speed wing would have been preferable because with the low-speed wing the same range of wing tilt is related to a smaller speed range.

Electromagnetic

The electromagnetic current meter is a spherical solid-state meter (fig. 5) that uses no external moving parts. Water flows through an electromagnetic field created by the meter, thereby producing a voltage that is proportional to the magnitude of the current speed (Faraday's principle). Although the meter is a new design, the electromagnetic operating principle has been in use for several years. The current direction is determined by using a flux-gate magnetometer. Water-temperature, electrical conductivity, and pressure sensors are available. Data are stored in a complementary metal-oxide semiconductor (CMOS) static random-access memory (RAM). Sample interval and operation mode (burst sampling or vector averaging) are user selectable. A 47-page service manual (InterOcean Systems, Inc., 1984) contains meter description and specifications, and procedures for communication, programming, diagnostics,

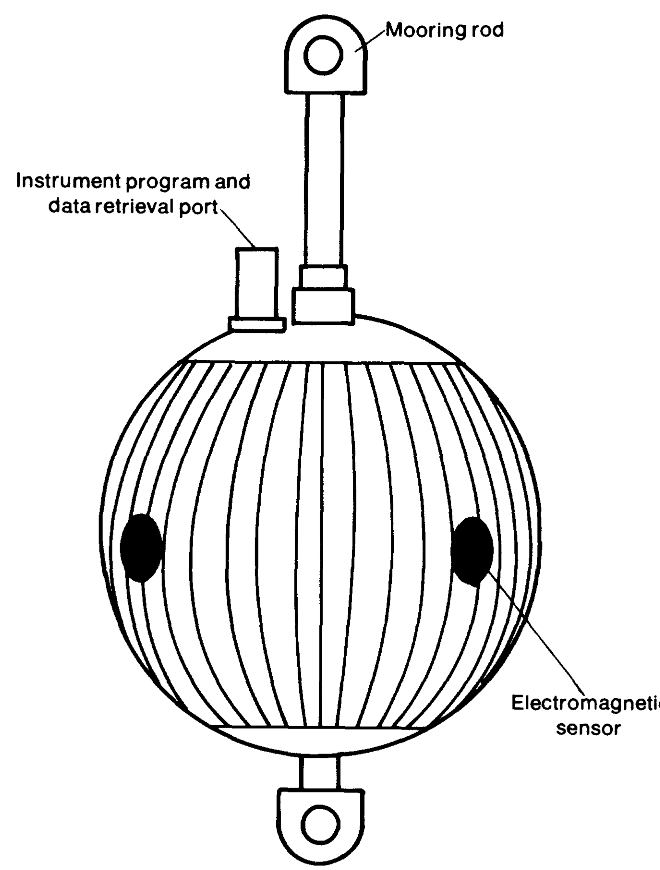


Figure 5. Electromagnetic current meter (sphere diameter 25 cm).

retrieval and reduction of data, deployment, and maintenance. Because of the operating principle, the meter is recommended by the manufacturer for use in all situations, including wave-zone applications.

DATA-SAMPLING CHARACTERISTICS

If possible, each current meter used in a comparison study of this type should be set at the same sampling interval and use the same speed-sampling mode (speed integrated over sampling interval, instantaneous (burst), or vector averaged). Unfortunately, differences in equipment design, available sampling options, and data-storage capacities among the four instruments made this comparison impossible for this study.

The only speed-sampling mode available for the horizontal-axis ducted impeller and vertical-axis rotor meters is integration over a selected sampling interval. The horizontal-axis ducted impeller meters used in this study already were set for a 2-minute sampling interval. Because the data-tape capacity was sufficient to store data for the expected deployment period--and for consistency with the 1979-80 data already collected--the 2-minute sampling interval for the horizontal-axis ducted impeller meter was not changed. However, the data-tape storage capacity of the vertical-axis rotor meter was not sufficient to allow the use of a 2-minute interval. Also, existing data-processing software required 10-minute-interval input data. Therefore, a 10-minute interval was selected for the vertical-axis rotor meter.

The inclinometer and electromagnetic meter do not have an option for averaging speed over the sampling interval. Both meters can be programmed to make a number of instantaneous readings at a selected sampling interval. In the case of the inclinometer, the data-tape capacity for the expected deployment length was the limiting factor in the choice of four instantaneous readings (bursts) per sample and a 15-minute sample interval. The four readings are made approximately 1.0 second apart. The electromagnetic meter also was programmed with a 15-minute sample interval, and four data points were recorded at each sampling. However, the electromagnetic meter data points are vector averages of 120 1/2-second readings. These four readings were later vector averaged (refer to "Data Translation" section) to provide an average velocity at the time of sampling; the same procedure was used for the four inclinometer readings.

Therefore, the inclinometer data represent an average over an interval of approximately 4 seconds every 15 minutes; the electromagnetic meter data represent an average over a 4-minute interval every 15 minutes; and the horizontal-axis ducted impeller and vertical-axis rotor meter data represent averages over consecutive 2- and 10-minute intervals, respectively. The time-series data for each meter then were vector averaged to 30-minute time series for use in plotting routines. Nevertheless, the original data are of two types: (1) integrated (averaged) over the sample interval (horizontal-axis ducted impeller and vertical-axis rotor meters), and (2) instantaneous (even though vector averaged in the case of the electromagnetic meter) for the inclinometer and electromagnetic meter.

DATA COLLECTION

DATA-COLLECTION PLAN

The data-collection plan consisted of deploying current meters attached to fixed mooring platforms in a shallow-water region of the bay that was not sheltered from the wind. To avoid disrupting the flow field at one current meter because of the presence of another, the platforms were deployed 9 to 10 m apart in a line approximately perpendicular to the flood- and ebb-current directions. All meters were positioned approximately 1.2 m above the bottom of the bay. Water-level data were collected to provide a record of varying water depth (tidal fluctuations) at the current-meter site. Wind data recorded at San Francisco International Airport (13.5 km (kilometer) west of the current-meter site) were used to define windy periods when wind-generated waves were present.

Selection of the deployment site was based on the following requirements: (1) a flat, hard bottom to provide a firm foundation for the equipment, (2) an area of unobstructed flow, (3) a minimum water depth of 2 m, and (4) an area not sheltered from the wind (that is, a long fetch). The site was selected using NOS/NOAA sounding charts, and the results of fathometer traverses and bottom probes (a pole was used to determine the firmness of the bottom). The site selected was in south San Francisco Bay approximately 4 km north of the San Mateo Bridge and 6 km from the east shore (fig. 6).

Current-meter and water-level data collection began June 13, 1984, and concluded October 2, 1984.

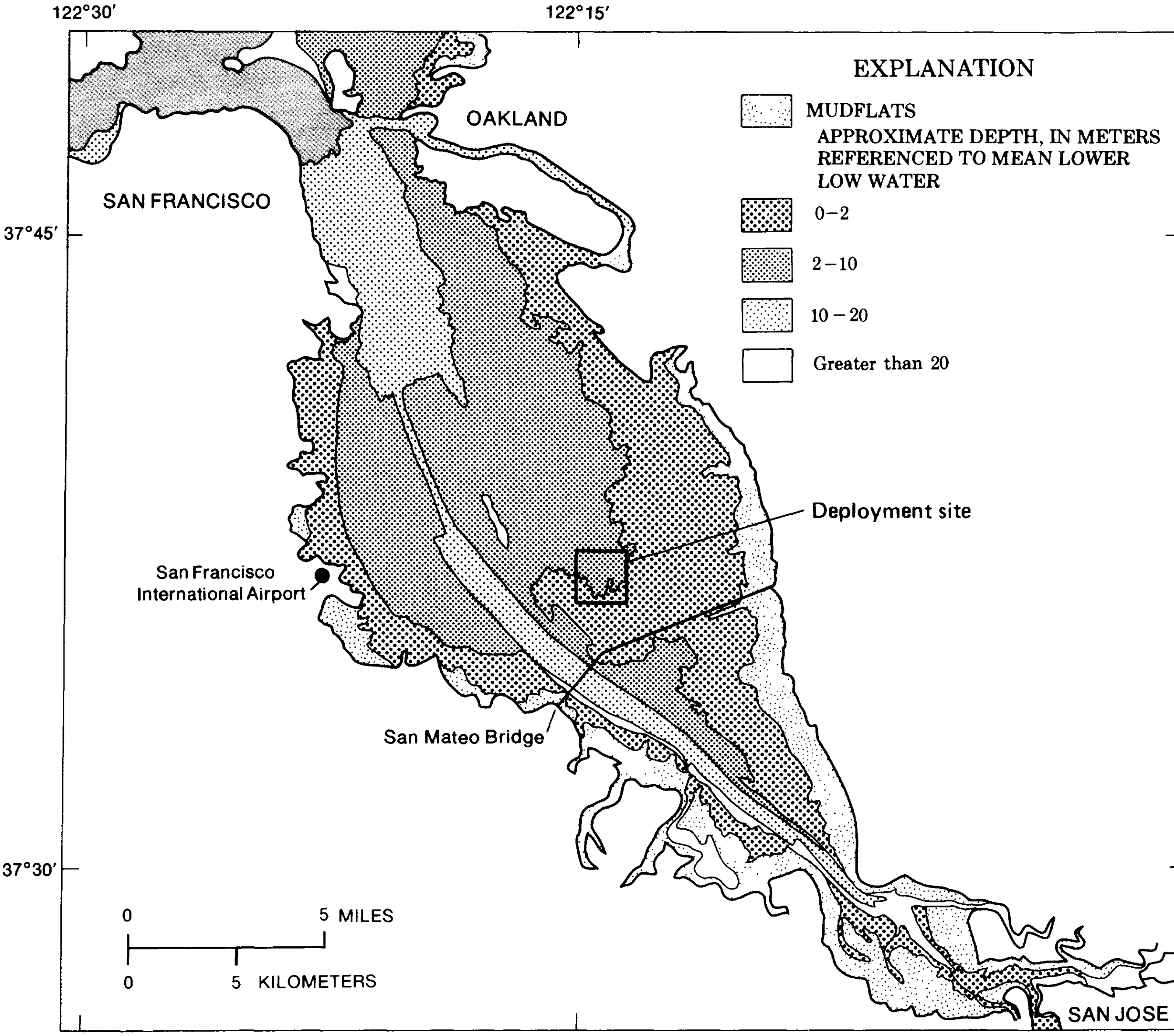


Figure 6. South San Francisco Bay, showing location of current-meter deployment site and surrounding bathymetry.

Deployments of equipment covered consecutive periods of about 28 days. The deployment periods for each of the instruments used during the study are shown in figure 7. Because multiple horizontal-axis ducted impeller and vertical-axis rotor meters were available, they were deployed to provide a comparison between meters of the same type and to increase the probability that at least one record from each would be available to compare with the inclinometer and electromagnetic meter. Velocity data are not available for all four current-meter types for the entire data-collection period because of meter acquisition problems, and because of equipment malfunctions and losses. (See "Lost Data" section.) An electromagnetic meter was not acquired for testing until about 1 week before the scheduled completion date (September 5) for data collection. Nevertheless, the meter was deployed at the study site on August 29, 1984. However, to provide a longer data-collection period, the electromagnetic meter was not retrieved on September 5 with the other meters. One horizontal-axis ducted impeller meter was redeployed

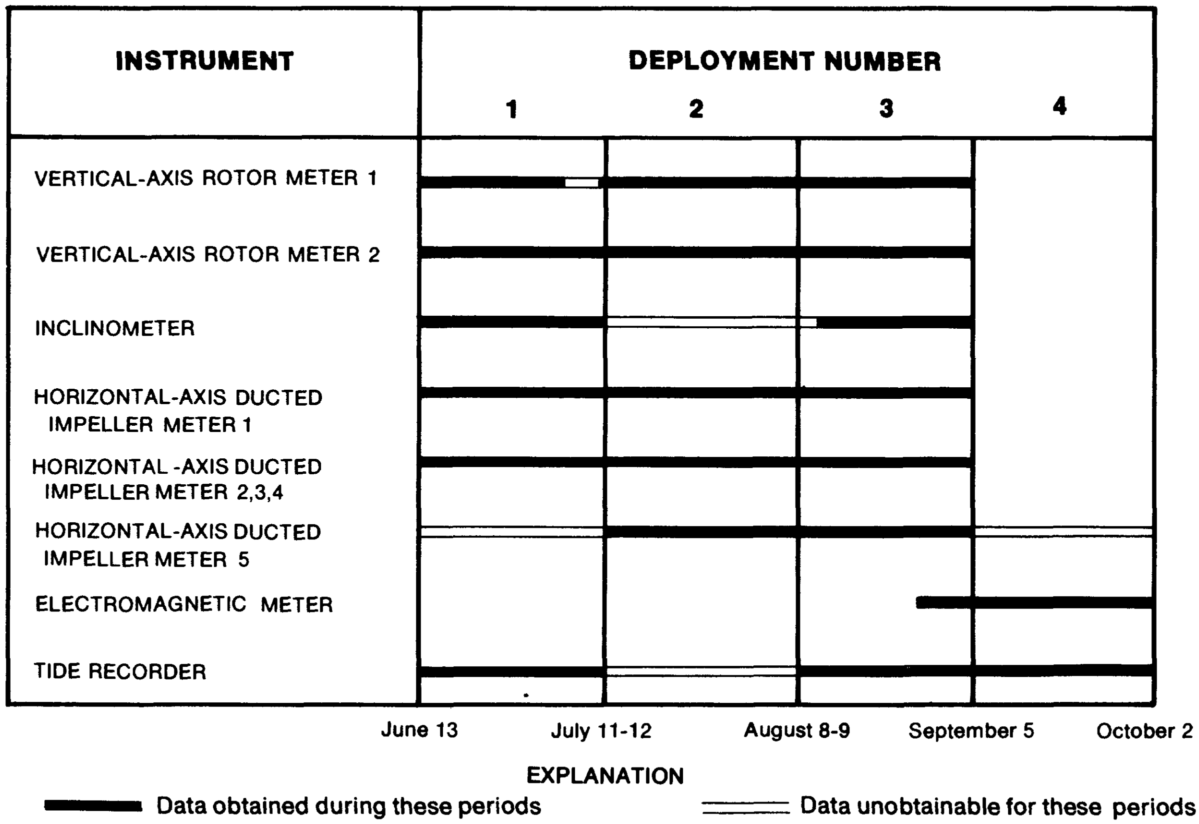


Figure 7. Periods of instrument deployment and of lost data.

on September 5 near the electromagnetic meter to provide a comparison record, but unfortunately the horizontal-axis ducted impeller meter could not be recovered when the electromagnetic meter was retrieved on October 2.

During each visit to the study site, electrical conductivity and temperature readings were taken to verify data recorded by those current meters that were equipped with electrical conductivity and temperature sensors. Also, water samples were collected for laboratory determination of salinity for comparison with current-meter records. (Salinity records were calculated from current-meter electrical conductivity and temperature data.) In addition, current-speed measurements were taken using a nonmoored, nonrecording current meter (Price AA current meter) suspended from the deployment vessel at the depth of the recording current meters (1.2 m above the bottom).

ADDITIONAL EQUIPMENT AND MODIFICATIONS

Current-Meter Moorings

The horizontal-axis ducted impeller and vertical-axis rotor meters were mounted on hexagonally shaped 1.7-m-diameter aluminum platforms (figs. 8 and 9) that weighed about 80 kg (kilograms) with bottom weights attached. The horizontal-axis ducted impeller meters were attached to the platforms using stainless-steel mounting brackets (figs. 8 and 10) designed so that the neutrally buoyant horizontal-axis ducted impeller meter could turn freely in water. The brackets were designed to allow up to 5 degrees of tilt to compensate for slight bottom irregularities. Compass calibrations were done by the manufacturer on two meters with and without brackets attached, and

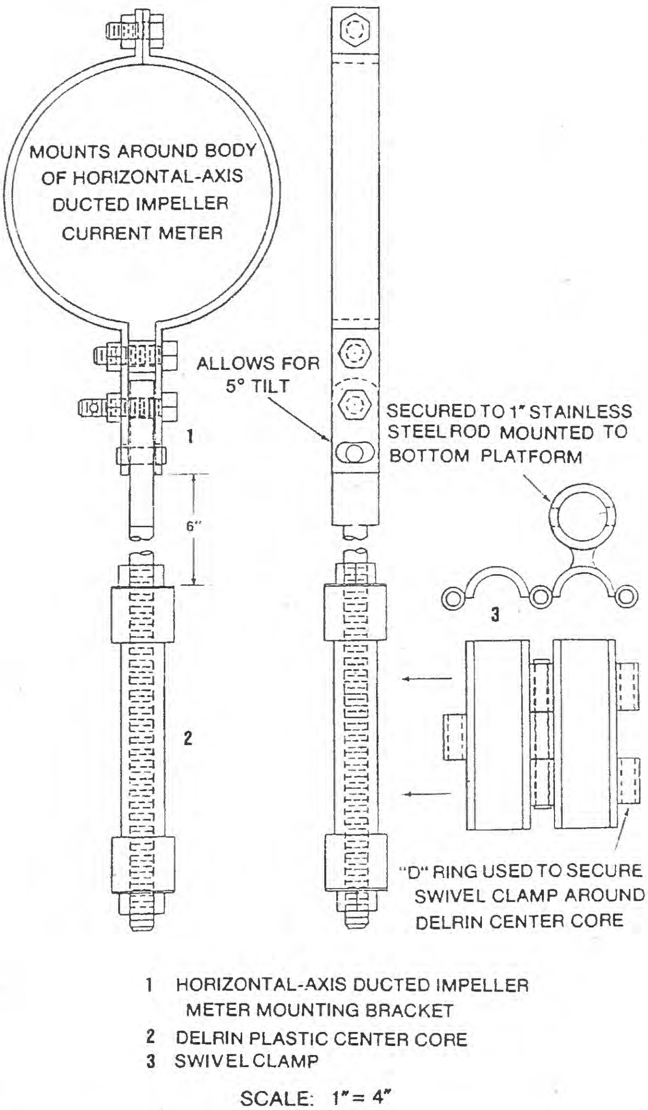


Figure 8. Horizontal-axis ducted impeller current-meter mounting bracket.

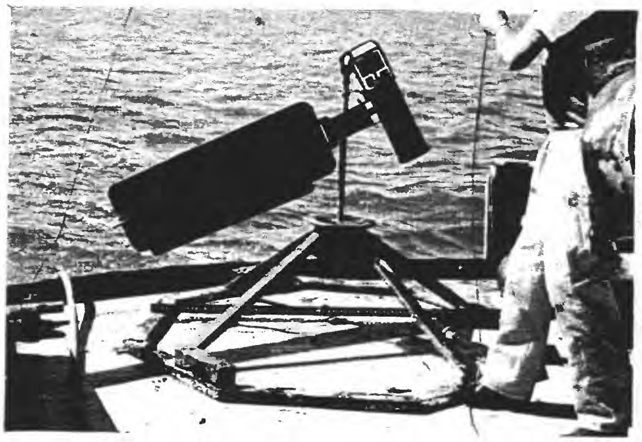


Figure 9. Vertical-axis rotor current-meter mounted on platform.

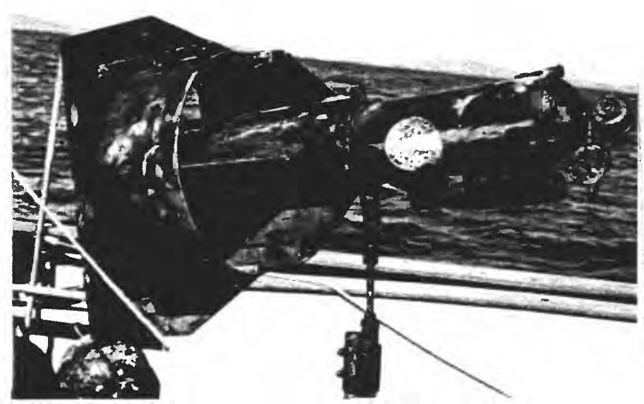


Figure 10. Horizontal-axis ducted impeller current meter with mounting bracket and attached vane (length 85.1 cm; diameter of shroud 40.6 cm).

no significant effect on compass calibration was noted. The vertical-axis rotor meters were mounted on the platforms using a connector rod (fig. 8). A bottom platform was used as an alternative to taut-wire mooring because the use of a platform (1) allowed deployment in shallower water than possible with a taut-wire mooring, (2) eliminated mooring-line motion, and (3), in the case of the horizontal-axis ducted impeller meter, eliminated compass lock if the gimbal tilt limit was exceeded.

The inclinometer was suspended from a frame provided by the manufacturer (fig. 11). The electromagnetic meter, rather than being rigidly fixed to a platform, was tethered between an anchor and subsurface buoy (fig. 12). The meter was not rigidly mounted because there was not sufficient time to design a rigid mounting bracket and still obtain data that could be compared with the data from the other meter types.

deployment and on two of the three meters that were used during subsequent deployments.

Figure 11. Inclinometer current meter and suspension-frame mooring platform.

Figure 12. Electromagnetic current meter mooring (array as shown is inverted relative to deployment position).

Vane Addition for Horizontal-Axis Ducted Impeller Current Meter

Because the horizontal-axis ducted impeller meters were to be rigidly mounted, rather than tethered, a 25- by 61-cm (centimeter) vertical vane was attached to the existing shroud-and-vane assembly (fig. 10) on some of the horizontal-axis ducted impeller meters. The additional vane was to be evaluated as a possible means of improving the meter's reaction time to current-direction changes. This modification was made on one meter that was used during the first deployment and on two of the three meters that were used during subsequent deployments.

Tide Recorder

Water-level data were recorded at the deployment site using a tide recorder (fig. 13). The recorder uses a semiconductor strain-gage pressure sensor. Data are recorded on eight-track-cartridge magnetic tape in a manner similar to that of the horizontal-axis ducted impeller current meter. The recorder was mounted on one of the horizontal-axis ducted impeller current-meter platforms (fig. 13), and deployed for the entire data-collection period. The unit utilizes a 60-second digital integration of pressure to determine a true average of pressure for each sample (a 2-minute sample interval was used). This method filters out unwanted variations in pressure caused by wave motion. The strain-gage pressure sensor is referenced to absolute pressure of 1.03 kg/cm^2 (kilograms per square centimeter), and deviations in atmospheric pressure from the reference value were accounted for during data translation to attain maximum accuracy. Daily atmospheric-pressure data as recorded at San Francisco International Airport were obtained from NOAA/National Climatic Data Center monthly summary sheets.

Nonmoored, Nonrecording Current Meter

A nonmoored, nonrecording Price AA current meter was used to collect current-speed data for comparison

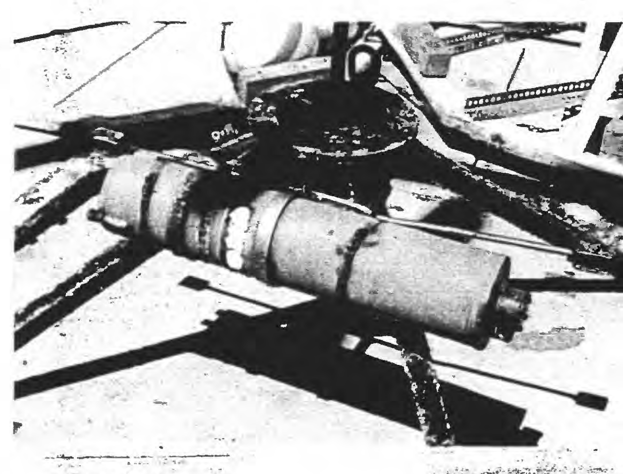


Figure 13. Tide recorder mounted on bottom platform.

with the data obtained using the recording meters. The Price AA current meter is a vertical-axis meter equipped with a rotor consisting of six cone-shaped cups. Each time the rotor makes a complete revolution, an electrical impulse produces an audible click in the headphone of the operator. The revolutions are counted and the corresponding count-time interval recorded. Current speed is determined using a current-meter rating established by towing the meter at a constant velocity through a long water-filled tank, and relating the linear and rotational velocities of the current meter. Studies by Carter and Anderson (1963) and Smoot and Carter (1968) have shown that a properly maintained Price current meter measures the true current speed within approximately 1 percent.

A Price meter was used during the July 12 and August 8-9 deployment-and-retrieval trips to obtain periodic current-speed measurements over count-time intervals of 45 to 60 seconds at the moored-current-meter height of 1.2 m above the bottom of the bay. The speed measurements were collected by suspending the meter over the side of the deployment vessel. Kallio (1966) showed that when a Price meter is subjected to vertical motion, data provided by the meter are adversely affected. Therefore, the Price meter could only be used when the water surface at the study site was smooth. Because a smooth water surface in south San Francisco Bay during summer months is a rare occurrence, limited amounts of useful current-speed data could be collected with the Price meter for comparison with data obtained using the recording meters.

DEPLOYMENT AND RETRIEVAL OF EQUIPMENT

Deployment and retrieval of equipment was accomplished using a 14-m vessel equipped with a stern-mounted A-frame and hydraulic winch. Because the deployed current meters were only 9 to 10 m apart, current-meter platforms were connected with stainless-steel cable, and an acoustic release was attached to each end of the multiple-platform array. This eliminated the requirement of having an acoustic release for each platform and provided a second acoustic release for retrieving the equipment if a malfunction occurred with the primary release. Each array consisted of three platforms, and all the equipment was deployed using two arrays. The meters were mounted on the platforms, and the platforms were connected sequentially on the deck of the deployment vessel before deploying the equipment from the stern of the vessel (fig. 14).

Figure 14. Horizontal-axis ducted impeller current meter, mounted on platform, being deployed from stern of vessel.

Equipment retrieval and redeployment consisted of the following procedures. After one entire array was completely retrieved, the equipment was inspected for damage, fouling, and corrosion, and marine growth was removed. In the case of the horizontal-axis ducted impeller meter, vertical-axis rotor meter, and inclinometer, the magnetic data-recording tape and batteries (excluding the inclinometer's lithium battery) were removed and replaced. The electromagnetic meter was deployed and retrieved only once; the meter was sent to the manufacturer for recovery of data from the meter's memory. After equipment was serviced, the array was redeployed in the reverse order of retrieval, and the process was repeated on the remaining array. Normally one array was retrieved, serviced, and redeployed per day.

LOST DATA

Figure 7 shows periods for which data were lost as a result of equipment or recording-media malfunctions or to equipment loss. Causes of data loss varied. During the first deployment, the spiral wire spring that drives the recording-tape takeup reel of vertical-axis rotor meter 1 broke. This resulted in a loss of about 6 days of data. Also during the first deployment, data were not recovered from horizontal-axis ducted impeller meter 5 because the data tape was unreadable. Data were not recovered from the second deployment of the inclinometer because a loose connector plug between the battery and the meter's electronic components resulted in intermittent power to the meter. In addition, usable water-level data were not recovered from the tide recorder during the second deployment. The reason for this malfunction is unknown.

The only equipment lost during the study was horizontal-axis ducted impeller meter 5, which was deployed on September 5, 1984, for the purpose of providing a record for comparison with the electromagnetic meter. This horizontal-axis ducted impeller meter was lost because the mounting bracket failed as a result of corrosion.

DATA TRANSLATION, DISPLAY, AND HARMONIC ANALYSIS

The reduction, display, and analysis of current-meter and water-level data involved several steps. These include the transfer of binary data from instrument storage media to computer storage, translation of binary data to engineering units, determination of data quality and quantity, and display and analysis of the data.

DATA TRANSLATION

Each of the current meters used in the study utilized a unique data format and type of storage medium (eight-track tape, cassette tape, reel-to-reel tape, and solid-state memory). Each storage medium required its own translation or interface unit and supporting software to allow the data tape or memory to be read, and the data to be retrieved, formatted, and output to computer storage. Translation of data from binary to engineering units involved the use of mathematical relations unique to each type of meter and calibration constants unique to each meter serial number.

Data tapes from the horizontal-axis ducted impeller (eight-track) and vertical-axis rotor (reel-to-reel) meters were processed using available tape readers interfaced with a minicomputer system. Data-processing procedures for velocity, temperature, and electrical conductivity (salinity) for the horizontal-axis ducted impeller current meter are described by Cheng and Gartner (1980). The vertical-axis rotor data were processed in a similar manner using software developed or modified as required. As part of data processing, the horizontal-axis ducted impeller meter (2-minute) and vertical-axis rotor meter (10-minute) time-series data were vector averaged to produce a new set of 30-minute time series data for input to subsequent plotting programs.

Data from the electromagnetic current meter were recovered from the meter's internal memory and supplied by the manufacturer. The data, in the form of binary numbers representing north and east speed components, subsequently were converted to engineering units and then to speed and direction values. Each set of four 1-minute vector averages (collected at 15-minute intervals) was vector averaged to form a new 15-minute time series of single readings. This time series later was vector averaged to a 30-minute time series for input to plotting programs.

The inclinometer data were provided by the manufacturer on nine-track tape in engineering units. The four-burst-per-sample speed and direction readings were vector averaged to form a new time series of single, 15-minute readings. It should be noted that the sample interval was not exactly 15 minutes, but rather an interval slightly less than 15 minutes. This was a result of timing intervals that are based on multiples of 7 seconds. Thus, a 15-minute interval was actually 896 seconds (14.93 minutes). Newer versions of the meter have sampling intervals equal to the exact number of minutes selected. The result of the noninteger sample interval was a shift in sample time of about 6 minutes every 24 hours. However, the meter contains a real-time clock and time is recorded with each sample: therefore, a linear interpolation could be performed. The original time series of quasi-15-minute data was first vector averaged to create a time series of 30-minute (approximate) data, and then a linear interpolation was done on that record to create a new time series of 30-minute data with all readings on the hour and half hour (required for input to plotting programs).

The horizontal-axis ducted impeller meter 2-minute and vertical-axis rotor meter 10-minute time-series data were used as input to harmonic-analysis programs, as were the 15-minute vector-averaged inclinometer and electromagnetic meter data. Within the harmonic-analysis programs, all input data were first vector averaged to 30-minute time-series data for consistency before proceeding with the analysis.

Water-level data recorded by the tide recorder and current-meter data from the horizontal-axis ducted impeller current meter were processed in a similar manner. The same tape reader was used; however, software modifications were required to format data correctly because pressure was recorded as a 12-bit word, whereas all data interpreted by the old-style (horizontal-axis ducted impeller) tape reader are seen as 8-bit words. After the data were formatted correctly, adjustments for variations in atmospheric pressure were incorporated, and the data were translated to engineering units, averaged to 1-hour values, and stored for later harmonic analysis and plotting.

DATA DISPLAY

Time-series plots of current-meter records are contained in Supplemental Data A (at end of report). The current velocity in the form of 30-minute vector-averaged speed and direction (relative to true north) is plotted against time. Hourly water-level data also are plotted (Supplemental Data B). The mean of the time series of water-level data is computed during harmonic analysis and is subtracted from the time-series values prior to plotting. For reference, one temperature and one salinity record (30-minute average) from each deployment is displayed in Supplemental Data C. Wind conditions during the study are displayed in the form of stick diagrams (Supplemental Data D). Source of the wind data is 3-hour-interval wind readings as recorded at San Francisco International Airport.

HARMONIC ANALYSIS

The method of harmonic analysis for tide (water level) and tidal-current data is well documented by Schureman (1940) and Cheng and Gartner (1984). In all cases the data sets for both water level and current are truncated to an even number of M_2 cycles (56 cycles maximum). The M_2 cycle (12.42 hours) is used because it is by far the largest partial tidal constituent in San Francisco Bay.

Results of harmonic analysis of the water-level records collected during the study are included in Supplemental Data B. The seven major tidal harmonic constituents (O_1, K_1, N_2, M_2, S_2, M_4, and MK_3) were computed using the least-squares method, and nine minor constituents (Q_1, M_1, P_1, J_1, μ_2 (MU_2), ν_2 (NU_2), L_2, T_2, and K_2) were computed by means of inference based on equilibrium theory. Results include the following variables used in the prediction of tides: height (H), local epoch (κ), and modified epoch (κ') for each constituent, as well as the mean of the water-level heights.

In the case of current-meter data, six harmonic constituents (O_1, K_1, N_2, M_2, S_2, M_4) were computed for east-west and north-south tidal-velocity components. Minor constituents were not calculated using the inference method for two reasons: (1) The equilibrium theory of tides is less reliable in the case of tidal currents, and (2) the accuracy of current measurements in estuaries is less than that of water-level measurements. Results of harmonic analysis of current-meter records collected during the study are included in Supplemental Data A. In addition to harmonic constituents, the summary sheets shown in Supplemental Data A include some general properties of tidal currents computed by the harmonic-analysis program such as the root-mean-square (RMS) current speed, maximums of spring- and neap-tidal currents, principal tidal-current direction, tidal-current form number, and Eulerian residual current (time-averaged velocity). Depending on the usable length of the record, the time-averaged velocities are computed for every 12 M_2 tidal cycles, and an even number less than 12 M_2 cycles for the remaining available data in the record. The time average for the entire record length (maximum even M_2 cycles) also is given.

COMPARISON OF CURRENT-METER RECORDS

COMPARISON METHODS

The accuracy of velocity data that were collected using the current meters was evaluated by comparing respective current-meter data records. Special care was given to examining records during several specific flow and field conditions. Responses of the meters' speed sensors were compared during slack water and maximum ebb and flood flows during calm and windy conditions, and during high and low tide. Accuracy of current speeds recorded by different meters can be evaluated only during slack-water periods (essentially a known value). During times of higher current speeds, actual current speeds are unknown because it is extremely difficult to measure current speed accurately from a boat (Kallio, 1966); therefore, during higher current speeds, only the relative speeds as recorded by the meters can be compared. It also should be noted that current speed during slack-water periods does not always equal zero; however, the speed approaches zero as the current direction gradually rotates from ebb to flood or vice versa. Water depth is of importance because as the magnitude of the wind increases, so does the size of the surface waves and the depth of penetration of the orbital wave motion. The responses mentioned above were evaluated by: (1) comparison of current-meter speed data with nonmoored, nonrecording Price AA meter speed readings; (2) comparison of speed and direction time-series plots; (3) speed intercomparison plots; and (4) comparison of results of harmonic analyses, including time-averaged velocity calculations (Eulerian residuals).

FIELD CONDITIONS DURING DATA-COLLECTION PERIOD

Time-series plots of water-level, water temperature, salinity, and wind velocity data (Supplemental Data B, C, and D) show that the field conditions during the data-collection period were relatively constant. Except for very short periods when winds were from the southwest, the winds consistently were from the west to northwest and windspeed generally varied between 5 and 10 m/s (meter per second) (Supplemental Data D). The average daily windspeed for each of the three deployments was 6.7, 6.0, and 6.2 m/s, respectively. Water-level records show that water depth at the current-meter site ranged from about 2.0 to 5.1 m, with a mean of 3.7 m. Salinity at the study site ranged from 28.5 to 30.8 ‰ (parts per thousand), and no salinity stratification was detected. Water temperature ranged from 17.5 to 24.0 °C.

COMPARISON WITH SPEED DATA FROM NONMOORED, NONRECORDING METERS

Three sets of speed data (tables 2-4) were collected using nonmoored, nonrecording Price AA meters for comparison with speeds recorded by deployed current meters. Price-meter data are not available to compare with the inclinometer and electromagnetic meter because either: data were lost, the meter was being serviced (inclinometer) when the Price-meter data were being collected, or the water-surface conditions precluded the collection of Price-meter data (electromagnetic meter). Although the amount of Price-meter data is limited, the data are useful in comparing speed readings obtained using deployed meters during the absence of wave motion.

The vertical-axis rotor meter 10-minute data were linearly interpolated, in compiling tables 2-4, to provide speed data that would coincide with the times of the Price-meter readings. The horizontal-axis ducted impeller meter 2-minute data were used as recorded.

Generally, the Price-meter readings are higher than the horizontal-axis ducted impeller and vertical-axis rotor current-meter values; however, speed differences commonly are within expected limits--considering the meters' speed resolution and accuracy specifications. The elapsed time since the previous servicing of the deployed meters may explain some of the discrepancies between the speed values. Fouling of moving speed sensors by marine growth or debris affects meters to some extent, and it seems to affect the vertical-axis rotor meters more than the horizontal-axis ducted impeller meters. In all cases, when the Price-meter readings were collected shortly (about a day) after the deployed meters had been serviced (cleaned), the speed differences were less for serviced meters than it was for those meters collected at the end of a 4-week deployment.

Although some of the discrepancies in the data shown in tables 2-4 can be explained by partial fouling, there also are differences among recently

Table 2. Comparison of speed data recorded by Price AA current meter and by deployed current meters, July 12, 1984

Time	Recorded speed (centimeters per second)					
	Price AA	Horizontal-axis ducted impeller 2	Horizontal-axis ducted impeller 5	Horizontal-axis ducted impeller 1	Vertical-axis rotor 2	Vertical-axis rotor 1
09:42	39	27	31	27	29	32
09:44	39	27	37	27	28	32
09:46	38	27	32	28	28	33
09:56	33	27	32	29	27	32
09:58	35	23	32	29	27	31
10:00	34	24	33	30	27	31
10:02	34	23	35	26	27	31
10:04	31	23	32	24	27	31
10:06	34	24	33	24	26	30
10:12	28	23	31	26	26	30
10:15	34	23	31	26	25	29
10:18	35	22	30	28	25	29
Deployment vessel moved						
10:56	26	17	21	20	Meter	24
10:58	25	17	21	21	retrieved	24
11:12	24	17	16	17	for	21
11:14	26	16	18	15	servicing	21
11:18	23	16	18	16		20
11:20	26	14	17	15		20
11:22	23	13	17	15		20
Date deployed meters last serviced		June 13	July 11	July 11	June 13	July 11

serviced meters of the same type. (See July 12 and August 9 data for horizontal-axis ducted impeller meters 5 and 1.) These 10- to 30-percent differences demonstrate the variance that exists among meters of the same type. This variance, in part, may be attributed to speed resolution (0.25 cm/s, vertical-axis rotor meter; 0.89 cm/s, horizontal-axis ducted impeller meter) and speed accuracy (±1 cm/s, vertical-axis rotor; ±6.7 cm/s, horizontal-axis ducted impeller) of the meters (table 1). Also, these data were not collected at the exact location of the compared current meter. Although the assumption was made that a homogeneous flow field existed at the study site, some minor differences would be expected. Therefore, caution must be exercised in drawing conclusions from such a limited data set.

Table 3. Comparison of speed data recorded by Price AA current meter and by deployed current meters, August 8, 1984

Time	Recorded speed (centimeters per second)		
	Price AA	Horizontal-axis ducted impeller 3	Vertical-axis rotor 2
09:52	15	16	10
09:58	14	14	8
10:00	15	15	8
10:06	12	14	8
10:08	18	14	7
10:10	17	12	7
10:12	15	10	7
10:14	14	11	6
10:16	13	9	5
10:26	9	9	3

Deployed meters last serviced on July 12

Table 4. Comparison of speed data recorded by Price AA current meter and by deployed current meters, August 9, 1984

Time	Recorded speed (centimeters per second)			
	Price AA	Horizontal-axis ducted impeller		Vertical-axis rotor
		5	1	1
09:42	28	25	24	27
09:44	30	26	24	26
09:54	25	24	22	25
09:56	26	24	20	25
10:08	26	20	22	23
10:10	23	22	21	23
10:12	26	22	19	23
10:14	24	19	19	23

Deployed meters last serviced on August 8

TIME-SERIES PLOTS

Time-series plots of 30-minute vector-averaged velocity data for each deployment (approximately 28 days) for each current meter are shown in Supplemental Data A.

Examination of individual plots reveals variations in data recorded by the same meter type as well as some significant anomalies. The record from horizontal-axis ducted impeller meter 3 obtained during the second deployment (p. 45) includes numerous spikes in the speed readings during the last 9 days of the record. These probably are the result of incorrect recording of the speed encoder's bit pattern on the data tape. Also during the second deployment, vertical-axis rotor meter 2 (p. 63) recorded a speed of zero for an abnormal length of time on July 14. Abnormal zero-speed periods also occurred several times for both vertical-axis rotor meters during the third deployment (p. 65, 67) near the end of the records (between August 27 and September 5). A possible explanation may be marine growth or debris temporarily fouling the speed rotor or shaft. The records for both vertical-axis rotor meters for the latter part of the third deployment appear to be of questionable accuracy, also probably due to partial fouling.

Except as described below, the direction data from the various meters are in reasonable agreement given the accuracy and resolution of the direction sensors of the individual meters. However, there seems to be a consistent, nearly 10-degree difference between the two vertical-axis rotor meter direction sensors. This difference probably is due to a calibration problem. During the first week of the first deployment, and also 3 days near its end, the horizontal-axis ducted impeller meter 2 (p. 41) unexplainably recorded direction data lower than that recorded by all other meters during the same time period. In addition, direction records from horizontal-axis ducted impeller meter 3 for the second deployment (p. 45) and horizontal-axis ducted impeller meter 4 for the third deployment (p. 51) show several periods of abnormal data during neap tides. At least in the case of meters 3 and 4, these abnormal data seem to be the result of poor response of the current meter to direction changes during periods of lower flows. None of these horizontal-axis ducted impeller meters were equipped with the additional vane, whereas the five remaining direction records were collected by horizontal-axis ducted impeller meters with the vane addition--and only one of those records shows any type of abnormal data. These abnormal data were for horizontal-axis ducted impeller meter 1 during the third deployment (p. 55); the data appear somewhat less stable than do data from horizontal-axis ducted impeller meter 5 (p. 53). It is not known if the variation in this record is associated with the vane addition. Refer to the "Comparison of Horizontal-Axis Ducted Impeller Current Meters With and Without Vane Addition" (p. 32) section for further discussion of vane addition.

Comparison of the time-series plots from different current-meter types also reveals useful information. For example, the data from the inclinometer and electromagnetic meter show higher speed values during maximum-flood and maximum-ebb currents than do data from the horizontal-axis ducted impeller and vertical-axis rotor meters; the inclinometer data also are more variable than the data from the other meters. In addition, slack water seems to be more accurately recorded by the horizontal-axis ducted impeller and electromagnetic meters than by the vertical-axis rotor meter and inclinometer.

These conditions are evident from the current-speed overlay plots shown in figures 15-17. The plots are each 7 days long and cover (1) a spring-tide period, (2) a neap-tide period, and (3) the only period when records are available from all four meter types. Windspeed and water-level plots also have been added in order to examine the relations between speed data and field conditions.

The first 7-day overlay plot is for June 26 through July 2 (first deployment) and includes a spring-tide condition (fig. 15). The record from horizontal-axis ducted impeller meter 2 was chosen because analyses showed that speed readings from meter 1 were slightly high during the first deployment, and slightly low during the second and third deployments, relative to other horizontal-axis ducted impeller meters. The record from vertical-axis rotor meter 2 was arbitrarily chosen for comparison. The plot shows that the inclinometer was recording speed values 20 to 30 percent higher than the horizontal-axis ducted impeller and vertical-axis rotor meters for all maximum-ebb and maximum-flood periods, and also was recording higher values during numerous slack-water periods. The record from the vertical-axis rotor meter also includes higher speed values in comparison with the record from the horizontal-axis ducted impeller meter during several slack-water periods, and during a few maximum-ebb and maximum-flood periods.

Further investigation of figure 15 reveals that agreement or lack of agreement between speed values for the horizontal-axis ducted impeller, vertical-axis rotor, and inclinometer meters is dependent on wind and water-depth conditions. For example, for the first two slack-water periods on June 27, when windspeed was relatively low (less than 5 m/s), the horizontal-axis ducted impeller and vertical-axis rotor meters are in close agreement, and the inclinometer readings are only slightly higher. However, when the windspeed exceeds about 5 m/s, such as in the third slack-water period on June 26 and 27, the vertical-axis rotor meter values are higher than the horizontal-axis ducted impeller meter values, and the inclinometer values are the highest of the three vertical-axis rotor sets of values. In contrast, when windspeed was between 5 and 10 m/s and the water depth was about 3.5 m or greater, such as occurred during the second and fourth slack-water periods on June 26, little or no difference can be seen between the records for the horizontal-axis ducted impeller and vertical-axis rotor meters; the inclinometer seems to show substantial wave-motion effects (fourth slack-water period on June 26). These wave-motion effects are observed at numerous places in the records--whenever windspeed exceeds about 5 m/s, regardless of water depth (for example, during the fourth and third slack-water periods for June 26 and 27, respectively). These examples seem to imply that for these shallow-water conditions, the inclinometer is more sensitive to orbital wave motion than the vertical-axis rotor meter when using the described mooring configurations.

The second 7-day overlay plot is for August 16 through August 22 (third deployment) and includes a neap-tide condition (fig. 16). The selection of the comparison vertical-axis rotor meter was arbitrary. Horizontal-axis ducted impeller meter 4 was not considered because it was not equipped with a vane addition, and horizontal-axis ducted impeller meter 1 was not used for the reason stated previously. The effects of the various field conditions discussed above again are apparent and can be found throughout all the records.

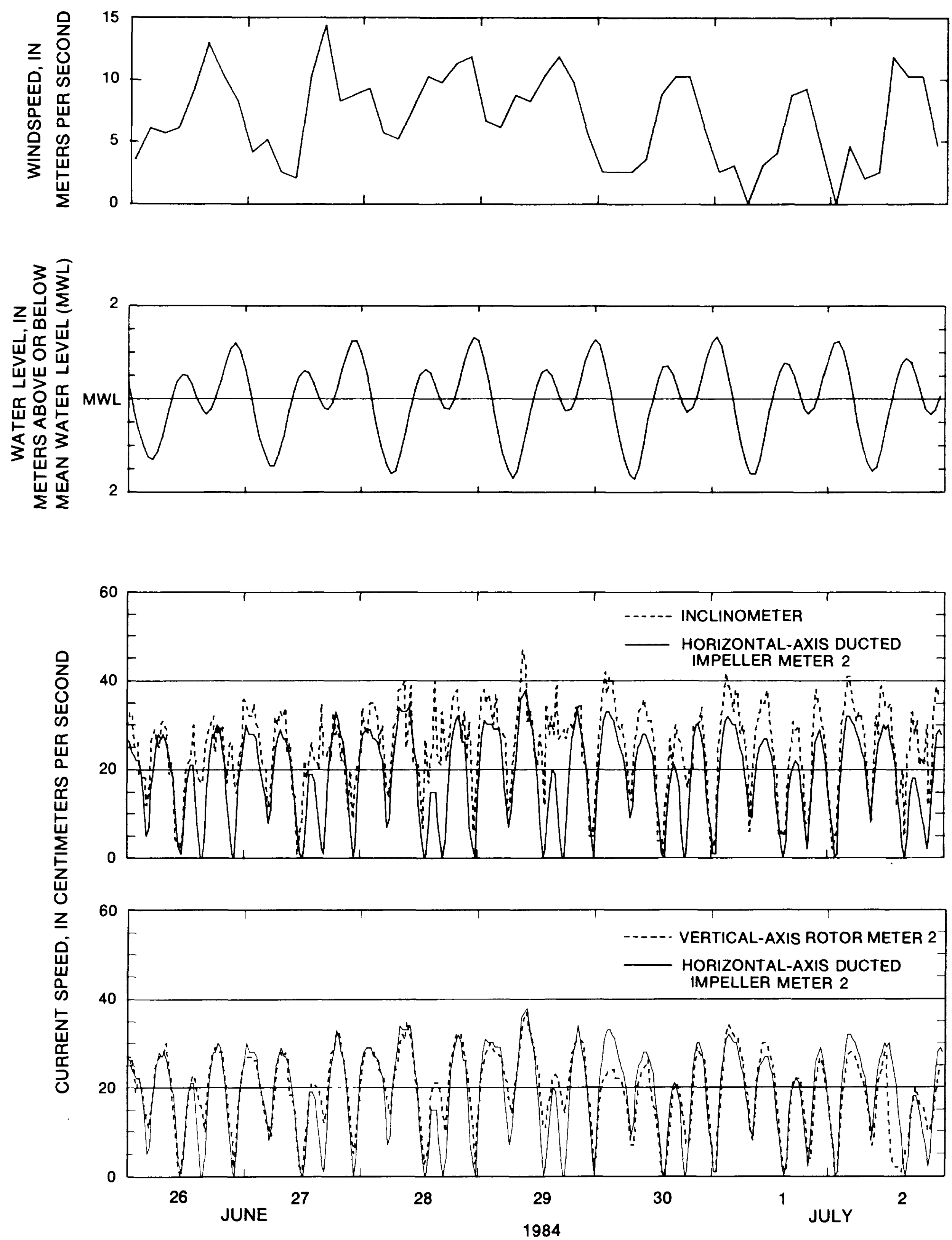


Figure 15. Time-series plots of windspeed, water level, and current speed for spring-tide period (June 26-July 2, 1984).

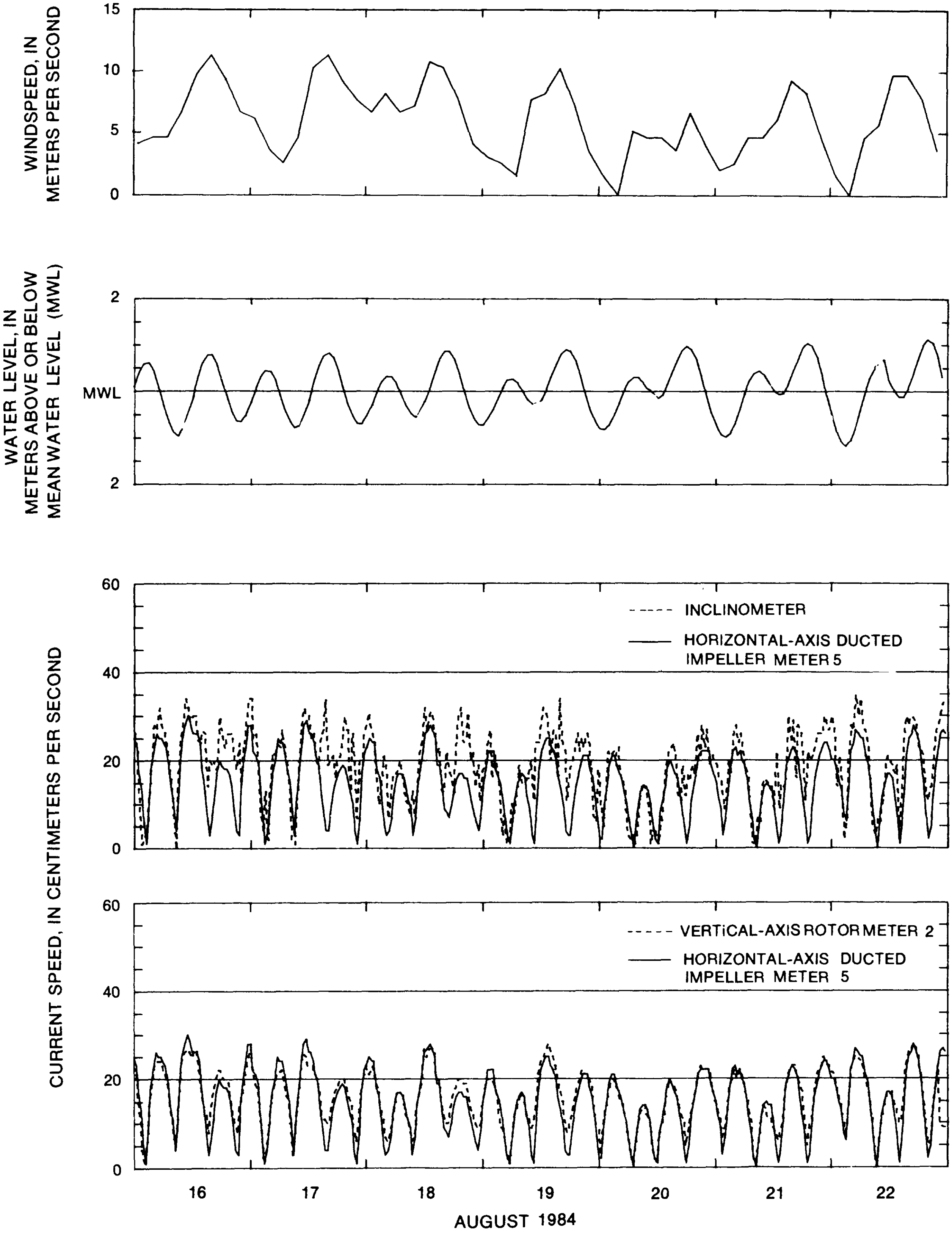


Figure 16. Time-series plots of windspeed, water level, and current speed for neap-tide period (August 16-22, 1984).

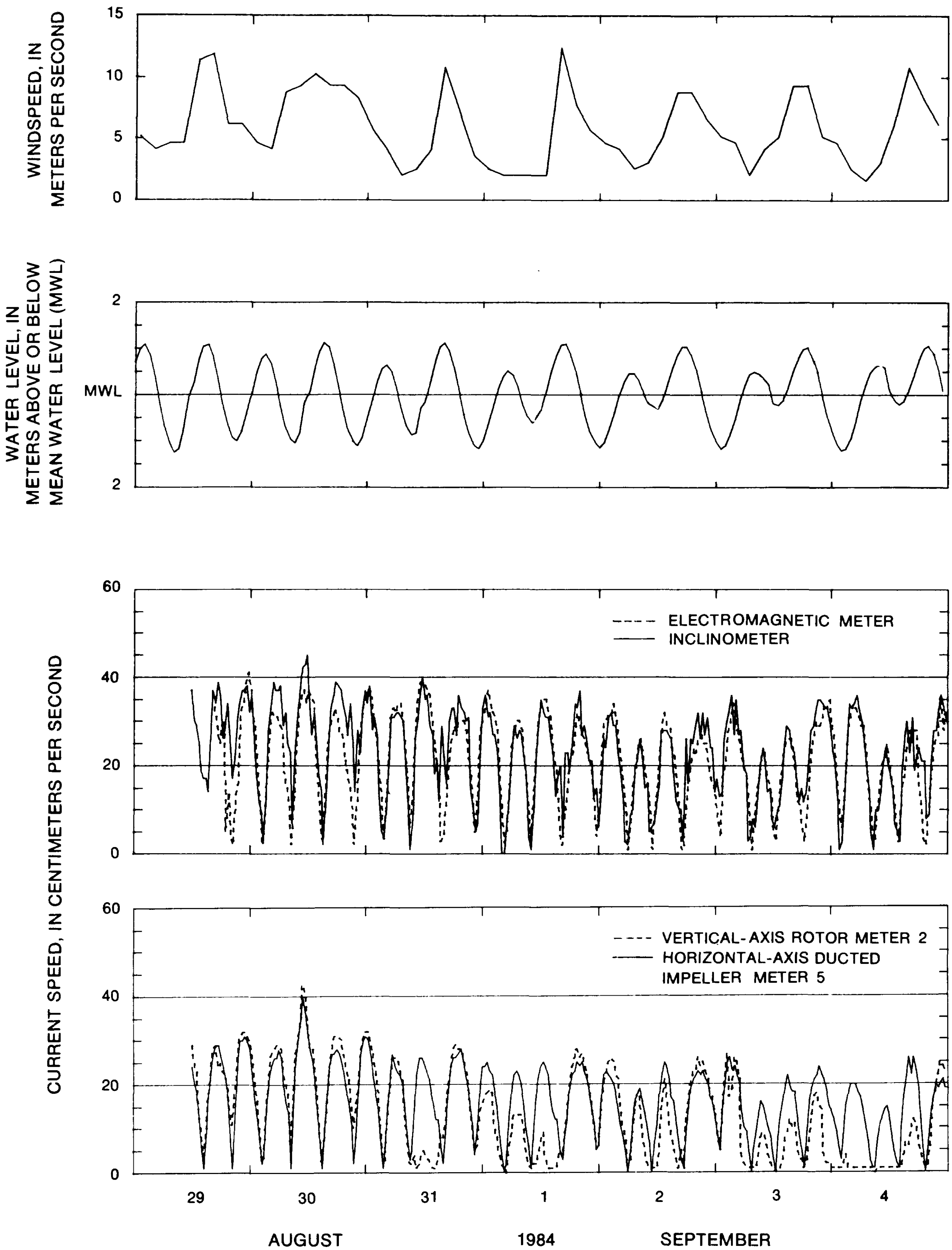


Figure 17. Time-series plots of windspeed, water level, and current speed for period when electromagnetic current meter was deployed (August 29-September 4, 1984).

The last 7-day overlay plot includes data from August 29 through September 4 (fig. 17), the only period when records are available from all four meter types. As previously stated, records for both vertical-axis rotor meters for this period contain erroneous data that probably are due to partial fouling of the rotor. This partial fouling explains some of the data anomalies shown for the vertical-axis rotor meter plot. The same effects resulting from the different wind and water-depth relations discussed above again are evident for the horizontal-axis ducted impeller, vertical-axis rotor, and inclinometer meter records. The record from the electromagnetic meter compares well with the record from the inclinometer at maximum ebb and maximum flood when the windspeed is less than about 5 m/s (first two ebb and flood periods for August 31 and September 1-2); the inclinometer recorded higher speeds than did the electromagnetic meter when windspeed exceeded about 5 m/s (August 30). At slack water, both the electromagnetic and horizontal-axis ducted impeller meters seem to record slack water without any apparent effects due to wave motion (August 30). However, the electromagnetic and horizontal-axis ducted impeller meter records generally differ by 20 to 50 percent during maximum-ebb and maximum-flood periods (first three ebb and flood periods of August 31).

SPEED INTERCOMPARISON PLOTS

Speed intercomparison plots of current-meter data were made by plotting the resultant 30-minute, vector-averaged speed values of one current meter on the x-axis against the corresponding 30-minute, vector-averaged speed values of a second current meter on the y-axis. If the current meters recorded identical speeds, the plotted points fall on a line with a slope equal to 1 and with a y-axis intercept equal to zero. As it is assumed that the flow regime was homogeneous for all deployed meters, systematic differences between meters are indicated if the trend of the data points deviates from a slope of 1 and an intercept of zero. This method of comparison is especially useful for examining the relations between meters at or near slack water. Speed intercomparison plots for the three deployment periods and for the 8-day period when data are available for all four meter types are shown in figure 18. Simple linear regression has been applied to the data shown on the plots. The y-axis intercept (A), the slope (B) of the regression line, and the coefficient of determination (r^2) are shown on each plot. The r^2 value ($0 < r^2 < 1.0$) is used as an indicator of the amount of scatter in the speed readings (the higher the value, the less the scatter). Plots for the same meter type will be discussed first.

Comparisons of horizontal-axis ducted impeller meters: (plot a, deployment 1; plots a, b, and c, deployments 2 and 3) and

Vertical-axis rotor meter 2 compared with vertical-axis rotor meter 1: (plot f, deployment 1; plot j, deployments 2 and 3).

1. Scatter of data is much less for the horizontal-axis ducted impeller meter intercomparison plots (r^2 range of 0.94 to 0.97) than for the vertical-axis rotor meter intercomparison plots (r^2 range of 0.77 to 0.85). There is no apparent pattern to the scatter, which appears about the same throughout the entire speed range.

2. All intercept values for plots comparing the horizontal-axis ducted impeller and vertical-axis rotor meters are close to zero, with a range of -0.15 to 2.5 cm/s.

3. Slopes for plots comparing the horizontal-axis ducted impeller and vertical-axis rotor meters generally are similar, ranging from 0.84 to 0.98.

When meters of the same type are compared, an intercept value near zero and a slope near 1.0 does not necessarily mean that the meters are recording correct values, because both meters should be similarly affected when subjected to the same adverse condition (wave motion). Also, the scatter should not increase significantly near the origin (zero speed); nor should the number of data points decrease substantially near the origin, indicating a lack of readings at the low end of the speed range (slack water).

The higher r^2 values for the horizontal-axis ducted impeller meter intercomparison plots clearly show that under the field conditions of this study, the horizontal-axis ducted impeller meters demonstrated better repeatability than did the vertical-axis rotor meters. As has been previously mentioned, the vertical-axis rotor meters are affected by wind waves, which probably caused the scatter of the speed readings throughout the speed range. The greater overall scatter apparent in the plot of the vertical-axis rotor meter speed data for deployment 3 probably is the result of intermittent fouling, as discussed in the preceding section. Because the comparisons are for meters of the same type, the slopes are expected to be

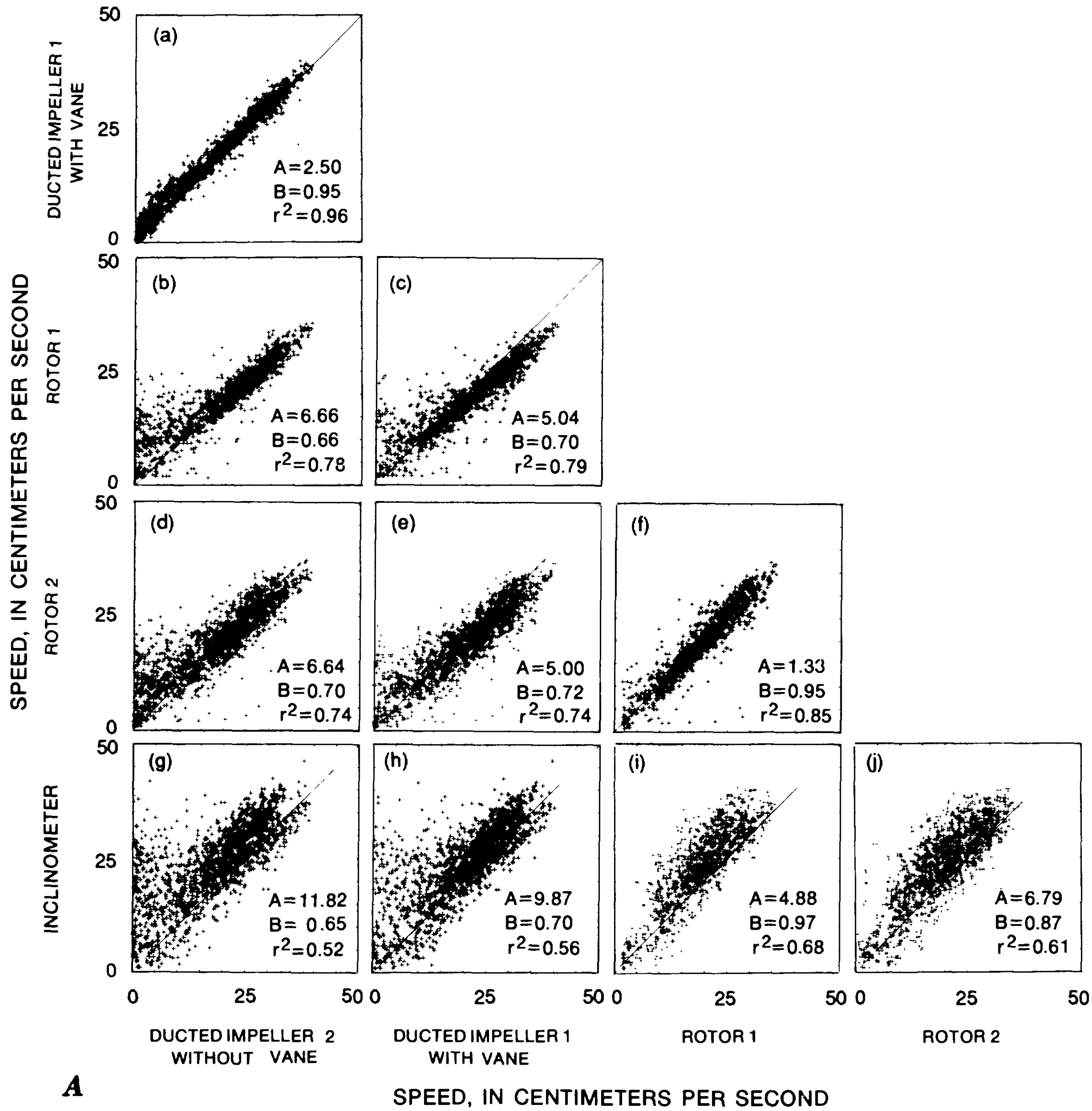


Figure 18. Comparisons of plots of current speed. (A is the intercept, B is the slope, and r^2 is the coefficient of determination). *A*, deployment 1 (June 13-July 11, 1984). *B*, deployment 2 (July 12-August 8, 1984). *C*, deployment 3 (August 9-September 5, 1984). *D*, eight-day period (August 29-September 5, 1984) of deployment 3 when electromagnetic current meter was deployed.

close to 1.0 and the intercepts near zero, and this is the case, except for those plots using horizontal-axis ducted impeller meter 1 data. The cause of the lower slope values is that horizontal-axis ducted impeller meter 1 recorded somewhat lower speed values during deployments 2 and 3 (possibly due to fouling) in comparison with the other horizontal-axis ducted impeller meters (horizontal-axis ducted impeller meter 1 data plotted on y-axis).

Comparing the density of points near the origin on the horizontal-axis ducted impeller and vertical-axis rotor meter plots shows that there are fewer points in this region for the vertical-axis rotor meter plots than for the horizontal-axis ducted impeller meter plots. This density of points again is indicative of the vertical-axis rotor meters' susceptibility to wave motion.

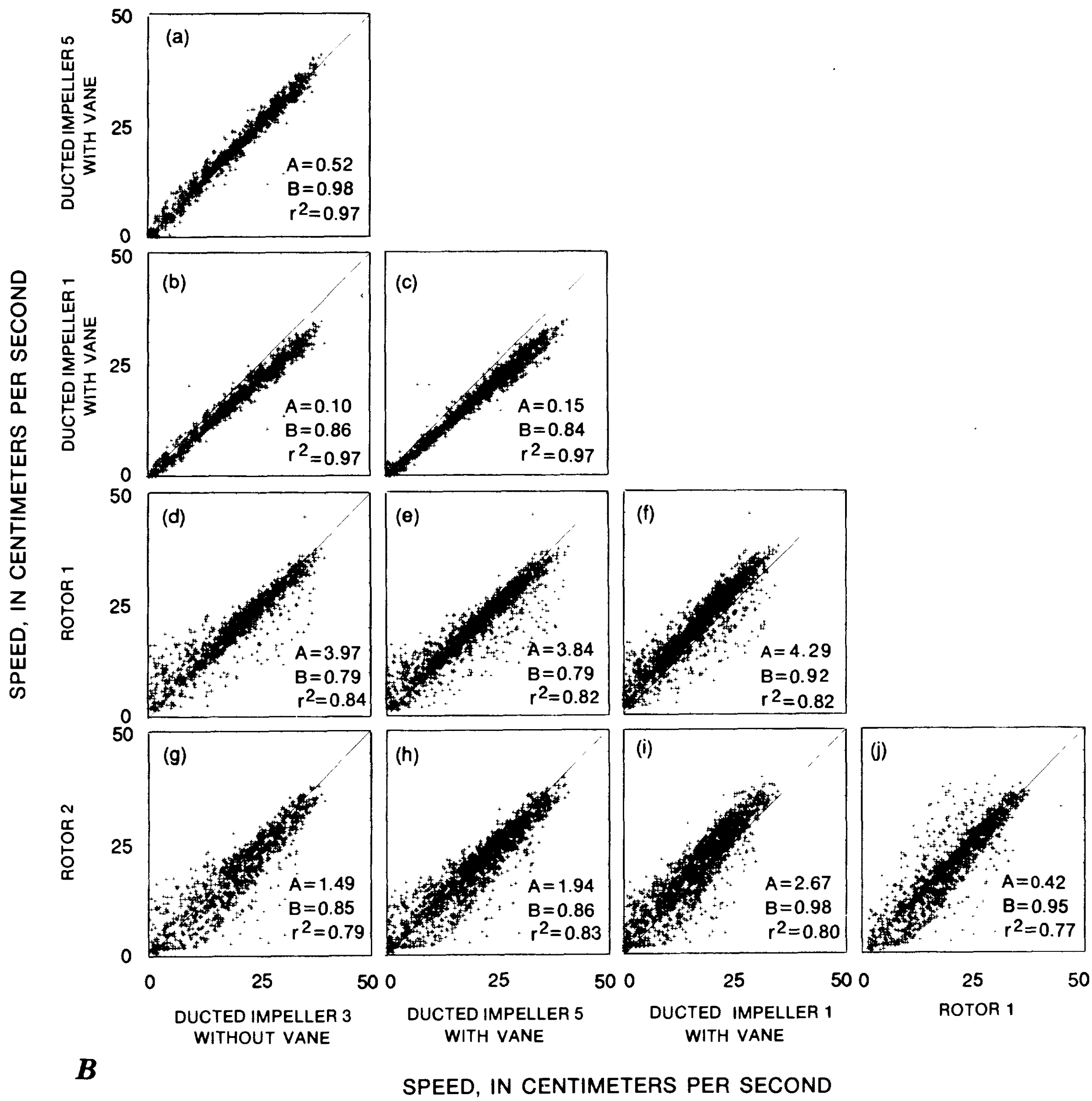


Figure 18.--Continued.

Horizontal-axis ducted impeller meters compared with vertical-axis rotor meters: (plots b through e, deployment 1; plots d through i, deployments 2 and 3). Vertical-axis rotor meter data are plotted on the y-axis.

1. Scatter of data for the plots comparing the horizontal-axis ducted impeller and vertical-axis rotor meters (mean r^2=0.78) is very similar to that for the plots comparing the vertical-axis rotor meters (mean r^2=0.81).

2. Intercept values for plots comparing the horizontal-axis ducted impeller and vertical-axis rotor meters (mean intercept is 3.75 cm/s) are higher than for the plots comparing the two vertical-axis rotor meters and the four horizontal-axis ducted impeller meters.

3. Slopes generally are substantially lower for the plots comparing the horizontal-axis ducted impeller and vertical-axis rotor meters (0.66 to 0.86) than for those plots that compare like

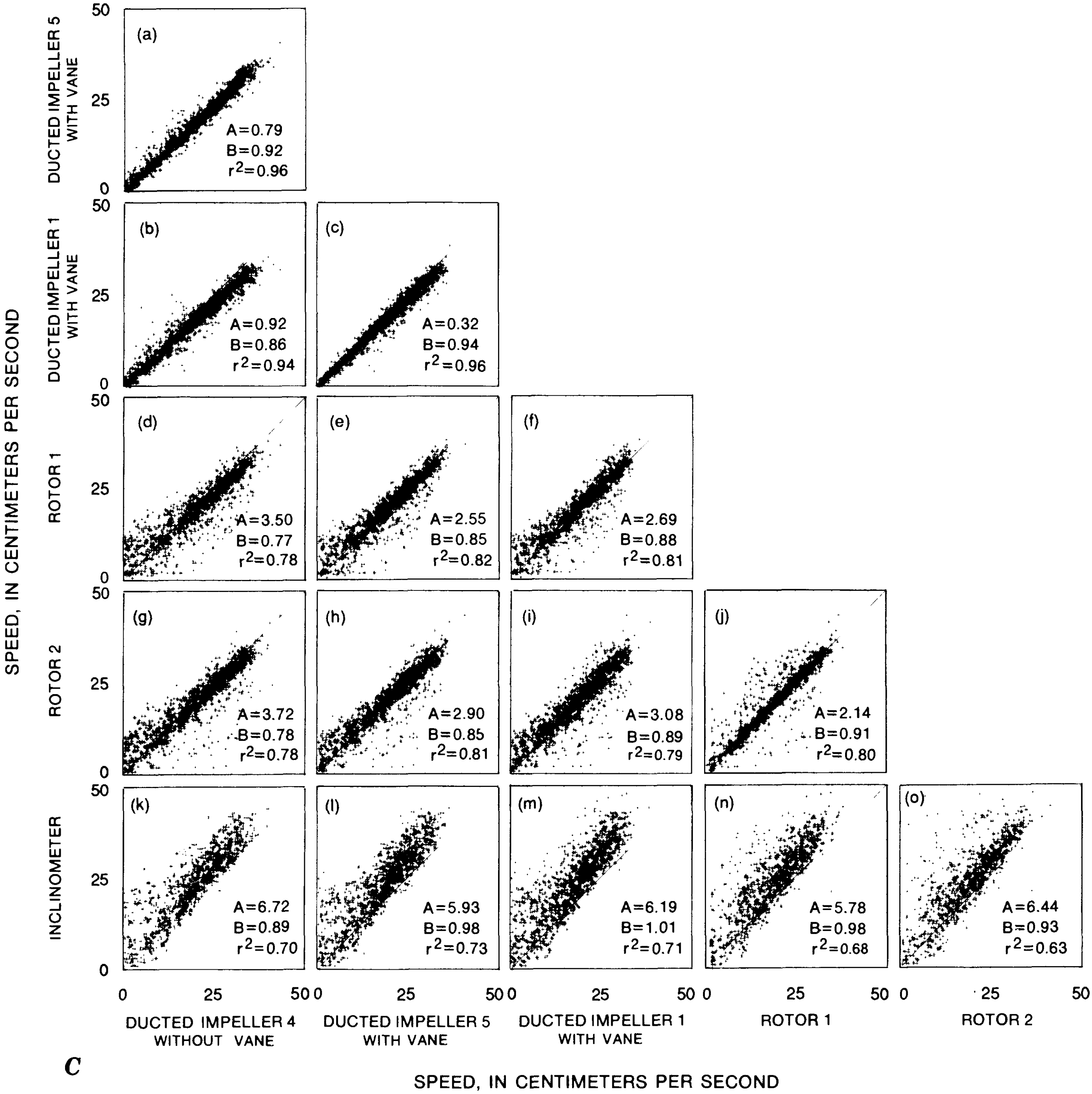


Figure 18.--Continued.

meters. The exceptions are horizontal-axis ducted impeller meter 1 plots, for which slopes ranged from 0.88 to 0.98 for deployments 2 and 3. These values are believed to be erroneously high because horizontal-axis ducted impeller meter 1 was reading low during these deployments.

These results are not surprising, considering the discussion of the time-series plots. The majority of scatter in the plots in the low speed range, and the resulting high intercept values and low slope values are caused by the vertical-axis rotor meters' tendency to record erroneously high speeds in shallow water when subjected to wave motion.

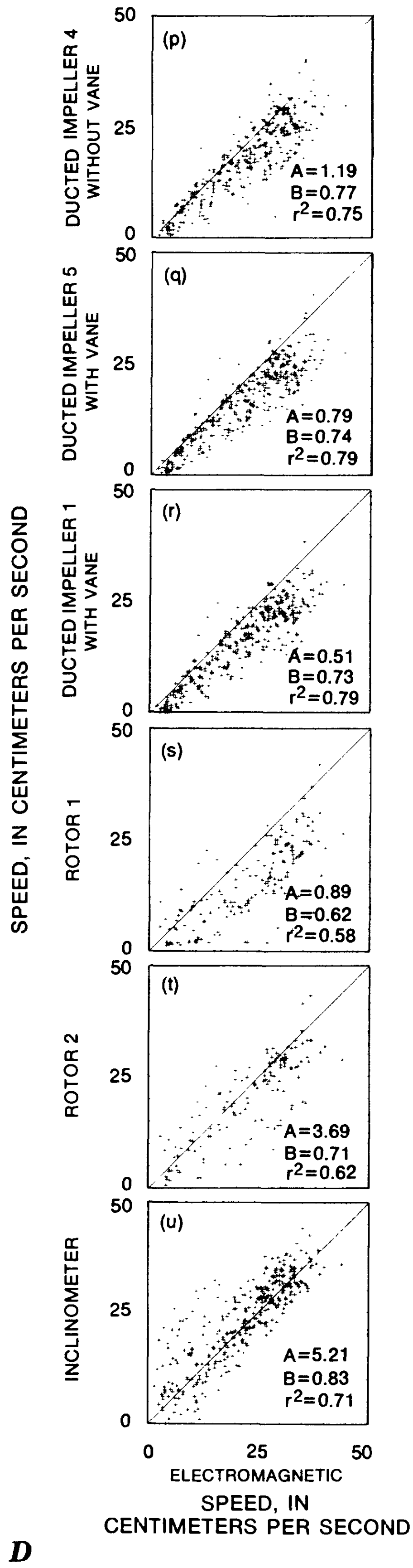


Figure 18.--Continued.

Horizontal-axis ducted impeller meters compared with inclinometer: (plots g and h, deployment 1; plots k, l, and m, deployment 3). Inclinometer data are plotted on the y-axis.

1. Scatter of data for the plots comparing the horizontal-axis ducted impeller meter and inclinometer (mean r^2=0.64) is greater at both low and high speeds than in the plots comparing horizontal-axis ducted impeller and vertical-axis rotor meters.

2. Intercept values (mean intercept is 8.10 cm/s) are about twice those for the horizontal-axis ducted impeller and vertical-axis rotor meters plots comparing for the same two deployments.

3. The mean of the slopes for the plot comparing the horizontal-axis ducted impeller meter and inclinometer is 0.85.

The greater and more evenly distributed scatter and the higher intercept values in comparison with the corresponding values for the plots comparing the horizontal-axis ducted impeller and vertical-axis rotor meters indicate that the inclinometer is affected to a greater extent than is the vertical-axis rotor meter by wind-wave orbital motion when the vertical-axis rotor meter is attached to a fixed mooring platform. The plots also show that the inclinometer was recording higher speed values throughout the entire speed range in comparison with the horizontal-axis ducted impeller meters. (The majority of points are above the slope-equal-to-1.0 line in the high speed range.) This comparison also explains why the slope for the horizontal-axis ducted impeller meters compared to inclinometer plots generally is closer to 1.0 than is the slope for the horizontal-axis ducted impeller compared to vertical-axis rotor meter plots. There is a considerable difference in the mean values of all three variables for deployments 1 and 3. Deployment 1 showed a higher degree of scatter (mean r^2 is 0.54 for deployment 1 and 0.71 for deployment 3), a higher intercept (10.84 compared with 6.28), and a lower slope (0.68 compared with 0.96). All three factors probably are the result of stronger winds during the first deployment than during the third deployment (6.7 and 6.2 m/s average daily windspeed, respectively).

Vertical-axis rotor meters compared with inclinometer: (plots i and j, deployment 1; plots n and o, deployment 3). Inclinometer data are plotted on the y-axis.

1. The scatter of data for the plots comparing the vertical-axis rotor meters and inclinometer (mean r^2=0.65) is virtually the same as for the plots comparing the horizontal-axis ducted impeller meters and inclinometer.

2. The mean of the intercept values for the plots comparing the vertical-axis rotor meters and inclinometer is 5.97 cm/s.

3. The mean of the slopes for the plots comparing the vertical-axis rotor meters and inclinometer is 0.94.

Note that the distribution of points on the speed plots for the vertical-axis rotor meters and inclinometer differs from other meter intercomparison combinations. Most points are grouped near the center of the plot, with relatively fewer points located in the low speed region, and there is more scatter in the midspeed and high-speed ranges. This would tend to reinforce the conclusion that under these field conditions, both the inclinometer and vertical-axis rotor meters are reacting to wind-wave conditions by recording values that are too high, and that the inclinometer is recording speeds generally higher than are the vertical-axis rotor meters. For the third deployment period, values for the mean intercept for the plots comparing the horizontal-axis ducted impeller meters and the vertical-axis rotor meters to the inclinometer are virtually the same (6.28 and 6.11 cm/s, respectively). Likewise, the mean of the slope values are the same (0.96). However, values for the first deployment are very different for these two comparisons. Whereas the intercept (5.84 cm/s) and slope (0.92) values for the plots comparing the vertical-axis rotor meter to the inclinometer are similar to those of deployment 3, the values for the plots comparing the horizontal-axis ducted impeller meter to the inclinometer are very different, as explained in the preceding section. This comparison again indicates that both the inclinometer and vertical-axis rotor meters were reacting to wave motion produced by the higher winds during the first deployment.

Electromagnetic meter intercomparison plots: Six speed intercomparison plots (plots p through u, deployment 3) were generated from a subset of data for deployment 3 for the only period (8 days) during the study when data were available from all four meter types. The six plots compare the electromagnetic meter speed readings with the other deployed meters for the period. The electromagnetic meter data are plotted on the x-axis.

1. Scatter of data for the three plots comparing the electromagnetic and horizontal-axis ducted impeller meters is less (r^2 values of 0.75 to 0.79) than for plots comparing the electromagnetic and vertical-axis rotor meters (r^2 values of 0.58 and 0.62) and the electromagnetic meter and inclinometer (r^2 of 0.71).

2. The intercept values for the plots comparing the electromagnetic meter and inclinometer are the highest (5.21 cm/s), followed by electromagnetic compared to vertical-axis rotor (mean value is 2.29 cm/s), and electromagnetic compared to horizontal-axis ducted impeller (mean value is 0.83 cm/s) meters.

3. The slope for the plots comparing the electromagnetic meter and inclinometer is 0.83; the mean of the slopes for the three plots comparing the electromagnetic and horizontal-axis ducted impeller meters is 0.75, and the mean is 0.68 for the two plots comparing electromagnetic and vertical-axis rotor meters.

These data indicate that the horizontal-axis ducted impeller meters compare most consistently with the electromagnetic meter (highest r^2 values); however, the low slope values indicate that the electromagnetic meter was recording higher speed values than the horizontal-axis ducted impeller meters during maximum-flood and maximum-ebb periods. The latter is also the case for the vertical-axis rotor meter plots. The slope for the inclinometer compared to the electromagnetic meter plot is the closest to 1.0 because the inclinometer also records higher speeds during maximum flood and maximum ebb in comparison with the horizontal-axis ducted impeller and vertical-axis rotor meters. It can be deduced that the electromagnetic meter, like the horizontal-axis ducted impeller meter, is not substantially affected by wave motion under these particular deployment conditions. Additionally, the electromagnetic meter tends to record higher speed values than do either the horizontal-axis ducted impeller or vertical-axis rotor meters during periods of higher flows.

HARMONIC-ANALYSIS RESULTS, INCLUDING EULERIAN RESIDUAL

Harmonic-analysis summary sheets from each current-meter record collected during the field study are tabulated in Supplemental Data A. Harmonic analysis was not performed for the 8-day period during deployment 3 when records for all four meter types were available, because of the short period of record. However, harmonic analysis was performed on the entire electromagnetic meter record, which began 8 days before the end of deployment 3 and continued 27 days past the end of deployment 3. Horizontal-axis ducted impeller meter 5 was to have provided a record for comparison with the electromagnetic meter during this period, but the meter was not recovered. Since the record length and field conditions for the electromagnetic meter deployment were similar to those for the other records collected during deployment 3, it reasonably may be assumed that the results of harmonic analysis for the electromagnetic meter record are comparable with the results of the other records analyzed during deployment 3. In fact, harmonic-analysis results for all records for all three deployments are very similar, except as noted below.

For comparison purposes, some of the information on the harmonic-analysis sheets in Supplemental Data A has been given in table 5. This information includes computed root-mean-square (RMS) current speeds, principal current direction, amplitude and phase of the primary tidal constituents, and Eulerian-residual values for each of the different meter records.

The RMS speed value for the inclinometer is about 25 percent higher than the values for the vertical-axis rotor and horizontal-axis ducted impeller meters, and about 15 percent higher than the electromagnetic meter values. These results are consistent with the time-series and speed intercomparison results. For the first deployment, the RMS speed value for horizontal-axis ducted impeller meter 1 is about 6 percent higher than the values for the other horizontal-axis ducted impeller and vertical-axis rotor meters. However, during the following two deployments, the RMS speed values for horizontal-axis ducted impeller meter 1 were 4 to 17 percent lower than the values for the other horizontal-axis ducted impeller meters. Except for the inconsistencies mentioned above, the RMS speed values for the horizontal-axis ducted impeller and vertical-axis rotor meters are in close agreement, even though, as shown in the previous sections, the vertical-axis rotor meter overestimates speed when subjected to wave motion. This apparent discrepancy is because the RMS technique gives less "weight" to low speeds (that is, near slack water) than to higher speeds. Therefore, the vertical-axis rotor meters' overestimations of speed during slack-water periods are not detectable from examination of the RMS speed values. Higher RMS speed values for the inclinometer indicate higher recorded speeds at both high and low current speeds during the tidal cycle.

Examination of the computed principal direction values for the vertical-axis rotor meters shows the approximately 10-degree direction difference that was discussed previously. It seems that vertical-axis rotor meter 2 reads a few degrees high and vertical-axis rotor meter 1 reads a few degrees low relative to the mean for all records. The mean value indicates that the principal ebb/flood direction at the study site is approximately 309/129 degrees true. The approximate 10- and 20-degree differences in principal direction for horizontal-axis ducted impeller meter 2 (deployment 1) and horizontal-axis ducted impeller meter 1 (deployment 3) are substantial differences. These results quantitatively show the direction inconsistencies for these meters that are apparent in the time-series plots. The inclinometer seems to be calculating directions a few degrees lower than the indicated 309/129-degree principal direction. Nevertheless, with the exception of the two horizontal-axis ducted impeller meter records discussed above and one of the vertical-axis rotor meter records, all meters recorded directions during the deployment within the respective meter's accuracy and resolution range of the mean value.

Examination of the tidal constituent shows that the M_2 tidal constituent clearly is dominant, and the average phase angle from all records analyzed is 268 degrees. The range of M_2-phase angles for all the records is 265 to 272 degrees. Because a 1-degree shift in M_2 phase represents only about a 2-minute shift in time, this range is quite narrow and indicates that all meters are measuring similar tidal occurrences at nearly simultaneous times. In reality, the constituent phase angle for any location in an estuary can vary somewhat because of changing meteorological conditions and river inflows. The small variation in phase angles indicates that field conditions were nearly constant during the course of the study. The differences in the major-axis amplitudes for the various constituents from one meter type to another are indicative of the differences in the RMS speeds as measured by the different meter types.

Also included in each harmonic-analysis summary are the results of the time-averaged velocity (Eulerian-residual) computations. Understanding that

Table 5. Summary of current-meter harmonic-analysis results

[Results by meter type and number. cm/s, centimeter per second]

Variable	Horizontal-axis ducted impeller			Vertical-axis rotor		Inclino-meter	Electro-magnetic[2]
	5	1	2,3,4[1]	1	2		
Deployment 1							
Root-mean-square (cm/s)	--	21.8	20.6	20.4	20.7	25.3	--
Principal direction (degrees)	--	130	118	120	131	126	--
M_2 (major) (cm/s)	--	28.2	25.5	26.3	26.5	31.8	--
M_2 (phase) (degrees)	--	266	265	265	270	271	--
K_1 (major) (cm/s)	--	8.5	8.0	7.2	7.6	9.0	--
K_1 (phase) (degrees)	--	38	38	40	41	36	--
Time-average velocity (cm/s)							
East-West	--	1.5	1.6	1.2	0.9	-0.1	--
North-South	--	-1.4	-1.4	-0.7	-2.1	-1.3	--
Deployment 2							
Root-mean-square (cm/s)	22.1	18.6	22.5	21.2	20.9	--	--
Principal direction (degrees)	129	129	129	125	133	--	--
M_2 (major) (cm/s)	28.0	23.9	27.8	27.2	26.2	--	--
M_2 (phase) (degrees)	268	267	265	268	269	--	--
K_1 (major) (cm/s)	7.6	6.5	7.8	7.1	7.0	--	--
K_1 (phase) (degrees)	46	49	55	43	49	--	--
Time-average velocity (cm/s)							
East-West	-1.2	0.6	-0.1	0.8	-0.2	--	--
North-South	-3.8	-0.8	-2.4	-1.2	-1.8	--	--
Deployment 3							
Root-mean-square (cm/s)	20.5	19.6	21.6	19.3	20.0	26.0	22.6
Principal direction (degrees)	129	149	131	124	134	124	130
M_2 (major) (cm/s)	26.0	24.8	24.5	23.6	24.4	32.1	28.7
M_2 (phase) (degrees)	267	265	268	266	267	272	271
K_1 (major) (cm/s)	5.3	4.6	5.6	4.2	4.4	7.3	4.6
K_1 (phase) (degrees)	59	49	65	61	55	53	47
Time-average velocity (cm/s)							
East-West	-0.3	0.9	2.1	0.5	0.3	0.5	0.2
North-South	-2.7	-0.8	-1.4	-0.5	-0.9	-1.6	-1.7

[1]Meter 2 was used for deployment 1, meter 3 for deployment 2, and meter 4 for deployment 3.

[2]Deployment of the electromagnetic meter began late in deployment 3 but extended 27 days past the end of deployment 3; results are assumed comparable with other meter results for deployment 3.

the calculated residuals are at least an order of magnitude smaller than the tidal velocities, and that the values of the residuals are near the accuracy of the current-meter speed sensors, the following results are of interest. For the first deployment, the average of the computed Eulerian residuals of the five current-meter records was 1.0 cm/s east and 1.4 cm/s south. Individual records did not vary substantially from the average--with the possible exception of the inclinometer, which shows an average east/west component toward the west at 0.1 cm/s. The average of the five residual-velocity records for deployment 2 is 0.1 cm/s west and 2.0 cm/s south, again indicating a southerly Eulerian-residual flow. The mean of the Eulerian residuals for the third deployment also is similar; Eulerian-residual flow is primarily south-southeast (0.7 cm/s east and 1.3 cm/s south). None of the records vary substantially from these mean values.

Except for horizontal-axis ducted impeller meter 5, which shows a slightly larger southerly component to the residual flow, only one record (meter 5, deployment 2) shows an Eulerian residual that varied by more than 1.5 cm/s from the mean values of all meters for a given deployment. Examination of the time-series plot for that record indicates that this is the result of numerous ebb flows that were recorded as more westerly than northwesterly. The uniformity of the southerly residual flow indicates a consistency of the field conditions, in addition to the basic consistency in meter measurement, averaged over the record length. It is of interest to note that even with some known errors in current-direction information, and the given speed accuracy of the current meters, computed long-term Eulerian residuals are similar to preliminary model results. Cheng and Gartner (1984, 1985) determined that Eulerian-residual circulation patterns in the vicinity of the shallow-water study site as determined by a mathematical model were generally to the southeast when a 5 m/s westerly wind was applied to the model. Residual patterns were northwest at that location under no-wind conditions.

COMPARISON OF HORIZONTAL-AXIS DUCTED IMPELLER CURRENT METERS WITH AND WITHOUT VANE ADDITION

As stated previously, the horizontal-axis ducted impeller meter has demonstrated a directional-response problem when tethered. Even though the meters used in this study were rigidly mounted, a vane extension was added to some horizontal-axis ducted impeller meters to see if the vane might increase the meter's response to current-direction changes at low speeds. Table 6 is a tabulation of 2-minute-interval current speeds as recorded by all horizontal-axis ducted impeller meters at slack water and at times of current reversals during three neap-tide slack-water periods. Neap-tide periods were chosen because weaker flow velocities are associated with neap tides--the worst situation encountered for this problem. Also shown in table 6 are the times of estimated slack water, and the time between slack water and a change in meter direction of at least 90 degrees from the previous principal direction. When the meter turn lagged the time of slack water, the time delay and current speed are an indication of the current speed that was required to turn the meter.

The data for June 21-23 indicate that meter 1 (with vane) generally responded to a change in current direction more quickly and at a lower current speed than did meter 2 (without vane). Meter 1 led meter 2 about 75 percent of the time, and the meters turned within 2 minutes of each other about 25 percent of the time.

The results are not as straightforward for the July 22-24 data for three meters--two with added vane and one without. One meter with the added vane (meter 5) seemed to respond most quickly (of the three) to current-direction changes; however, the meter without the added vane (meter 3) responded before the other meter with the added vane (meter 1). For about 60 percent of the tidal reversals, the lag time was 2 minutes or less for two or all three meters, and each of the meters turned first about the same number of times.

The data for August 19-21 indicate that meter 4 (without vane) responded more quickly to changes in current direction than did the meters with the vanes (meters 1 and 5). Over the period, the meter without the vane addition turned first nearly twice as often (five times) as the other two meters combined. As the speeds recorded by all the meters were low at the time of meter turning and the length of low (or zero-recorded) flow was generally long, these results would seem to indicate that the added vane either makes no difference or makes little difference in how the meter responds to flow-direction changes. Nevertheless, examination of the entire time-series plots (Supplemental Data A) for each deployment does indicate periods when each of the meters without the vane addition responded slowly to current direction changes. Thus, the vane addition results in an overall improvement in the direction response of the meters, although the improvement may not be noticeable over a short period of record.

Table 6. Comparison data for horizontal-axis ducted impeller current meters with and without vane additions

[Time of slack water estimated from lowest speed or midtime of consistent zero-speed readings. Lag time is defined as the time from slack water to a consistent turn of more than 90° from previous flood or ebb direction (assumed to be 309°/129°). A minus lag indicates that turn leads estimated slack-water time. cm/s, centimeter per second]

	Estimated time of slack water			Lag time (minutes)			Speed at time of turning (cm/s)			Speed at slack water (cm/s)		
	Without added vane	With added vane		Without added vane	With added vane		Without added vane	With added vane		Without added vane	With added vane	
Meter	2	--	1	2	--	1	2	--	1	2	--	1
June 21	0530	--	0536	18	--	12	0	--	1	0	--	0
	1124	--	1124	-2	--	-4	5	--	4	5	--	4
	1900	--	1854	26	--	16	5	--	5	0	--	3
June 22	0032	--	0052	-20	--	-8	3	--	2	2	--	0
	0630	--	0634	44	--	34	7	--	3	0	--	0
	1216	--	1216	-14	--	-6	3	--	3	2	--	1
	1918	--	1922	36	--	12	5	--	5	0	--	3
June 23	0130	--	0144	-14	--	-12	3	--	0	0	--	0
	0750	--	0800	24	--	10	2	--	1	0	--	0
	1318	--	1320	-8	--	-6	4	--	5	3	--	4
	2012	--	2002	28	--	16	3	--	4	0	--	2
Meter	3	5	1	3	5	1	3	5	1	3	5	1
July 22	0102	0112	0106	2	-4	2	1	0	0	0	1	0
	0710	0712	0708	6	8	16	0	0	0	0	0	0
	1218	1224	1224	-2	-4	6	2	3	0	1	2	0
	1844	1850	1852	6	4	-4	1	0	0	0	0	0
July 23	0206	0210	0208	-18	-6	2	4	3	2	1	3	0
	0832	0840	0828	8	2	40	0	0	1	0	0	0
	1336	1334	1334	2	-4	10	0	0	0	0	0	0
	1942	1938	1950	2	18	-2	3	0	2	0	3	0
July 24	0258	0302	0302	-26	-2	-2	3	5	3	10	2	3
	0946	0946	0948	16	10	0	0	0	0	3	0	0
	1406	1416	1406	-2	-16	-4	0	1	0	0	2	0
	2036	2032	2032	2	4	2	0	0	0	3	2	0
Meter	4	5	1	4	5	1	4	5	1	4	5	1
August 19	0526	0528	0532	14	-4	8	2	0	0	0	0	0
	1018	1022	1022	-28	-10	-14	3	1	4	0	0	0
	1720	1740	1740	-18	10	-20	3	3	2	0	4	2
August 20	0018	0020	0016	2	-8	-2	0	2	0	0	1	0
	0658	0704	0704	4	4	4	0	0	0	0	0	0
	1146	1150	1152	4	20	28	0	2	4	0	0	0
	1802	1800	1804	-4	12	-16	0	1	3	0	0	0
August 21	0128	0138	0138	-18	-2	-2	5	3	3	2	3	3
	0818	0824	0826	6	10	8	0	0	0	0	0	0
	1252	1808	1306	-14	10	4	1	2	0	0	0	0
	1900	1916	1902	-14	0	0	1	2	1	0	2	1

SUMMARY AND CONCLUSIONS

The purpose of this study was to compare various types of recording current meters to be used for collection of velocity data in shallow, tidally affected waters under the influence of wind-generated waves (table 7). Four current meters, each having a different type of speed sensor, were field tested at a site in south San Francisco Bay where water depth ranged from 2.0 to 5.1 m, and windspeeds generally were 5 to 10 m/s. The four meters tested were the horizontal-axis ducted impeller, vertical-axis rotor, inclinometer, and the electromagnetic.

The most significant finding of the meter comparison is the effect that water depth and windspeed have on the accuracy of the current-speed values recorded by the different meter types. When conditions were calm (lack of wind waves), all four meter types recorded slack water (near zero speed). However, when windspeed was 5 m/s or greater and the water depth was less than about 3.5 m (current meters were moored at 1.2 m above the bed), wind-induced orbital wave motion often caused speeds recorded by the vertical-axis rotor meters and inclinometer to be substantially higher than the corresponding speeds recorded by the horizontal-axis ducted impeller and electromagnetic meters.

When water depth was greater than 3.5 m, the vertical-axis rotor meters on fixed moorings generally recorded slack water correctly, even at windspeeds of 5 to 10 m/s. However, the inclinometer recorded higher speed values in comparison with the other three meter types during these conditions. When windspeeds exceeded about 10 m/s, the vertical-axis rotor meter also recorded higher speeds, even when water depths were greater than 3.5 m. In another study (Cheng 1978) it was concluded that if the vertical-axis rotor meter were rigidly mounted, wave motion would not have a substantial influence on speed readings. That was found to be true in this study only if the meter had sufficient water depth above it. The inclinometer requires something greater than about 2.5 m of water above the meter to be free of wind-induced contamination of velocity readings. Results of the aforementioned study indicated that the inclinometer recorded accurate speed readings during both calm and windy conditions; however, results of this study indicate that the inclinometer is even more sensitive to wave motion than the vertical-axis rotor meter. The difference in the two studies apparently is a function of water depth; meters were located a minimum of 3 m below the water surface in the other study in comparison with a minimum of only 1 m in this study. The horizontal-axis ducted impeller and electromagnetic meters recorded speeds close to zero at slack water independent of water depth or wind conditions.

Table 7. Summary of characteristics of current meters for wave-zone measurements

[Characteristics refer to meter as tested in this study. <, less than; >, greater than]

Meter characteristics	Meter type			
	Horizontal-axis ducted impeller	Vertical-axis rotor	Inclin-ometer	Electro-magnetic
Moving speed sensor	Yes	Yes	No	No
Subject to fouling	Minor	Major	No	No[1]
Overestimates speed at slack water; windspeed <5 meters per second, water depth >3.5 meters	No	No	No	No
Overestimates speed at slack water; windspeed 5 to 10 meters per second, water depth >3.5 meters	No	No	Yes	No
Overestimates speed at slack water; windspeed >10 meters per second, water depth <3.5 meters	No	Yes	Yes	No
Delay in direction response	Probable	Possible	No	No
Multiple sampling schemes	No	No	Yes	Yes

[1]Fouling of electromagnetic sensors is possible; effect is unknown.

Because current speed (approximate) is known only at slack water, speed values measured by current meters during ebb and flood currents can only be compared relative to each other. As the tide in south San Francisco Bay propagates primarily as a standing wave, maximum currents at the study site occur near time of mean tide elevation (3.7 m). Therefore, the depth of the water above the current meters during these maximum-current periods remains nearly constant and does not vary to the extent that the depth varies for slack-water periods (high and low tide).

During maximum-ebb and maximum-flood periods, the vertical-axis rotor and horizontal-axis ducted impeller meters recorded speeds that were in general agreement, as did the inclinometer and the electromagnetic meter; however, the latter set of meters recorded speeds that were 30 to 50 percent higher than those recorded by the vertical-axis rotor and horizontal-axis ducted impeller meters. To resolve such discrepancies, Price AA current-meter readings were collected; however, inclinometer or electromagnetic meter data were not available for periods when the Price meter data were collected. The Price meter readings generally were high when compared with the horizontal-axis ducted impeller and vertical-axis rotor meter readings, although data were not sufficient to be conclusive. Laboratory tow-tank tests are required to resolve the question of measurement accuracy at higher flow velocities (although tow-tank tests may be subject to their own sources of error, such as tow-tank wall effects and mounting-carriage vibrations). Because the inclinometer readings were consistently higher than the vertical-axis rotor and horizontal-axis ducted impeller meters and approximately equal to the electromagnetic meter readings (dependent on field conditions) throughout the entire speed range encountered at the deployment site, the differences do not seem to be a function of the type of speed wing (that is, low speed or standard) used for the inclinometer.

Other findings of the study are that the use of the mounting-bracket assembly designed for the horizontal-axis ducted impeller meter permitted deployments of the meter within about 0.75 m of the water surface without the use of the tether rope normally used to damp out wind-generated orbital motions. In general, horizontal-axis ducted impeller meters with vane addition responded to current-direction changes more quickly and smoothly than did meters without the vane. Of the two meter types with moving speed sensors, the vertical-axis rotor meters seem to foul at the speed rotor more readily than do the horizontal-axis ducted impeller meters (at least in this highly productive estuarine environment).

In addition to meter accuracy, the reliability of a meter is important. All meters tested were subject to some data loss, except for the electromagnetic meter equipped with solid-state memory. Solid-state memory, a feature available on new or retrofitted horizontal-axis ducted impeller and vertical-axis rotor meters, should eliminate many problems inherent with current meters that use magnetic tape for data storage. Because the electromagnetic meter was deployed only once (in comparison with three times for the other meters) and the deployment-overlap period was just slightly more than 1 week, the meter's durability and data reliability cannot be fully evaluated.

Clearly, no single current meter surpasses the others in all areas evaluated. Under certain field conditions, some special properties are more important than others. In the case of measuring velocities in very shallow water, the ability to record horizontal mean flows while rejecting vertical-flow components from wind-wave-induced orbital water motions is of primary importance.

REFERENCES CITED

Aanderaa Instruments Ltd., 1983, Operating manual: Recording current meter models 4/5: Bergen, Norway, 84 p.

Appell, G.F., and Crump, D.R., 1977, Current measurement sub-system technology assessment, Sensor Test Branch, Test and Evaluation Laboratory, NOAA-Code C651: Rockville, Maryland, unpublished manuscript, 29 p.

Beardsley, R.C., Boicourt, William, Huff, L.C., and Scott, J., 1977, CMICE 76: A current meter intercomparison experiment conducted off Long Island in February-March 1976: Woods Hole Oceanographic Institution Technical Report 77-62, unpublished manuscript, 123 p.

Carter, R.W., and Anderson, I.E., 1963, Accuracy of current meter measurements: American Society of Civil Engineers, Journal of the Hydraulics Division, v. 89, no. HY4, p. 105-115.

Cheng, R.T., 1978, Comparison of a few recording current meters in San Francisco Bay, California, *in* Woodward, W., Mooers, C.N.K., and Jensen, K., eds., Proceedings of a working conference on current measurement, January 11-13, 1978, Technical Report DEL-SG-3-78: University of Delaware, Newark, Delaware, p. 293-301.

Cheng, R.T., and Gartner, J.W., 1980, Working notes on current-meter deployment, recovery, maintenance, and data processing for San Francisco Bay, California: U.S. Geological Survey Open-File Report 80-1297, 71 p.

-----1984, Tides, tidal, and residual currents in San Francisco Bay, California--Results of measurements, 1979-1980, Part 1. Description of data: U.S. Geological Survey Water-Resources Investigations Report 84-4339, 72 p.

-----1985, Harmonic analysis of tides and tidal currents in South San Francisco Bay, California: Estuarine, Coastal and Shelf Science, v. 21, p. 57-74.

Environmental Devices Corporation, 1978, ENDECO Type 174 digital magnetic tape recording tethered current meter; service manual: Marion, Massachusetts, 16 p.

Fuyo Ocean Development Company and Institute of Central Electric Research, 1982, Test report: Current meter comparison test in shallow water under wave conditions (English translation): Japan, 46 p.

General Oceanics, Inc., 1982, Model 6011 MKII current meter instruction manual (preliminary): Miami, Florida, 20 p.

Halpern, David, and Pillsbury, D.R., 1976, Influence of surface waves on subsurface current measurements in shallow water: Limnology and Oceanography, v. 21, no. 4, p. 611-616.

InterOcean Systems, Inc., 1984, Model S4 current meter operation and maintenance manual (preliminary): San Diego, California, 47 p.

Kallio, N.A., 1966, Effect of vertical motion on current meters: U.S. Geological Survey Water-Supply Paper 1869-B, 20 p.

McCullough, J.R., 1978, Near-surface ocean current sensors: Problems and performance, *in* Woodward, W., Mooers, C.N.K., and Jensen, K., eds., Proceedings of a working conference on current measurement, January 11-13, 1978, Technical Report DEL-SG-3-78: University of Delaware, Newark, Delaware, p. 9-33.

Saunders, P.M., 1976, Near-surface current measurements: Deep-Sea Research, v. 23, p. 249-257.

Schureman, Paul, 1940, Manual of harmonic analysis and prediction of tides (reprint with corrections, 1976): U.S. Coast and Geodetic Survey, Special Publication No. 98, 317 p.

Smoot, G.F., and Carter, R.W., 1968, Are individual current-meter ratings necessary?: American Society of Civil Engineers, Journal of the Hydraulics Division, v. 94, no. HY2, p. 391-397.

GLOSSARY

Acoustic release: A submersible device used to relocate and recover oceanographic equipment. The release is moored between an anchor and a subsurface float. When activated electronically, the release separates from the anchor and rises to the water surface because of the buoyancy provided by the subsurface float.

Amplitude: A tidal coefficient corresponding to the height of the equilibrium tidal constituent for a prediction of tide; mean amplitude must be multiplied by the node factor (a longitude of the moon's node).

Bathymetry: The depths of a large body of water with respect to a reference plane.

Binary: Refers to a number system with 2 as its base. A binary number system represents numbers with the digits 0 and 1; successive digits are interpreted as coefficients of successive powers of the base 2.

Burst sampling: A noncontinuous sampling procedure whereby numerous samples are recorded and averaged over a short period of time--with the sampling device activated at a particular sampling interval.

Conductivity: The ability of a substance to conduct an electric current (the inverse of resistance); conductivity measurement provides an indication of ion concentration. Salinity can be calculated from temperature and conductivity.

CMOS static RAM (acronym): A complementary metal-oxide semiconductor device used for random access memory; that is, a semiconductor memory-storage device.

Encoder's bit pattern (horizontal-axis ducted impeller current meter): An encoder is a disk with a pattern of curved slits that allow light to pass through. A photo transistor/light-emitting diode array detects the position of the encoder disk (bit pattern). Current speed is found by determining the displacement of the encoder disk (coupled to the impeller through the end cap via a set of magnets) within the sampling interval.

Epoch (phase or phase lag): Represented by the symbol κ (kappa); the interval between the high-water phase of an equilibrium constituent (theoretical) and the following high water of the corresponding constituent in the actual tide. For predictions, the local longitudinal and time meridians are combined with the local epoch to form a modified epoch, κ' (kappap).

Equilibrium theory: The equilibrium (or gravitational) tide is the theoretical tide that would result if the entire earth were covered with water, and friction and inertia were disregarded. The real tide has tidal constituents that are analogous to, and can be compared with, the equilibrium tide; the periodicity of the tidal constituents are determined from known solar and lunar relations.

Eulerian-residual current: The net (long-term) water motion determined by averaging velocity measurements at a fixed point for at least one tidal cycle.

Fathometer: A sonar instrument used to measure water depths.

Flux-gate magnetometer: A magnetometer in which the degree of saturation of the core by an external magnetic field is used as a measure of the strength of the Earth's magnetic field; used to measure direction of Earth's magnetic field.

Form number: Form number (f) for tides is defined as the ratio of the sum of the amplitudes of diurnal tidal constituents to the sum of the amplitudes of semidiurnal tidal constituents. A simplified definition is $(O_1 + K_1)/(M_2 + S_2)$. For tidal currents (f'), the sum of semimajor axes are used instead of amplitudes. Form number is a measure of the type of tide: $f < 0.25$, tide is semidiurnal; $f > 3.0$, tide is diurnal; and $0.25 < f < 3.0$, tide is mixed.

Hall effect: The development of a transverse electric field in a current-carrying conductor placed in a magnetic field; ordinarily the conductor is positioned so that the magnetic field is perpendicular to the direction of current flow and the electric field is perpendicular to both. The Hall-effect device generates a voltage proportional to the component of the Earth's magnetic field that is parallel to the axis of the device.

Harmonic analysis: A procedure to determine the phase relations and amplitudes (harmonic constants) of various tidal constituents (partial tides) of a known period in an observed tidal or tidal-current record. Various techniques exist to perform this procedure, including least-squares and Fourier methods.

Inclinometer: An instrument used for measuring the angle of tilt of an object from its prescribed reference position.

Mean lower low water (MLLW): In this report, water levels are given in meters above or below the tidal datum of south San Francisco Bay. The datum is the average height of the daily lower low waters over a 19-year period.

Mean water level (MWL): As used in this report mean water level is the average water level between the measured low and high water levels.

Mooring-line motion: Motion of a current-meter mooring line due to the drag effects of wave motion on the submerged float that is used to keep the mooring line vertical. The motion is usually sensed as an erroneous addition to mean current speed.

Principal current direction: The current direction corresponding to the current's ebb and flood direction; calculated by a weighted average of the direction of the major axes of the four partial tidal ellipses (O_1, K_1, M_2, and S_2).

Salinity: Refers to the degree of saltiness of water or, by definition, the total dissolved solids in one kilogram of seawater when all carbonate is converted to oxide, all bromine and iodine are replaced by chlorine, and all organic matter is oxidized.

Salinity stratification: The layering of water of different densities due to salinity differences. Less-dense freshwater entering an estuary tends to ride over the top of denser seawater.

Slack water: The time when the current speed approaches or equals zero; occurs when the current direction changes due to tidal action.

Strain gage: A device that uses the change of electrical resistance of a wire under strain to measure pressure.

Tidal ellipse: The ellipse that results when the position of the head of the tidal-current velocity vector is traced over a tidal cycle.

Well-mixed estuary: The freshwater and seawater within the embayment is mixed so that the water column is vertically homogeneous; no salinity stratification exists.

Zinc-sacrificial anodes: Blocks of zinc that supply an external current that opposes and reverses the naturally occurring corrosion current caused by the oxidation of dissimilar metals in an electrolyte.

(PAGE 39 FOLLOWS)

SUPPLEMENTAL DATA A

Harmonic-Analysis Results and Time-Series Plots of Tidal Velocity

Summary of harmonic-analysis results

Meter type: Horizontal-axis ducted impeller meter 2
Start time of series: 6/13/84 1300 Pst.
Current meter station: 1SW84
Position: 37°37'26"N 122°13'52"W
Water depth: 2.7 m mean lower low water
Meter depth: 1.5 m below mean lower low water
Approximate record length is 52 M_2-cycles

Tidal ellipses of six major constituents

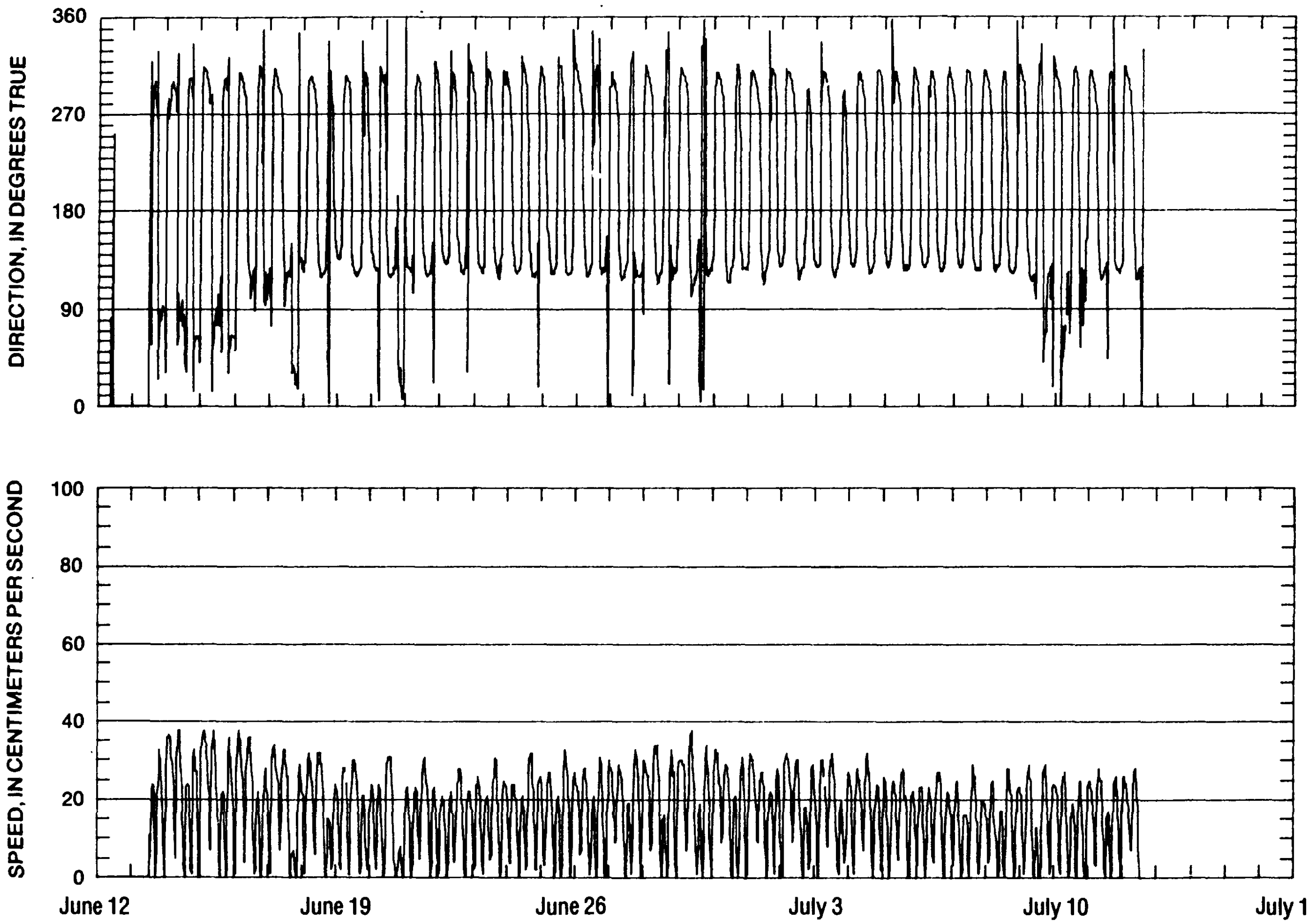
Constituent	Major (cm/s)	Minor (cm/s)	Direction (degrees true)	Phase (degrees)	Rotation
O_1	3.81	0.65	118.6	15.2	Counterclockwise
K_1	8.05	.54	116.3	38.3	Counterclockwise
N_2	2.39	1.39	153.0	296.0	Clockwise
M_2	25.52	1.99	120.8	265.3	Counterclockwise
S_2	3.11	.29	95.5	287.1	Clockwise
M_4	2.51	.82	45.6	143.5	Counterclockwise

Root mean square speed: 20.6 cm/s
Spring tidal current maximum: 40.5 cm/s
Neap tidal current maximum: 18.2 cm/s
Principal current direction: 117.7 degrees true
Tidal form number: 0.41
Standard deviation U-series: 4.15 cm/s
Standard deviation V-series: 5.47 cm/s

Time-averaged velocity

Interval	Number of M_2-cycles	East-West (cm/s)	North-South (cm/s)
1	12	1.6	1.7
2	12	2.5	-3.1
3	12	1.5	-1.8
4	12	.4	-2.9
5	4	3.3	.5
All	52	1.6	-1.4

Time-series plots of tidal velocity
(Observations are 30-minute averages)



Summary of harmonic-analysis results

Meter type: Horizontal-axis ducted impeller meter 1
Start time of series: 6/13/84 1300 Pst.
Current meter station: 1SW84
Position: 37°37'30"N 122°13'52"W
Water depth: 2.4 m mean lower low water
Meter depth: 1.2 m below mean lower low water
Approximate record length is 52 M_2-cycles

Tidal ellipses of six major constituents

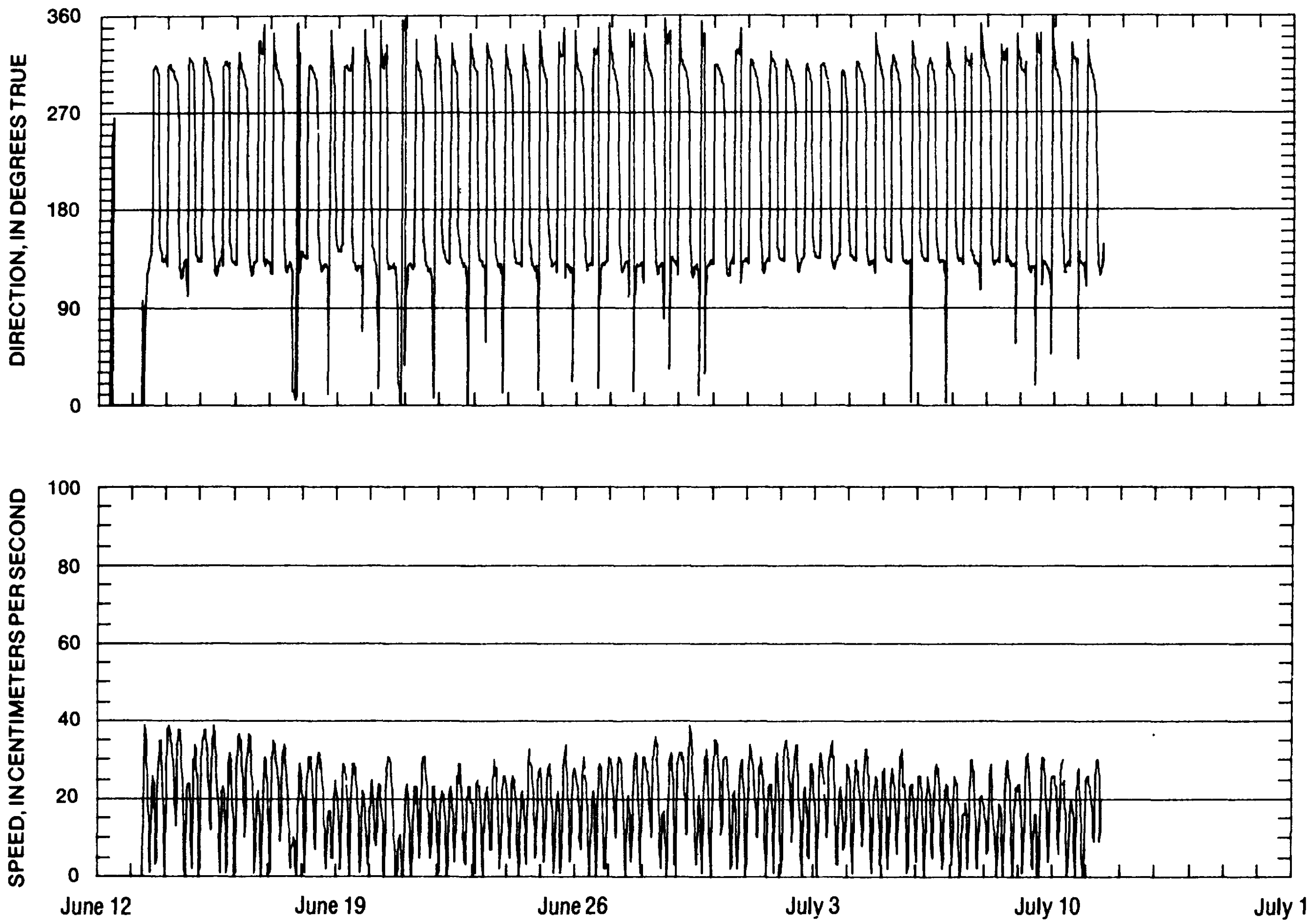
Constituent	Major (cm/s)	Minor (cm/s)	Direction (degrees true)	Phase (degrees)	Rotation
O_1	3.82	0.28	123.5	18.6	Counterclockwise
K_1	8.54	.97	123.0	37.7	Counterclockwise
N_2	2.53	.03	127.8	261.7	Counterclockwise
M_2	28.17	2.83	133.4	265.7	Counterclockwise
S_2	3.38	.30	127.0	287.1	Counterclockwise
M_4	1.95	1.12	88.4	130.3	Counterclockwise

Root mean square speed: 21.8 cm/s
Spring tidal current maximum: 43.9 cm/s
Neap tidal current maximum: 20.1 cm/s
Principal current direction: 130.0 degrees true
Tidal form number: 0.39
Standard deviation U-series: 3.77 cm/s
Standard deviation V-series: 3.46 cm/s

Time-averaged velocity

Interval	Number of M_2-cycles	East-West (cm/s)	North-South (cm/s)
1	12	0.8	-1.5
2	12	2.8	-1.3
3	12	1.5	-.7
4	12	.4	-2.1
5	4	3.2	-1.4
All	52	1.5	-1.4

Time-series plots of tidal velocity
(Observations are 30-minute averages)



Summary of harmonic-analysis results

Meter type: Horizontal-axis ducted impeller meter 3
Start time of series: 7/12/84 1330 Pst.
Current meter station: 2SW84
Position: 37°37'26"N 122°13'52"W
Water depth: 2.7 m mean lower low water
Meter depth: 1.5 m below mean lower low water
Approximate record length is 50 M_2-cycles

Tidal ellipses of six major constituents

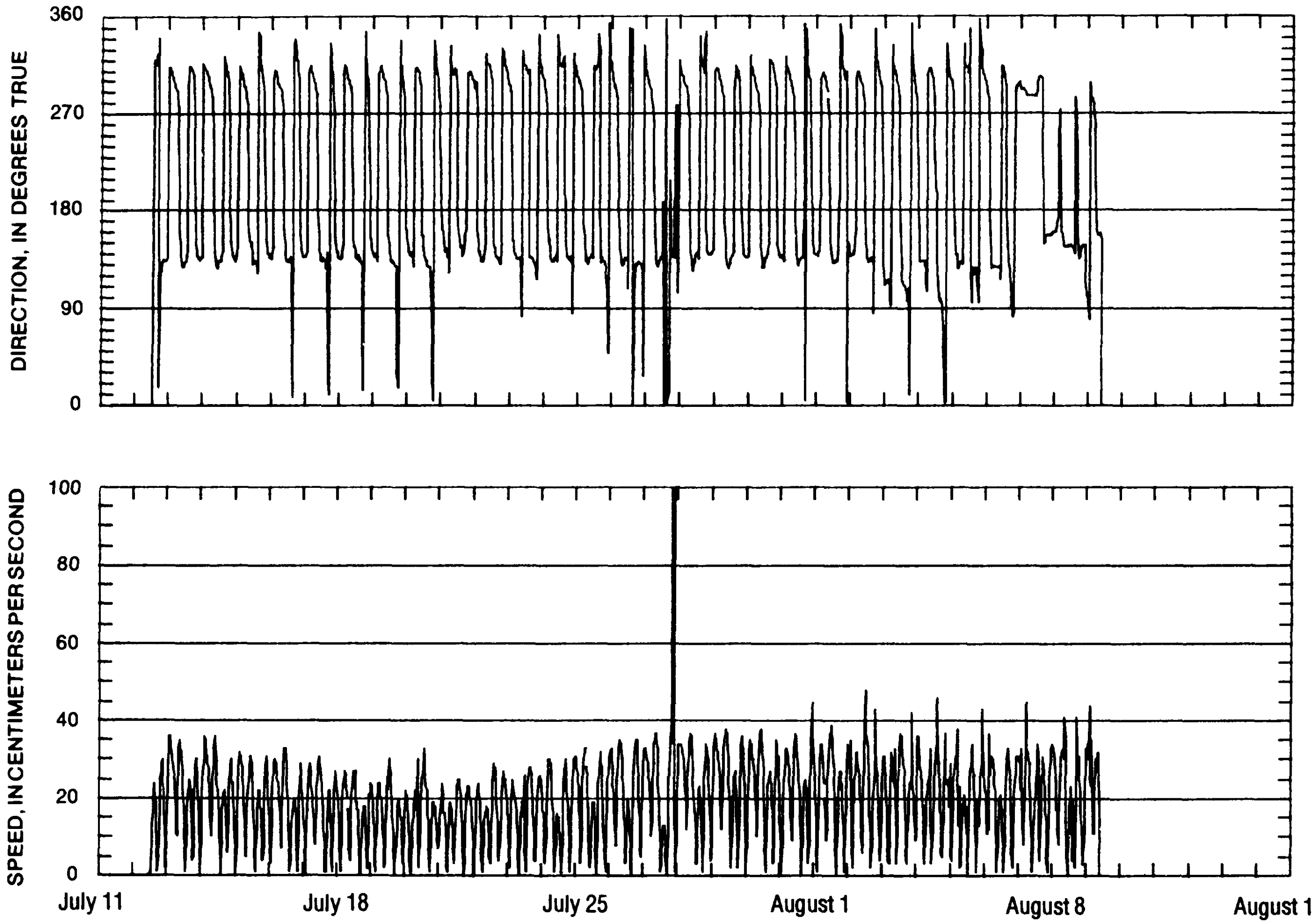
Constituent	Major (cm/s)	Minor (cm/s)	Direction (degrees true)	Phase (degrees)	Rotation
O_1	3.32	0.65	124.3	19.3	Counterclockwise
K_1	7.82	1.71	116.3	55.0	Counterclockwise
N_2	4.72	.44	126.0	283.8	Clockwise
M_2	27.76	3.25	131.1	265.3	Counterclockwise
S_2	4.34	.30	138.4	307.3	Counterclockwise
M_4	2.05	.53	105.0	112.9	Counterclockwise

Root mean square speed: 22.5 cm/s
Spring tidal current maximum: 43.2 cm/s
Neap tidal current maximum: 18.9 cm/s
Principal current direction: 128.6 degrees true
Tidal form number: 0.35
Standard deviation U-series: 5.76 cm/s
Standard deviation V-series: 4.47 cm/s

Time-averaged velocity

Interval	Number of M_2-cycles	East-West (cm/s)	North-South (cm/s)
1	12	-0.8	-2.5
2	12	.4	-2.7
3	12	.1	-3.1
4	12	1.7	-2.5
5	2	-10.6	4.8
All	50	-.1	-2.4

Time-series plots of tidal velocity
(Observations are 30-minute averages)



Summary of harmonic-analysis results

Meter type: Horizontal-axis ducted impeller meter 5
Start time of series: 7/12/84 1330 Pst.
Current meter station: 2SW84
Position: 37°37'29"N 122°13'50"W
Water depth: 2.4 m mean lower low water
Meter depth: 1.2 m below mean lower low water
Approximate record length is 50 M_2-cycles

Tidal ellipses of six major constituents

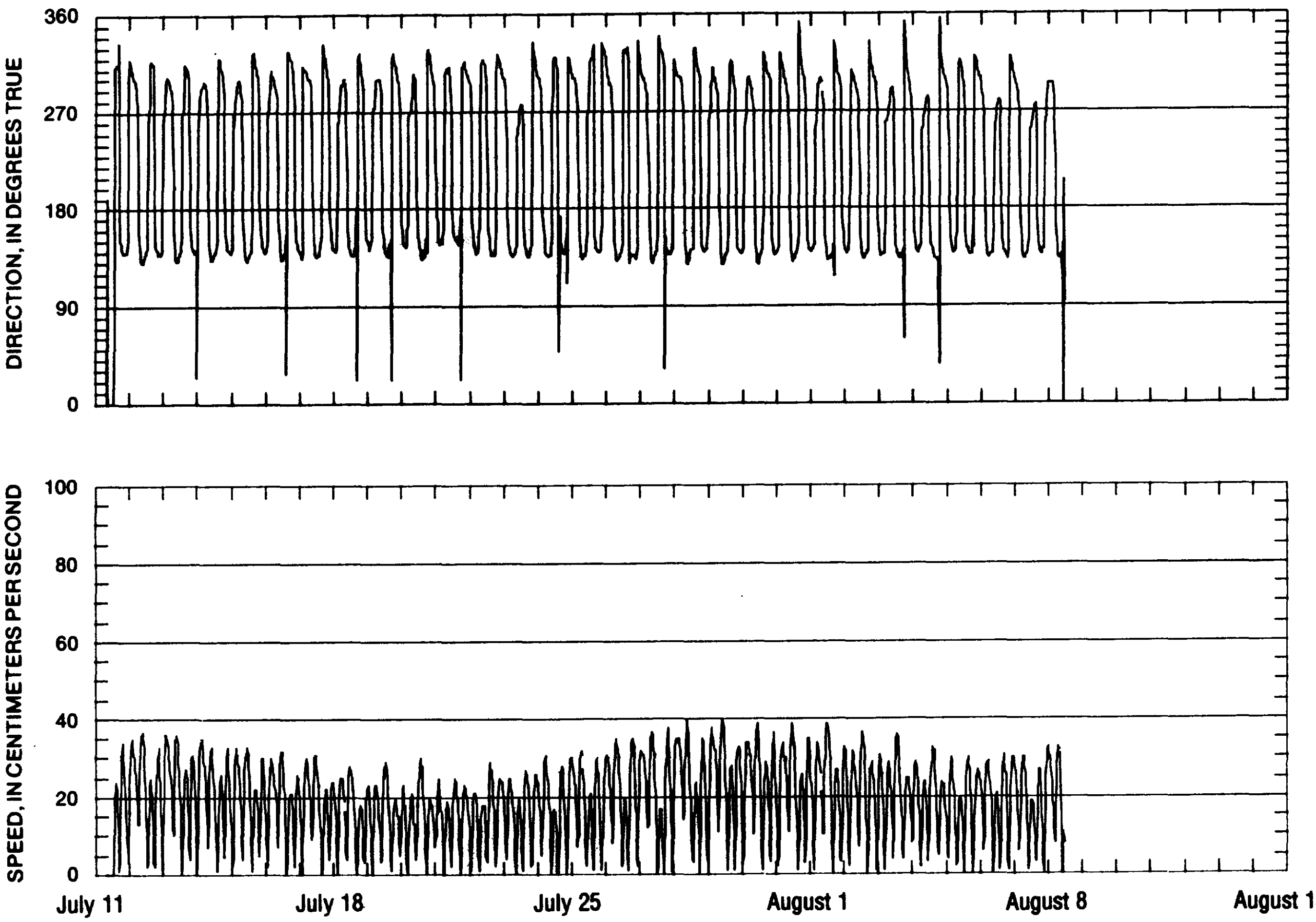
Constituent	Major (cm/s)	Minor (cm/s)	Direction (degrees true)	Phase (degrees)	Rotation
O_1	3.49	0.74	119.3	18.0	Clockwise
K_1	7.58	1.78	120.8	45.8	Counterclockwise
N_2	4.95	.26	129.0	278.7	Clockwise
M_2	27.95	2.18	132.2	268.0	Counterclockwise
S_2	4.78	.20	129.2	302.5	Clockwise
M_4	1.82	.87	121.2	121.5	Counterclockwise

Root mean square speed: 22.1 cm/s
Spring tidal current maximum: 43.8 cm/s
Neap tidal current maximum: 19.1 cm/s
Principal current direction: 128.9 degrees true
Tidal form number: 0.34
Standard deviation U-series: 3.59 cm/s
Standard deviation V-series: 3.56 cm/s

Time-averaged velocity

Interval	Number of M_2-cycles	East-West (cm/s)	North-South (cm/s)
1	12	-2.3	-3.5
2	12	-1.0	-3.4
3	12	-.9	-3.5
4	12	-.7	-4.8
5	2	-2.1	-4.2
All	50	-1.2	-3.8

Time-series plots of tidal velocity
(Observations are 30-minute averages)



Summary of harmonic-analysis results

Meter type: Horizontal-axis ducted impeller meter 1
Start time of series: 7/12/84 1330 Pst.
Current meter station: 2SW84
Position: 37°37'30"N 122°13'50"W
Water depth: 2.4 m mean lower low water
Meter depth: 1.2 m below mean lower low water
Approximate record length is 50 M_2-cycles

Tidal ellipses of six major constituents

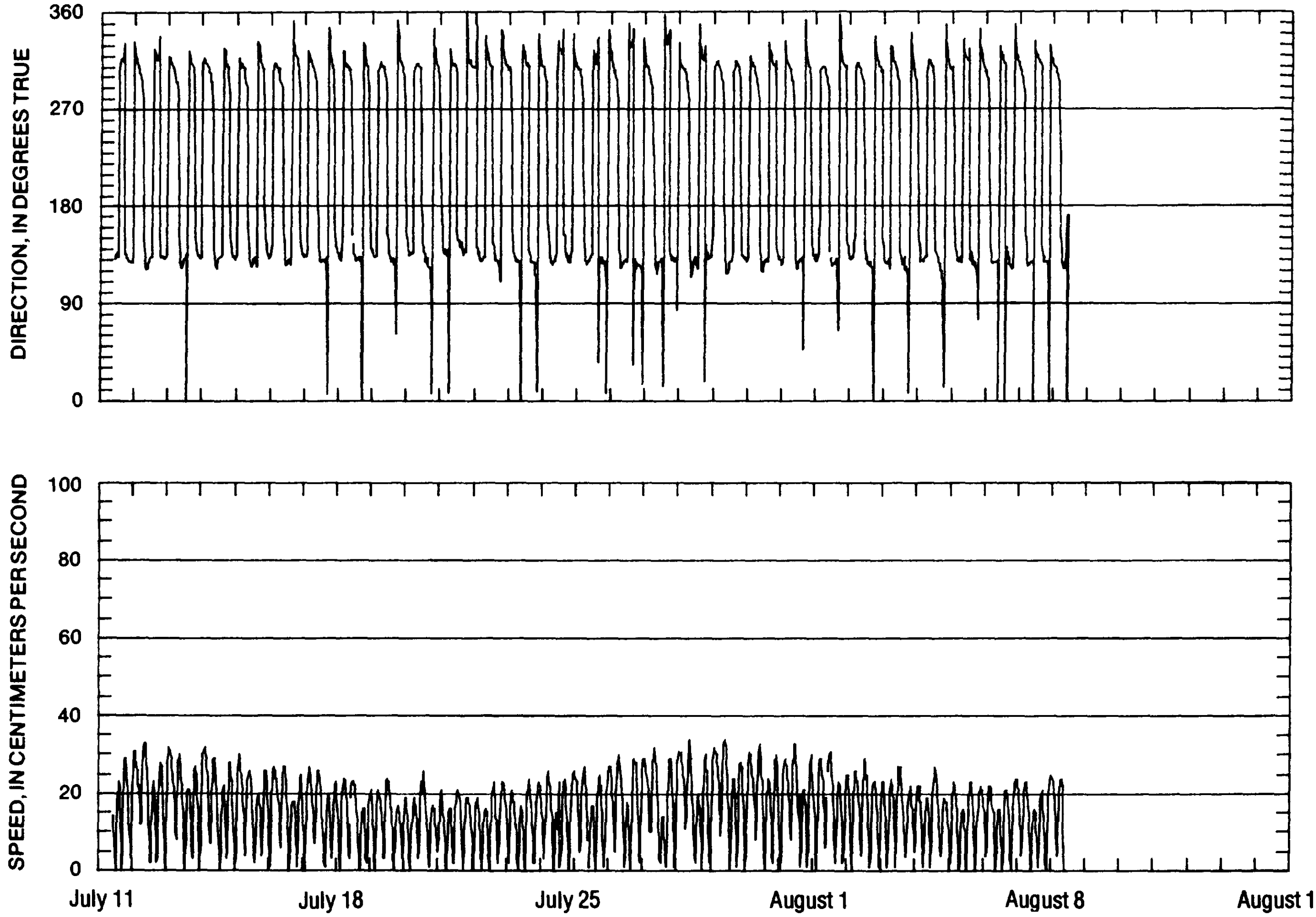
Constituent	Major (cm/s)	Minor (cm/s)	Direction (degrees true)	Phase (degrees)	Rotation
O_1	3.22	0.06	124.7	14.9	Counterclockwise
K_1	6.54	.87	121.7	49.0	Counterclockwise
N_2	3.70	.03	126.5	284.1	Counterclockwise
M_2	23.93	2.33	131.8	267.2	Counterclockwise
S_2	4.25	.17	128.8	300.8	Counterclockwise
M_4	1.69	.98	100.2	121.6	Counterclockwise

Root mean square speed: 18.6 cm/s
Spring tidal current maximum: 37.9 cm/s
Neap tidal current maximum: 16.4 cm/s
Principal current direction: 129.1 degrees true
Tidal form number: 0.35
Standard deviation U-series: 2.98 cm/s
Standard deviation V-series: 2.78 cm/s

Time-averaged velocity

Interval	Number of M_2-cycles	East-West (cm/s)	North-South (cm/s)
1	12	-0.4	-0.7
2	12	.6	-1.1
3	12	.9	-.7
4	12	1.3	-1.0
5	2	.2	.2
All	50	.6	-.8

Time-series plots of tidal velocity
(Observations are 30-minute averages)



Summary of harmonic-analysis results

Meter type: Horizontal-axis ducted impeller meter 4
Start time of series: 8/9/84 1230 Pst.
Current meter station: 3SW84
Position: 37°37'27"N 122°13'52"W
Water depth: 2.7 m mean lower low water
Meter depth: 1.5 m below mean lower low water
Approximate record length is 50 M_2-cycles

Tidal ellipses of six major constituents

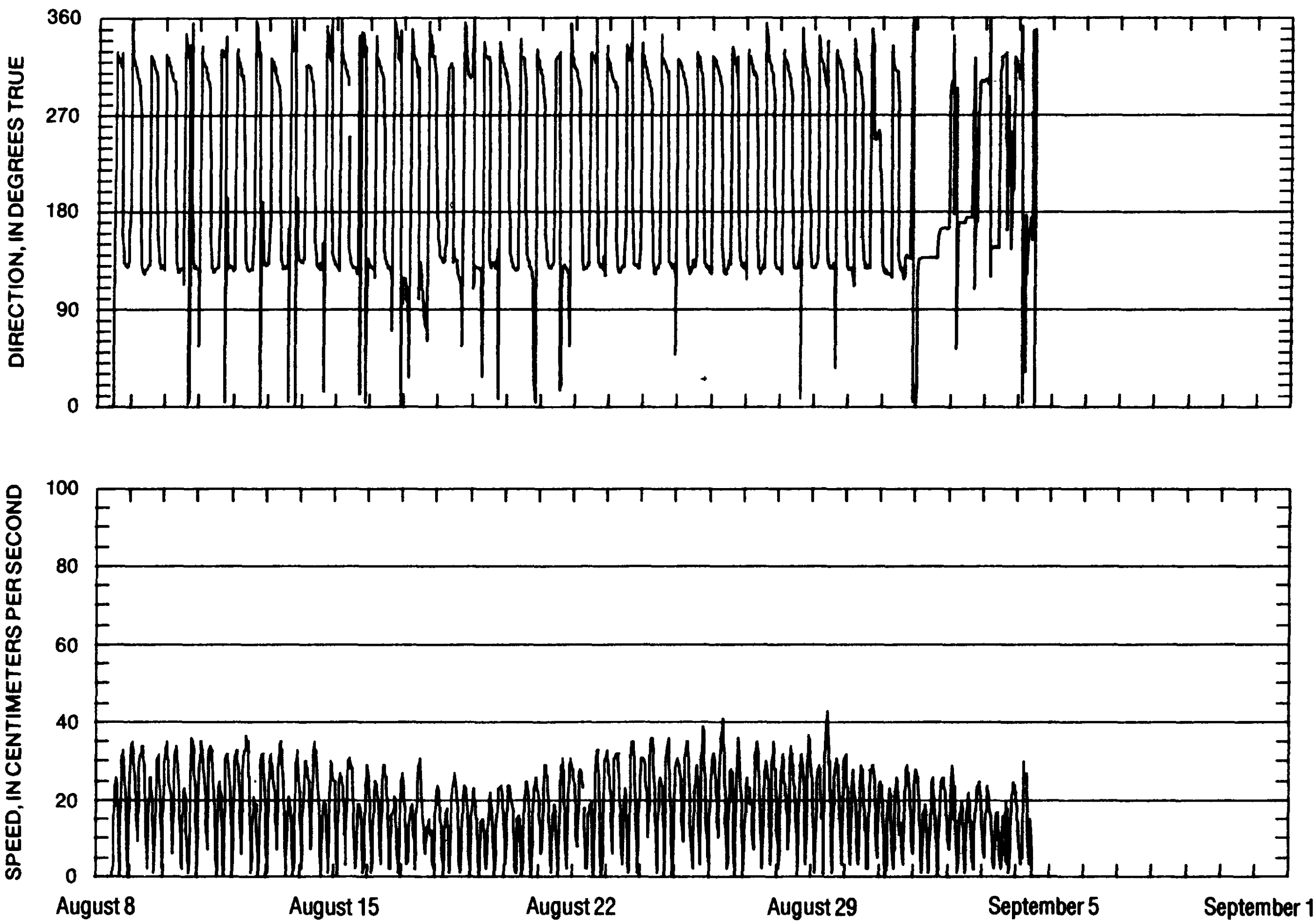
Constituent	Major (cm/s)	Minor (cm/s)	Direction (degrees true)	Phase (degrees)	Rotation
0_1	3.21	0.27	122.6	13.5	Counterclockwise
K_1	5.58	.70	122.7	65.2	Counterclockwise
N_2	5.17	.14	132.2	306.5	Counterclockwise
M_2	24.50	2.05	132.5	268.3	Counterclockwise
S_2	8.68	.87	135.1	287.1	Counterclockwise
M_4	2.41	.74	100.1	126.3	Counterclockwise

Root mean square speed: 21.6 cm/s
Spring tidal current maximum: 42.0 cm/s
Neap tidal current maximum: 13.4 cm/s
Principal current direction: 131.0 degrees true
Tidal form number: 0.26
Standard deviation U-series: 5.82 cm/s
Standard deviation V-series: 6.49 cm/s

Time-averaged velocity

Interval	Number of M_2-cycles	East-West (cm/s)	North-South (cm/s)
1	12	2.1	-0.8
2	12	3.3	-.4
3	12	1.4	-.6
4	12	2.3	-3.4
5	2	-3.2	-4.1
All	50	2.1	-1.4

Time-series plots of tidal velocity
(Observations are 30-minute averages)



Summary of harmonic-analysis results

Meter type: Horizontal-axis ducted impeller meter 5
Start time of series: 8/9/84 1230 Pst.
Current meter station: 3SW84
Position: 37°37'29"N 122°13'50"W
Water depth: 2.4 m mean lower low water
Meter depth: 1.2 m below mean lower low water
Approximate record length is 50 M_2-cycles

Tidal ellipses of six major constituents

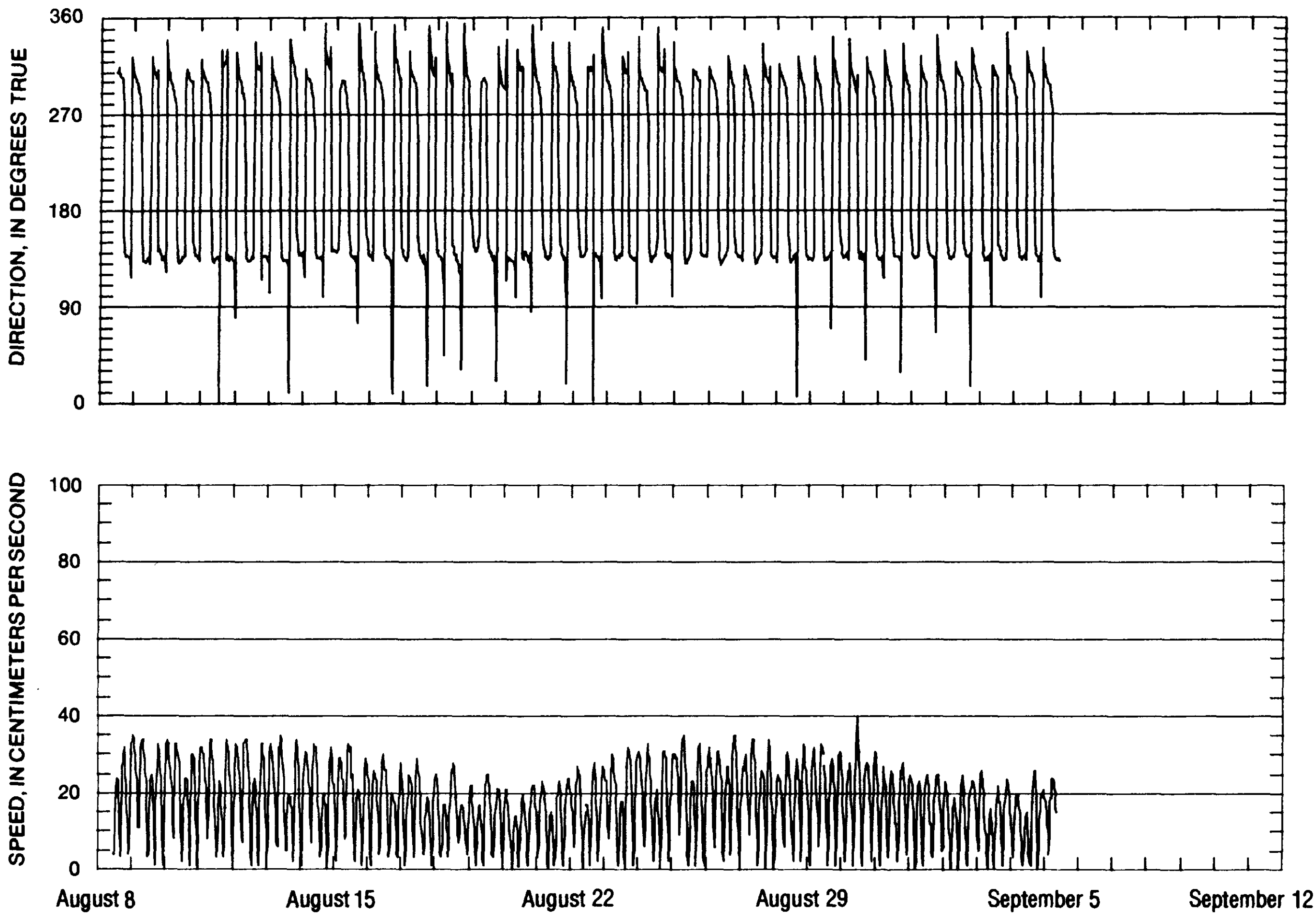
Constituent	Major (cm/s)	Minor (cm/s)	Direction (degrees true)	Phase (degrees)	Rotation
0_1	3.27	0.11	117.3	18.4	Counterclockwise
K_1	5.26	1.28	118.3	59.0	Counterclockwise
N_2	3.68	.09	128.5	274.9	Counterclockwise
M_2	26.03	2.74	131.9	266.8	Counterclockwise
S_2	6.31	.05	132.2	293.5	Counterclockwise
M_4	1.55	.35	122.7	103.7	Clockwise

Root mean square speed: 20.5 cm/s
Spring tidal current maximum: 40.9 cm/s
Neap tidal current maximum: 17.7 cm/s
Principal current direction: 129.0 degrees true
Tidal form number: 0.26
Standard deviation U-series: 3.39 cm/s
Standard deviation V-series: 3.31 cm/s

Time-averaged velocity

Interval	Number of M_2-cycles	East-West (cm/s)	North-South (cm/s)
1	12	-0.4	-3.1
2	12	.9	-2.5
3	12	-.8	-2.9
4	12	-.9	-2.4
5	2	-.9	-1.5
All	50	-.3	-2.7

Time-series plots of tidal velocity
(Observations are 30-minute averages)



Summary of harmonic-analysis results

Meter type: Horizontal-axis ducted impeller meter 1
Start time of series: 8/9/84 1230 Pst.
Current meter station: 3SW84
Position: 37°37'30"N 122°13'50"W
Water depth: 2.4 m mean lower low water
Meter depth: 1.2 m below mean lower low water
Approximate record length is 50 M_2-cycles

Tidal ellipses of six major constituents

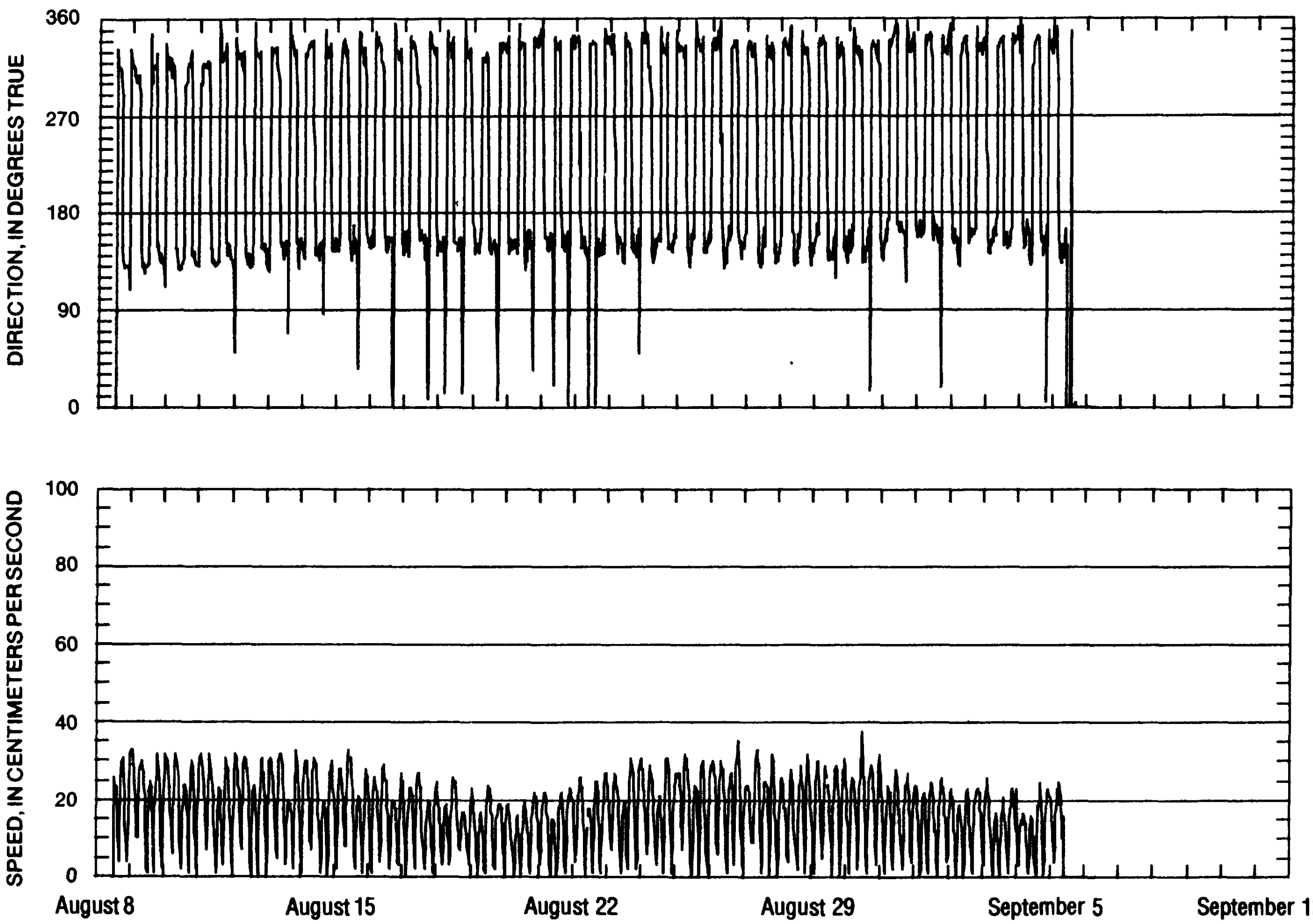
Constituent	Major (cm/s)	Minor (cm/s)	Direction (degrees true)	Phase (degrees)	Rotation
0_1	2.91	0.00	149.8	19.3	Counterclockwise
K_1	4.58	.34	150.9	48.9	Counterclockwise
N_2	3.62	.78	160.8	279.6	Clockwise
M_2	24.82	1.21	150.9	265.2	Counterclockwise
S_2	5.99	.50	139.8	293.1	Clockwise
M_4	1.54	.87	140.3	91.6	Counterclockwise

Root mean square speed: 19.6 cm/s
Spring tidal current maximum: 38.3 cm/s
Neap tidal current maximum: 17.2 cm/s
Principal current direction: 149.1 degrees true
Tidal form number: 0.24
Standard deviation U-series: 3.81 cm/s
Standard deviation V-series: 3.89 cm/s

Time-averaged velocity

Interval	Number of M_2-cycles	East-West (cm/s)	North-South (cm/s)
1	12	1.0	-1.1
2	12	1.1	-1.5
3	12	1.3	-.4
4	12	.4	-.3
5	2	.2	1.0
All	50	.9	-.8

Time-series plots of tidal velocity
(Observations are 30-minute averages)



Summary of harmonic-analysis results

Meter type: Vertical-axis rotor meter 1
Start time of series: 6/13/84 1300 Pst.
Current meter station: 1SW484
Position: 37°37'30"N 122°13'50"W
Water depth: 2.2 m mean lower low water
Meter depth: 1.1 m below mean lower low water
Approximate record length is 42 M_2-cycles

Tidal ellipses of six major constituents

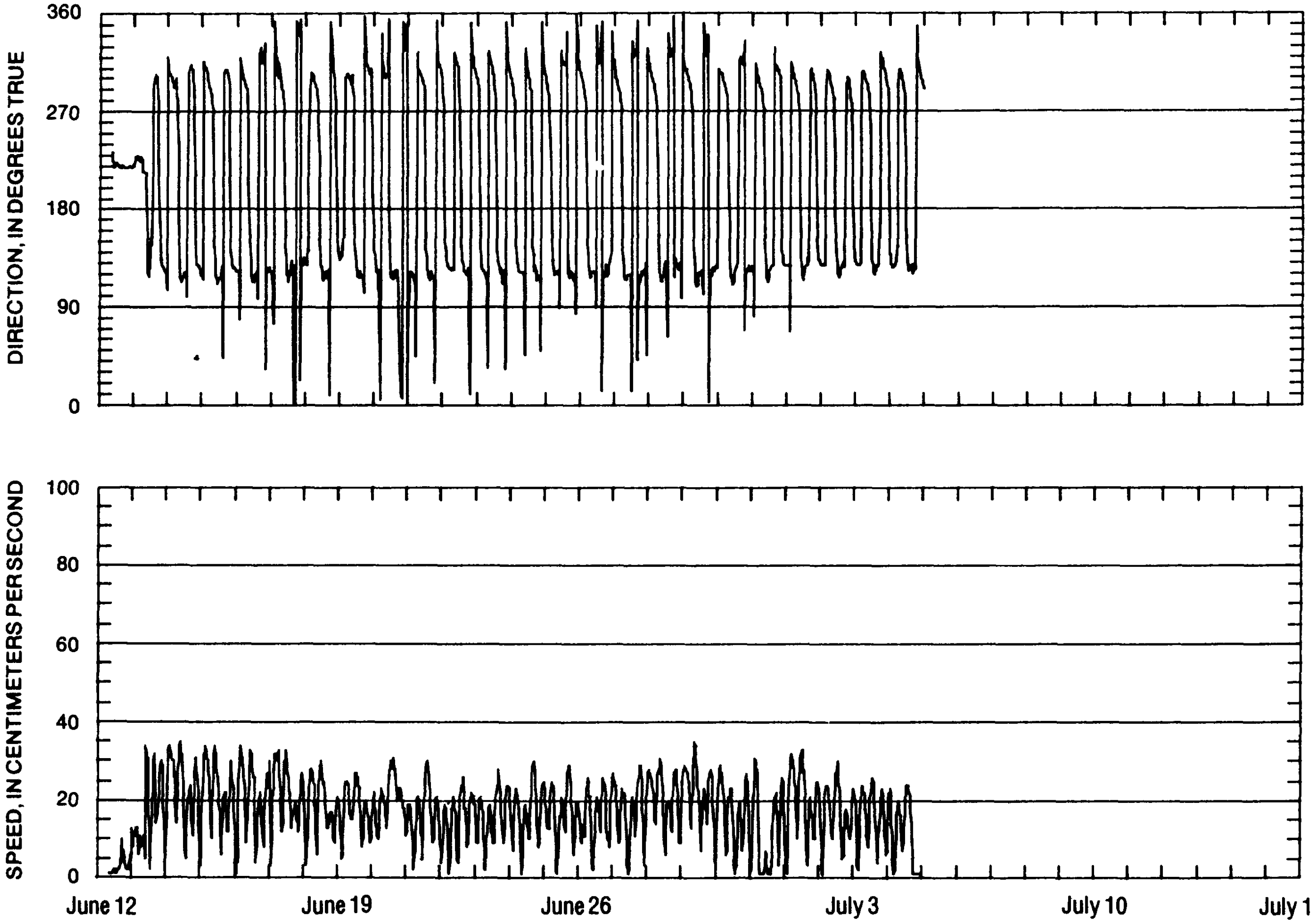
Constituent	Major (cm/s)	Minor (cm/s)	Direction (degrees true)	Phase (degrees)	Rotation
O_1	2.58	0.25	108.3	24.8	Counterclockwise
K_1	7.22	1.15	109.1	39.5	Counterclockwise
N_2	2.79	.62	102.1	217.6	Counterclockwise
M_2	26.29	3.42	125.2	264.6	Counterclockwise
S_2	1.54	.22	107.6	271.0	Clockwise
M_4	1.99	1.50	123.1	70.8	Counterclockwise

Root mean square speed: 20.4 cm/s
Spring tidal current maximum: 37.6 cm/s
Neap tidal current maximum: 20.1 cm/s
Principal current direction: 120.2 degrees true
Tidal form number: 0.35
Standard deviation U-series: 4.92 cm/s
Standard deviation V-series: 4.45 cm/s

Time-averaged velocity

Interval	Number of M_2-cycles	East-West (cm/s)	North-South (cm/s)
1	12	0.8	-1.1
2	12	2.6	-.3
3	12	1.0	.2
4	6	-.3	-2.3
All	42	1.2	-.7

Time-series plots of tidal velocity
(Observations are 30-minute averages)



Summary of harmonic-analysis results

Meter type: Vertical-axis rotor meter 2
Start time of series: 6/13/84 1300 Pst.
Current meter station: 1SW84
Position: 37°37'26"N 122°13'52"W
Water depth: 2.6 m mean lower low water
Meter depth: 1.5 m below mean lower low water
Approximate record length is 52 M_2-cycles

Tidal ellipses of six major constituents

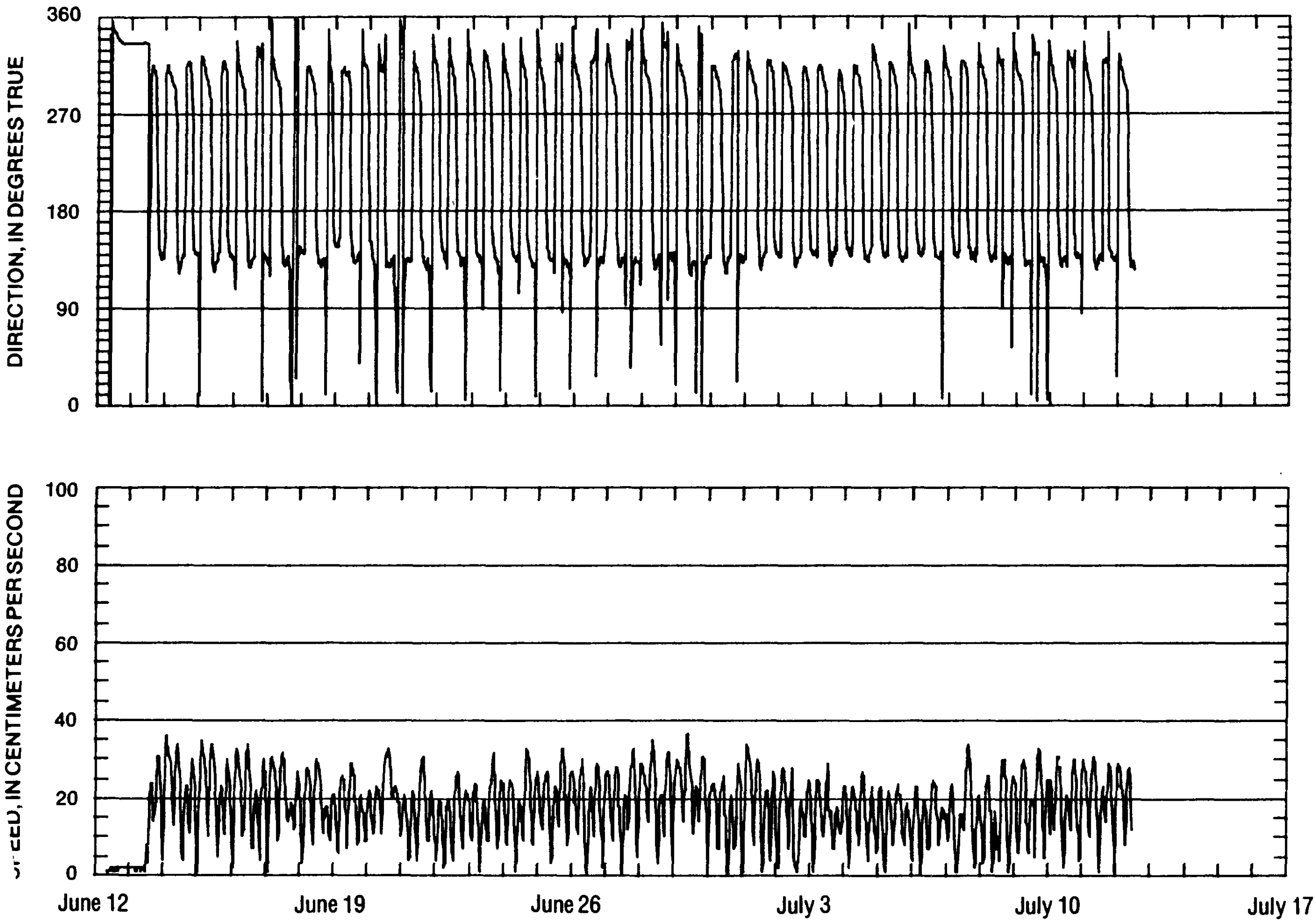
Constituent	Major (cm/s)	Minor (cm/s)	Direction (degrees true)	Phase (degrees)	Rotation
O_1	2.80	0.24	114.8	24.8	Counterclockwise
K_1	7.61	1.31	120.5	41.0	Counterclockwise
N_2	1.52	.01	112.7	247.0	Counterclockwise
M_2	26.54	3.02	136.0	270.4	Counterclockwise
S_2	3.16	.29	126.0	271.8	Counterclockwise
M_4	1.74	1.12	114.7	106.5	Counterclockwise

Root mean square speed: 20.7 cm/s
Spring tidal current maximum: 40.1 cm/s
Neap tidal current maximum: 18.6 cm/s
Principal current direction: 130.8 degrees true
Tidal form number: 0.35
Standard deviation U-series: 4.36 cm/s
Standard deviation V-series: 4.44 cm/s

Time-averaged velocity

Interval	Number of M_2-cycles	East-West (cm/s)	North-South (cm/s)
1	12	-0.2	-2.2
2	12	2.4	-1.9
3	12	.9	-1.3
4	12	-.4	-2.7
5	4	3.1	-3.2
All	52	.9	-2.1

Time-series plots of tidal velocity
(Observations are 30-minute averages)



Summary of harmonic-analysis results

Meter type: Vertical-axis rotor meter 1
Start time of series: 7/12/84 1330 Pst.
Current meter station: 2SW84
Position: 37°37'30"N 122°13'50"W
Water depth: 2.2 m mean lower low water
Meter depth: 1.1 m below mean lower low water
Approximate record length is 50 M_2-cycles

Tidal ellipses of six major constituents

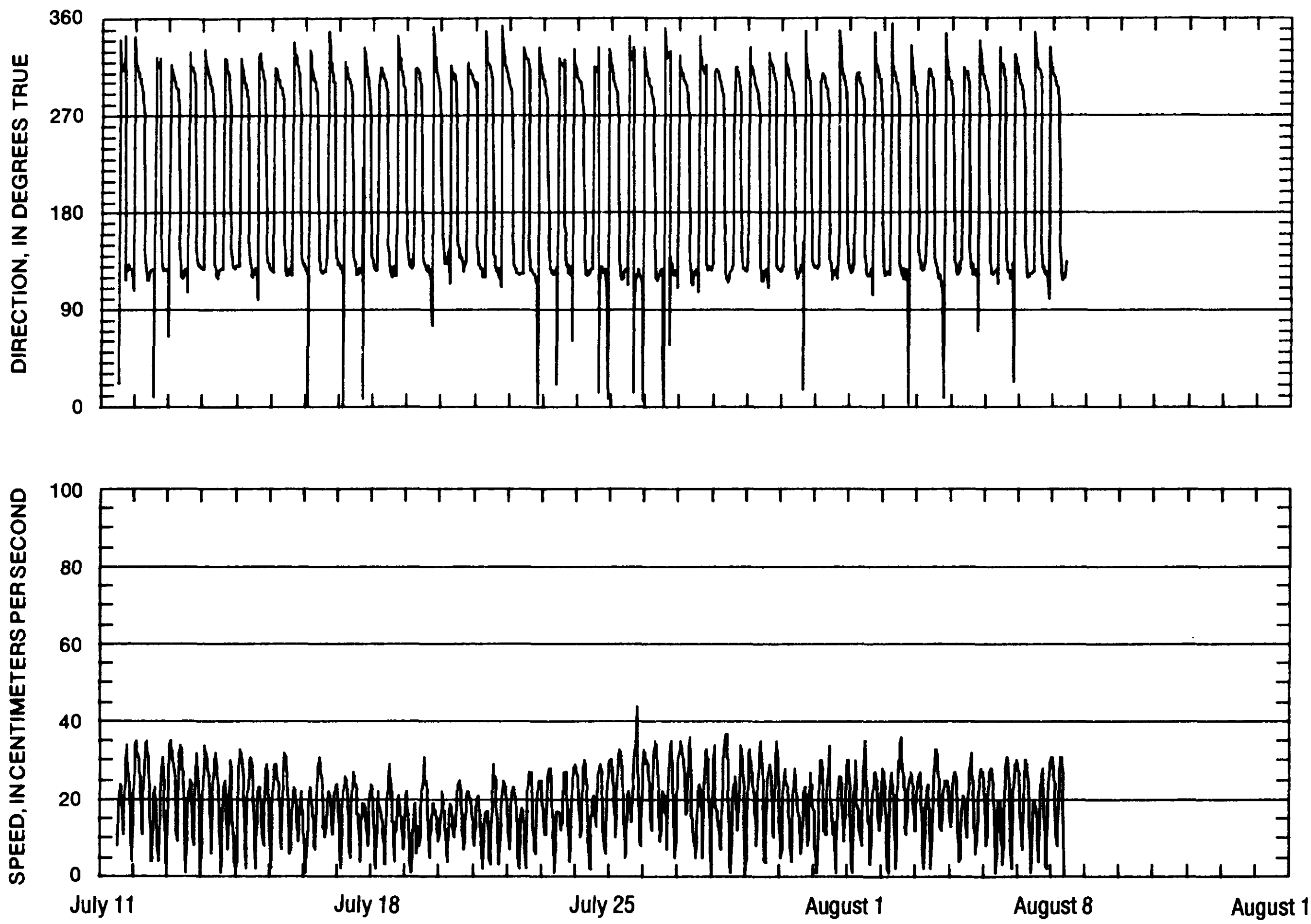
Constituent	Major (cm/s)	Minor (cm/s)	Direction (degrees true)	Phase (degrees)	Rotation
0_1	2.87	0.30	122.5	32.9	Counterclockwise
K_1	7.07	1.17	115.4	43.4	Counterclockwise
N_2	4.13	.05	121.8	273.7	Counterclockwise
M_2	27.17	3.44	128.0	268.1	Counterclockwise
S_2	3.87	.06	127.9	289.8	Counterclockwise
M_4	2.32	1.22	90.0	118.2	Counterclockwise

Root mean square speed: 21.2 cm/s
Spring tidal current maximum: 41.0 cm/s
Neap-tidal current maximum: 19.1 cm/s
Principal current direction: 125.4 degrees true
Tidal form number: 0.32
Standard deviation U-series: 4.34 cm/s
Standard deviation V-series: 3.93 cm/s

Time-averaged velocity

Interval	Number of M_2-cycles	East-West (cm/s)	North-South (cm/s)
1	12	0.0	-0.9
2	12	.9	-1.6
3	12	1.3	-.8
4	12	1.0	-1.5
5	2	.8	-.5
All	50	.8	-1.2

Time-series plots of tidal velocity
(Observations are 30-minute averages)



Summary of harmonic-analysis results

Meter type: Vertical-axis rotor meter 2
Start time of series: 7/12/84 1330 Pst.
Current meter station: 2SW84
Position: 37°37'26"N 122°13'52"W
Water depth: 2.6 m mean lower low water
Meter depth: 1.5 m below mean lower low water
Approximate record length is 50 M_2-cycles

Tidal ellipses of six major constituents

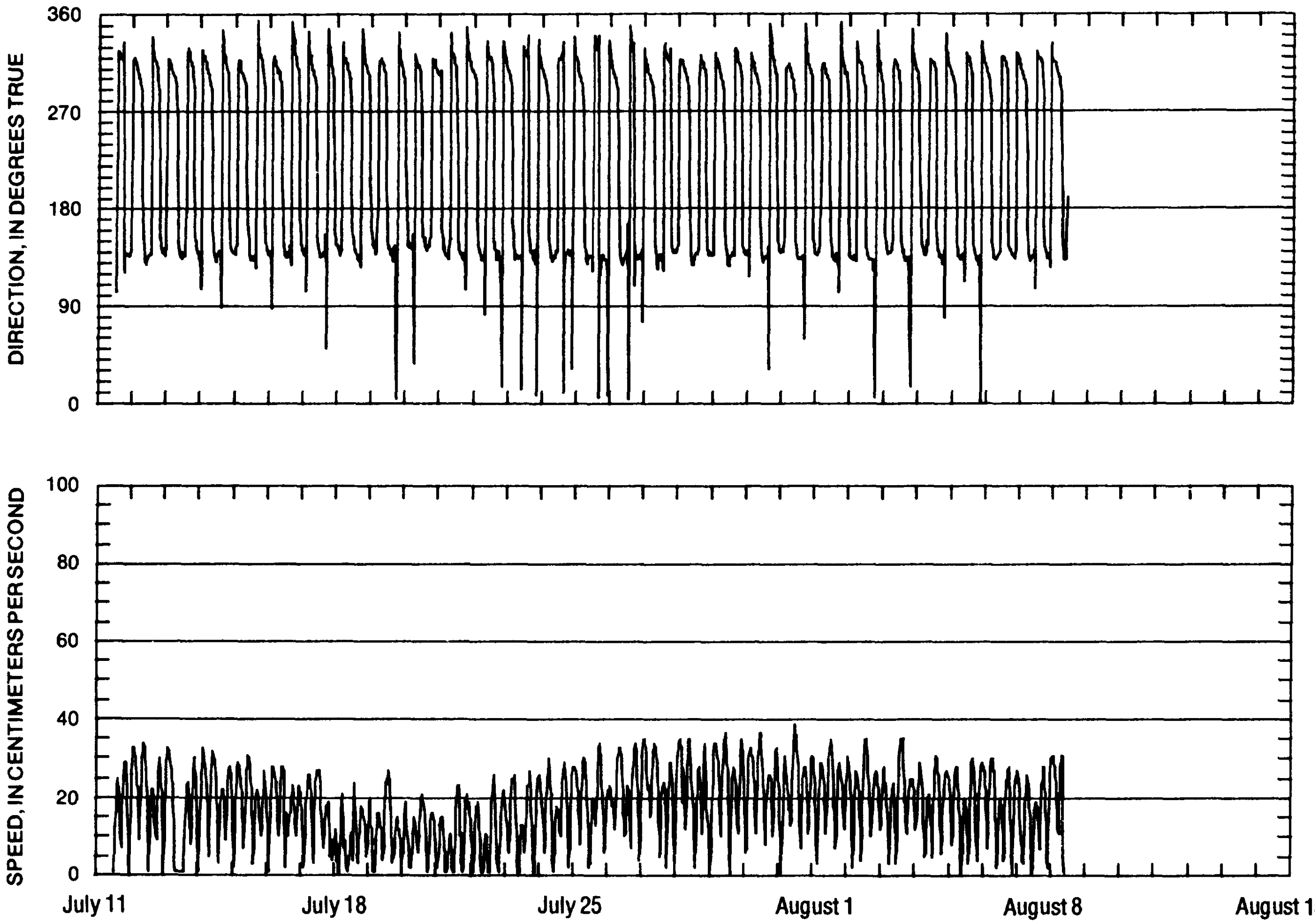
Constituent	Major (cm/s)	Minor (cm/s)	Direction (degrees true)	Phase (degrees)	Rotation
O_1	2.72	0.08	123.8	26.6	Counterclockwise
K_1	7.04	1.25	123.3	49.4	Counterclockwise
N_2	5.81	.41	130.8	267.3	Counterclockwise
M_2	26.20	3.12	136.1	269.2	Counterclockwise
S_2	4.79	.32	136.5	301.2	Counterclockwise
M_4	1.81	.65	107.7	110.1	Counterclockwise

Root mean square speed: 20.9 cm/s
Spring tidal current maximum: 40.7 cm/s
Neap tidal current maximum: 17.1 cm/s
Principal current direction: 133.1 degrees true
Tidal form number: 0.32
Standard deviation U-series: 4.02 cm/s
Standard deviation V-series: 4.38 cm/s

Time-averaged velocity

Interval	Number of M_2-cycles	East-West (cm/s)	North-South (cm/s)
1	12	-1.6	-0.9
2	12	.2	-1.7
3	12	.2	-1.9
4	12	.5	-2.8
5	2	.0	-1.6
All	50	-.2	-1.8

Time-series plots of tidal velocity
(Observations are 30-minute averages)



Summary of harmonic-analysis results

Meter type: Vertical-axis rotor meter 1
Start time of series: 8/9/84 1230 Pst.
Current meter station: 3SW84
Position: 37°37'30"N 122°13'50"W
Water depth: 2.2 m mean lower low water
Meter depth: 1.1 m below mean lower low water
Approximate record length is 50 M_2-cycles

Tidal ellipses of six major constituents

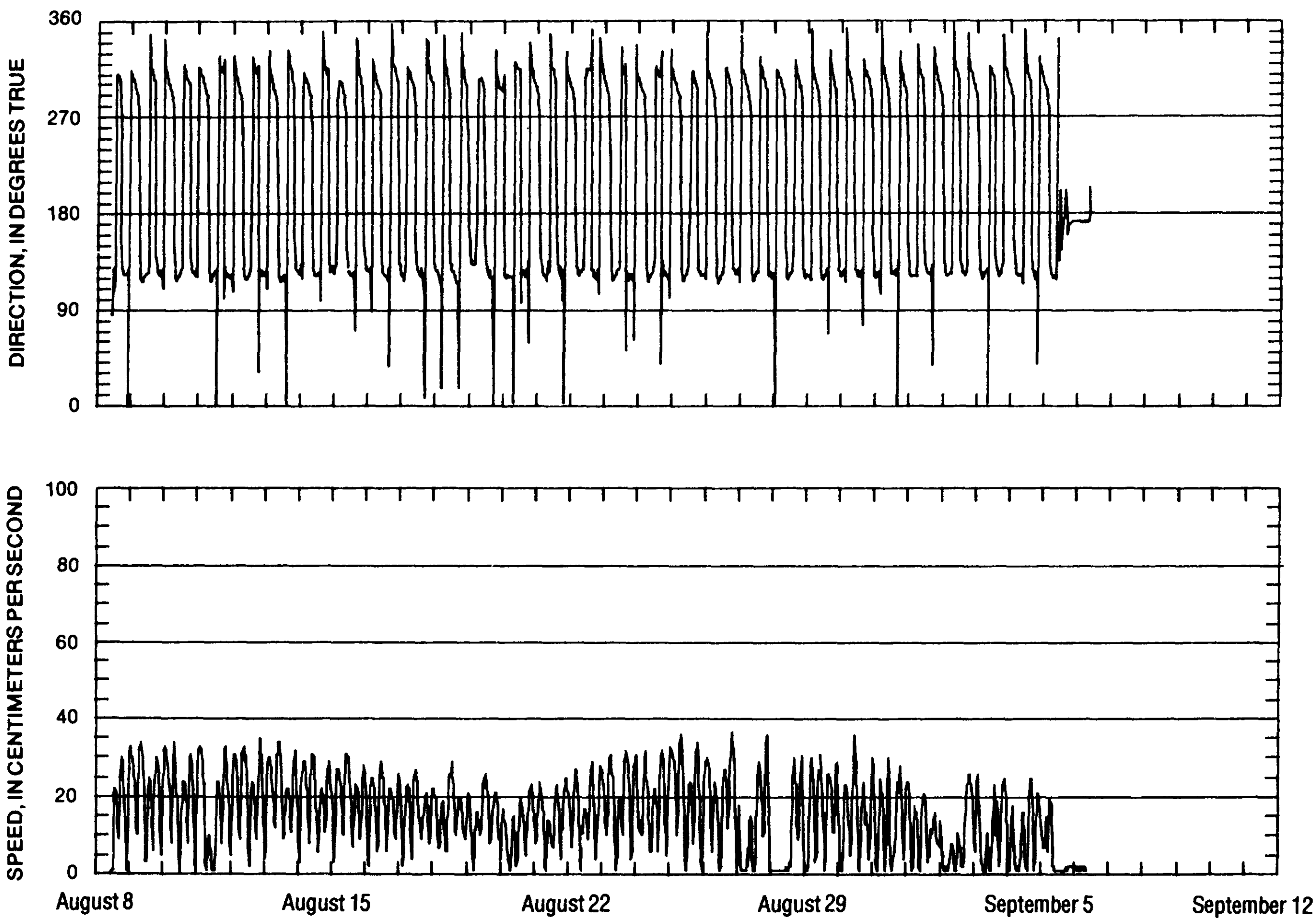
Constituent	Major (cm/s)	Minor (cm/s)	Direction (degrees true)	Phase (degrees)	Rotation
O_1	3.25	0.07	120.3	47.8	Counterclockwise
K_1	4.18	.96	110.5	61.1	Counterclockwise
N_2	1.98	.02	129.7	311.2	Counterclockwise
M_2	23.57	2.71	125.7	266.1	Counterclockwise
S_2	5.32	.03	128.1	292.5	Counterclockwise
M_4	2.28	.75	102.3	102.1	Counterclockwise

Root mean square speed: 19.3 cm/s
Spring tidal current maximum: 36.3 cm/s
Neap tidal current maximum: 17.3 cm/s
Principal current direction: 123.8 degrees true
Tidal form number: 0.26
Standard deviation U-series: 5.82 cm/s
Standard deviation V-series: 4.49 cm/s

Time-averaged velocity

Interval	Number of M_2-cycles	East-West (cm/s)	North-South (cm/s)
1	12	0.3	-0.5
2	12	1.5	-.9
3	12	.9	-1.0
4	12	-.6	.1
5	2	-.5	.4
All	50	.5	-.5

Time-series plots of tidal velocity
(Observations are 30-minute averages)



Summary of harmonic-analysis results

Meter type and number: Vertical-axis rotor meter 2
Start time of series: 8/9/84 1230 Pst.
Current meter station: 3SW84
Position: 37°37'26"N 122°13'52"W
Water depth: 2.2 m mean lower low water
Meter depth: 1.5 m below mean lower low water
Approximate record length is 50 M_2-cycles

Tidal ellipses of six major constituents

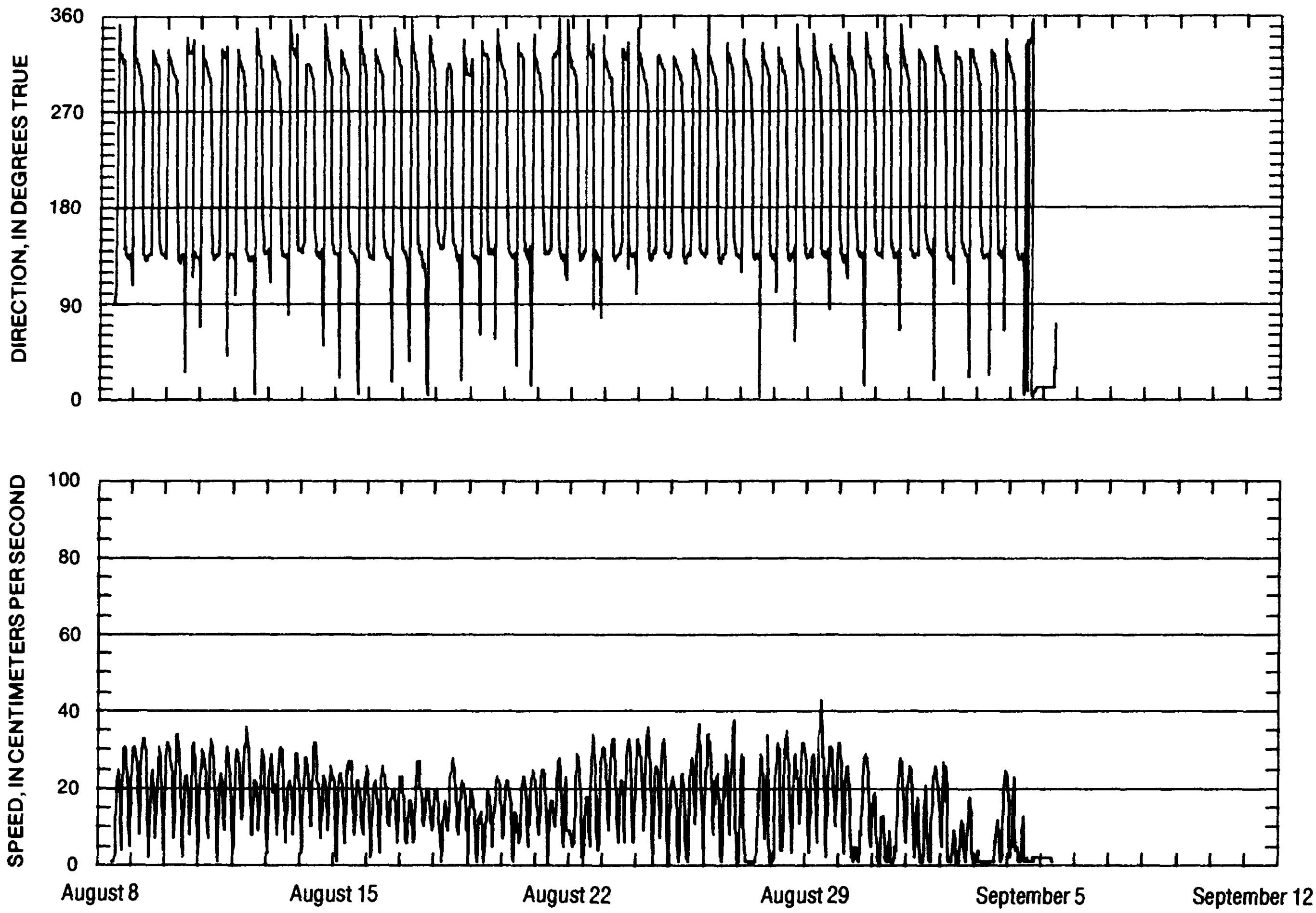
Constituent	Major (cm/s)	Minor (cm/s)	Direction (degrees true)	Phase (degrees)	Rotation
0_1	3.47	0.10	130.8	28.6	Counterclockwise
K_1	4.35	1.28	122.0	55.4	Counterclockwise
N_2	2.91	.02	137.0	291.8	Counterclockwise
M_2	24.40	2.77	136.1	267.3	Counterclockwise
S_2	.6.25	.08	138.6	294.3	Counterclockwise
M_4	1.40	.59	108.9	92.1	Counterclockwise

Root mean square speed: 20.0 cm/s
Spring tidal current maximum: 38.5 cm/s
Neap tidal current maximum: 17.3 cm/s
Principal current direction: 134.5 degrees true
Tidal form number: 0.26
Standard deviation U-series: 5.01 cm/s
Standard deviation V-series: 5.15 cm/s

Time-averaged velocity

Interval	Number of M_2-cycles	East-West (cm/s)	North-South (cm/s)
1	12	0.8	-1.5
2	12	1.4	-1.4
3	12	.4	-1.5
4	12	-1.3	.6
5	2	-.7	.8
All	50	.3	-.9

Time-series plots of tidal velocity
(Observations are 30-minute averages)



Summary of harmonic-analysis results

Meter type: Inclinometer
Start time of series: 6/13/84 1257 Pst.
Current meter station: 1SW84
Position: 37°37'27"N 122°13'52"W
Water depth: 2.6 m mean lower low water
Meter depth: 1.5 m below mean lower low water
Approximate record length is 54 M_2-cycles

Tidal ellipses of six major constituents

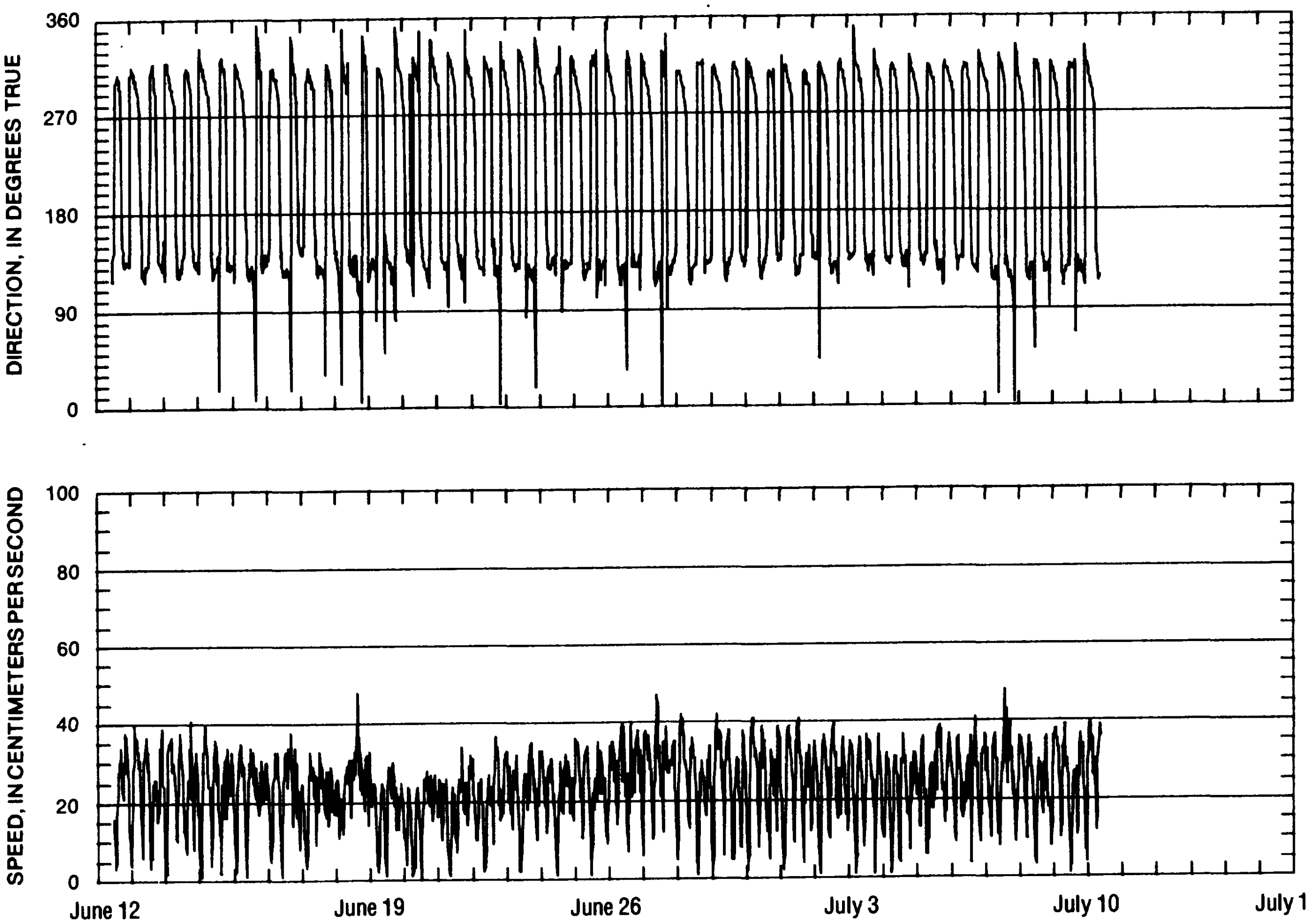
Constituent	Major (cm/s)	Minor (cm/s)	Direction (degrees true)	Phase (degrees)	Rotation
0_1	2.58	0.05	122.0	12.1	Clockwise
K_1	8.95	1.23	118.1	36.2	Counterclockwise
N_2	4.61	.13	120.4	260.7	Clockwise
M_2	31.77	4.14	130.1	270.6	Counterclockwise
S_2	3.59	.04	115.5	281.3	Clockwise
M_4	2.58	1.53	124.9	74.7	Counterclockwise

Root mean square speed: 25.3 cm/s
Spring tidal current maximum: 46.9 cm/s
Neap tidal current maximum: 21.8 cm/s
Principal current direction: 126.2 degrees true
Tidal form number: 0.33
Standard deviation U-series: 6.61 cm/s
Standard deviation V-series: 5.75 cm/s

Time-averaged velocity

Interval	Number of M_2-cycles	East-West (cm/s)	North-South (cm/s)
1	12	-0.8	-1.2
2	12	1.3	-.7
3	12	-.1	-.9
4	12	-1.0	-2.5
5	6	.7	-1.3
All	54	-.1	-1.3

Time-series plots of tidal velocity
(Observations are 30-minute averages)



Summary of harmonic-analysis results

Meter type: Inclinometer
Start time of series: 8/13/84 1210 Pst.
Current meter station: 3SW84
Position: 37°37'32"N 122°13'50"W
Water depth: 2.4 m mean lower low water
Meter depth: 1.5 m below mean lower low water
Approximate record length is 44 M_2-cycles

Tidal ellipses of six major constituents

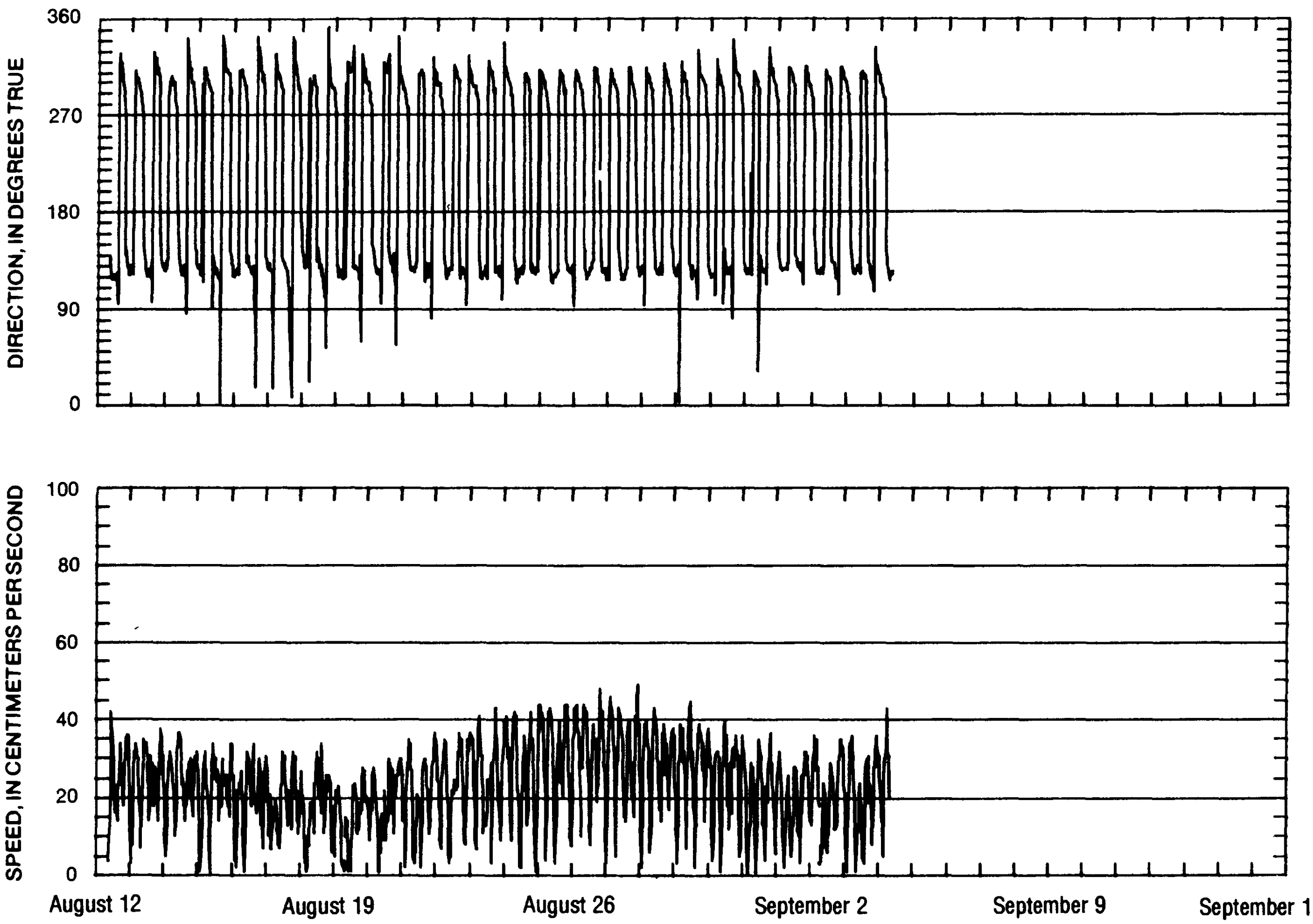
Constituent	Major (cm/s)	Minor (cm/s)	Direction (degrees truc)	Phase (degrees)	Rotation
0_1	4.82	0.27	128.2	23.3	Counterclockwise
K_1	7.33	1.15	117.6	52.8	Counterclockwise
N_2	6.86	.17	126.0	275.9	Counterclockwise
M_2	32.07	3.98	123.7	273.6	Counterclockwise
S_2	7.94	.11	125.7	299.0	Counterclockwise
M_4	2.31	.71	104.8	108.5	Counterclockwise

Root mean square speed: 26.0 cm/s
Spring tidal current maximum: 52.2 cm/s
Neap tidal current maximum: 21.6 cm/s
Principal current direction: 123.6 degrees true
Tidal form number: 0.30
Standard deviation U-series: 5.91 cm/s
Standard deviation V-series: 5.18 cm/s

Time-averaged velocity

Interval	Number of M_2-cycles	East-West (cm/s)	North-South (cm/s)
1	12	2.0	-1.8
2	12	.5	-1.4
3	12	-.7	-1.5
4	8	.2	-1.6
All	44	.5	-1.6

Time-series plots of tidal velocity
(Observations are 30-minute averages)



Summary of harmonic-analysis results

Meter type: Electromagnetic meter
Start time of series: 8/30/84 0802 Pst.
Current meter station: 3SW84
Position: 37°37'26"N 122°13'51"W
Water depth: 2.6 m mean lower low water
Meter depth: 1.1 m below mean lower low water
Approximate record length is 54 M_2-cycles

Tidal ellipses of six major constituents

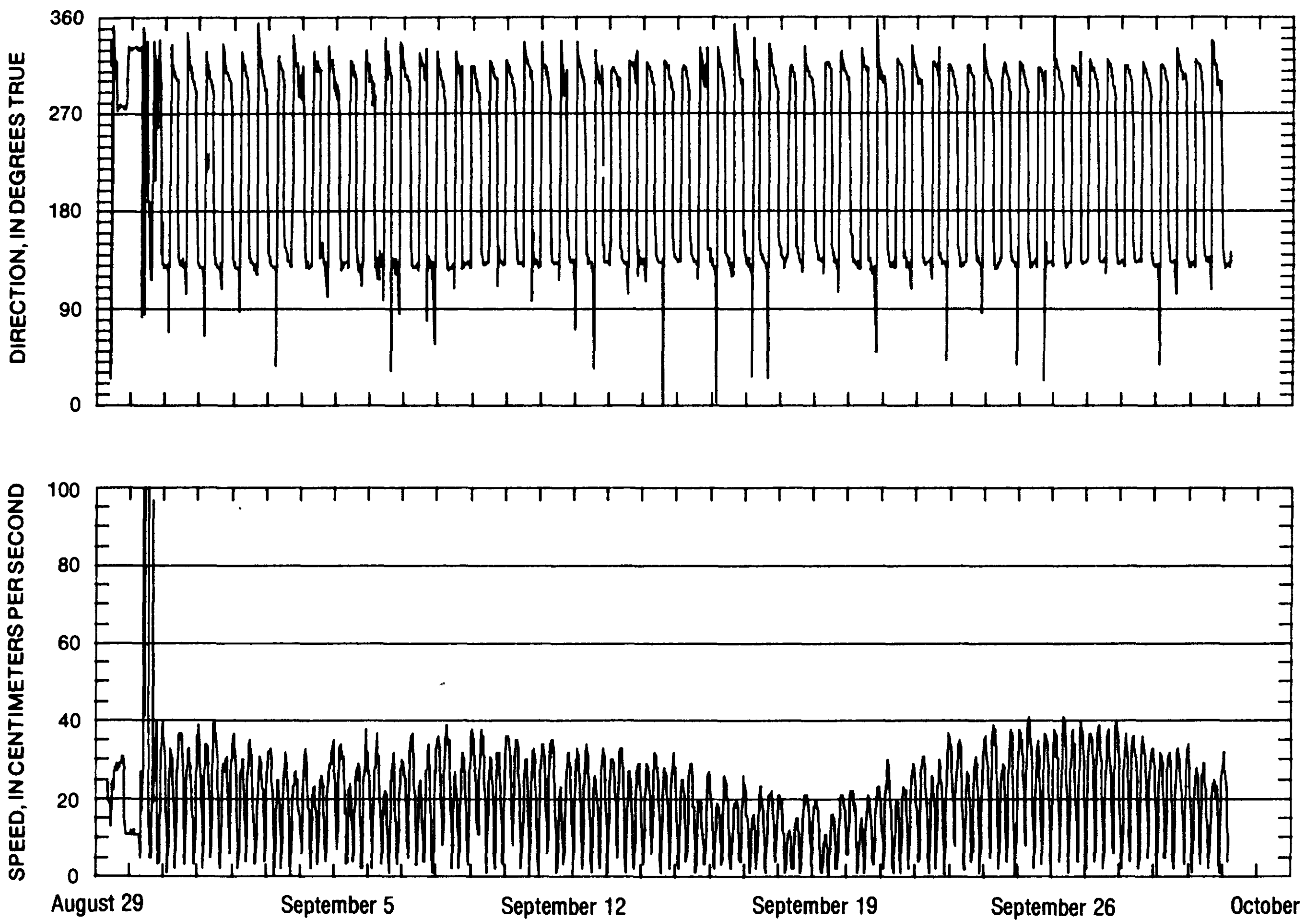
Constituent	Major (cm/s)	Minor (cm/s)	Direction (degrees true)	Phase (degrees)	Rotation
0_1	3.89	0.71	126.5	11.0	Counterclockwise
K_1	4.58	.73	125.9	47.2	Counterclockwise
N_2	7.74	.41	128.3	251.2	Counterclockwise
M_2	28.67	2.57	131.0	270.6	Counterclockwise
S_2	8.61	.26	131.5	277.5	Counterclockwise
M_4	1.21	.03	97.2	124.0	Counterclockwise

Root mean square speed: 22.6 cm/s
Spring tidal current maximum: 45.7 cm/s
Neap tidal current maximum: 19.4 cm/s
Principal current direction: 130.2 degrees true
Tidal form number: 0.23
Standard deviation U-series: 3.44 cm/s
Standard deviation V-series: 3.25 cm/s

Time-averaged velocity

Interval	Number of M_2-cycles	East-West (cm/s)	North-South (cm/s)
1	12	0.8	-2.0
2	12	.0	-1.5
3	12	.5	-1.8
4	12	.1	-1.4
5	6	-.8	-1.5
All	54	.2	-1.7

Time-series plots of tidal velocity
(Observations are 30-minute averages)



(PAGE 75 FOLLOWS)

SUPPLEMENTAL DATA B

Harmonic-Analysis Results and Time-Series Plots of Water Level

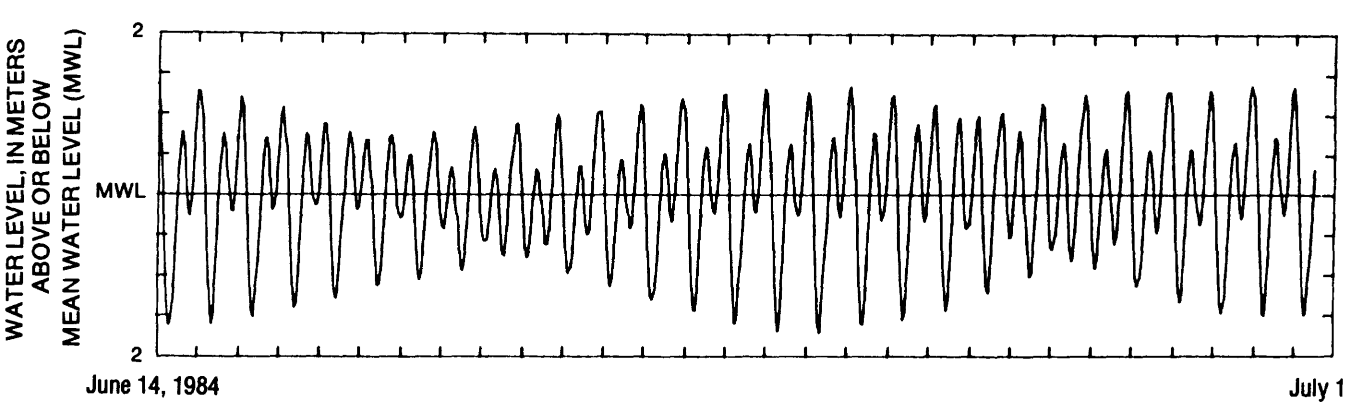
Summary of harmonic-analysis results

Start time of series: 6/14/84
Station position: 37°37'26"N 122°13'52"W
Approximate record length is 28 days
There are 684 data points

Results of least squares after tidal inference
[Mean value of the time series is 365.92
Standard deviation of the time series is 10.94 cm]

Name	Cycles per day	Height H (cm)	Kappa κ (degrees)	Kappap κ' (degrees)
Q_1	0.89324	4.41	84.39	99.43
O_1	0.92954	22.73	98.96	109.65
M_1	0.96645	1.61	113.65	119.91
P_1	0.99726	13.72	126.14	128.70
K_1	1.00274	41.45	128.34	130.24
J_1	1.03903	1.80	142.92	140.46
MU_2	1.86455	1.97	332.63	353.35
N_2	1.89598	15.09	343.88	0.82
NU_2	1.90084	2.93	345.23	1.59
M_2	1.93227	82.01	354.01	6.60
L_2	1.96857	2.30	4.14	12.38
T_2	1.99726	1.07	14.53	19.32
S_2	2.00000	18.06	15.39	19.85
K_2	2.00548	4.91	17.12	20.92
M_4	3.86455	0.84	240.33	265.51
MK_3	2.93501	3.49	76.11	90.60

Time-series plot of water level



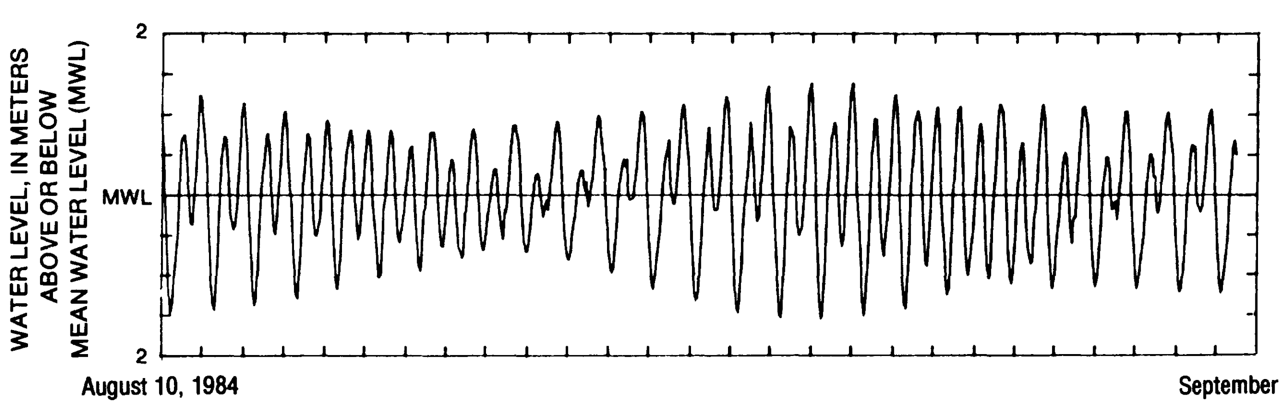
Summary of harmonic-analysis results

Start time of series: 8/10/84
Station position: 37°37'27"N 122°13'52"W
Approximate record length is 26 days
There are 636 data points

Results of least squares after tidal inference
[Mean value of the time series is 367.43 cm
Standard deviation of the time series is 12.09 cm]

Name	Cycles per day	Height H (cm)	Kappa κ (degrees)	Kappap κ' (degrees)
Q_1	0.89324	5.29	101.03	116.07
O_1	0.92954	27.28	104.77	115.46
M_1	0.96645	1.94	108.55	114.81
P_1	0.99726	11.55	111.77	114.33
K_1	1.00274	34.89	112.33	114.23
J_1	1.03903	2.16	116.08	113.63
MU_2	1.86455	1.89	4.03	24.75
N_2	1.89598	18.221	326.32	343.27
NU_2	1.90084	3.53	330.40	346.77
M_2	1.93227	78.93	356.77	9.36
L_2	1.96857	2.21	27.21	35.45
T_2	1.99726	1.44	349.79	345.59
S_2	2.00000	24.47	349.50	353.97
K_2	2.00548	6.66	348.92	352.72
M_4	3.86455	0.76	279.55	304.73
MK_3	2.93501	2.83	102.07	116.57

Time-series plot of water level



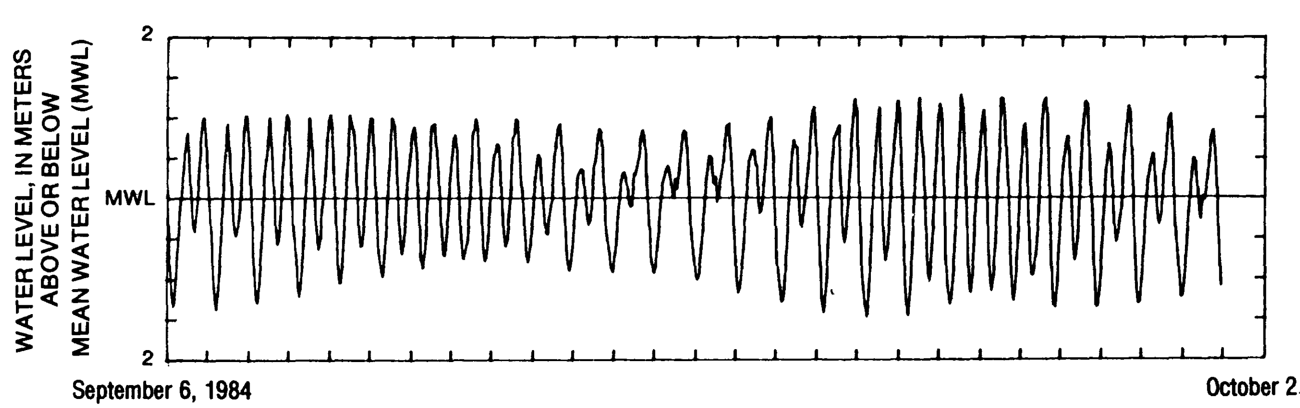
Summary of harmonic-analysis results

Start time of series: 9/6/84
Station position: 37°37'26"N 122°13'52"W
Approximate record length is 26 days
There are 624 data points

Results of least squares after tidal inference
[Mean value of the time series is 368.79 cm
Standard deviation of the time series is 13.76 cm]

Name	Cycles per day	Height H (cm)	Kappa κ (degrees)	Kappap κ' (degrees)
Q_1	0.089324	5.10	101.92	116.96
O_1	0.92954	26.27	103.33	114.02
M_1	0.96645	1.87	104.75	111.01
P_1	0.99726	14.11	105.96	108.52
K_1	1.00274	42.63	106.17	108.07
J_1	1.03903	2.08	107.58	105.13
MU_2	1.86455	1.83	12.64	33.36
N_2	1.89598	18.26	329.17	346.12
NU_2	1.90084	3.54	332.72	349.08
M_2	1.93227	76.40	355.66	8.25
L_2	1.96857	2.14	22.14	30.37
T_2	1.99726	0.92	339.35	344.14
S_2	2.00000	15.84	338.67	343.13
K_2	2.00548	4.31	337.29	341.10
M_4	3.86455	0.33	316.33	341.51
MK_3	2.93501	2.26	95.82	110.31

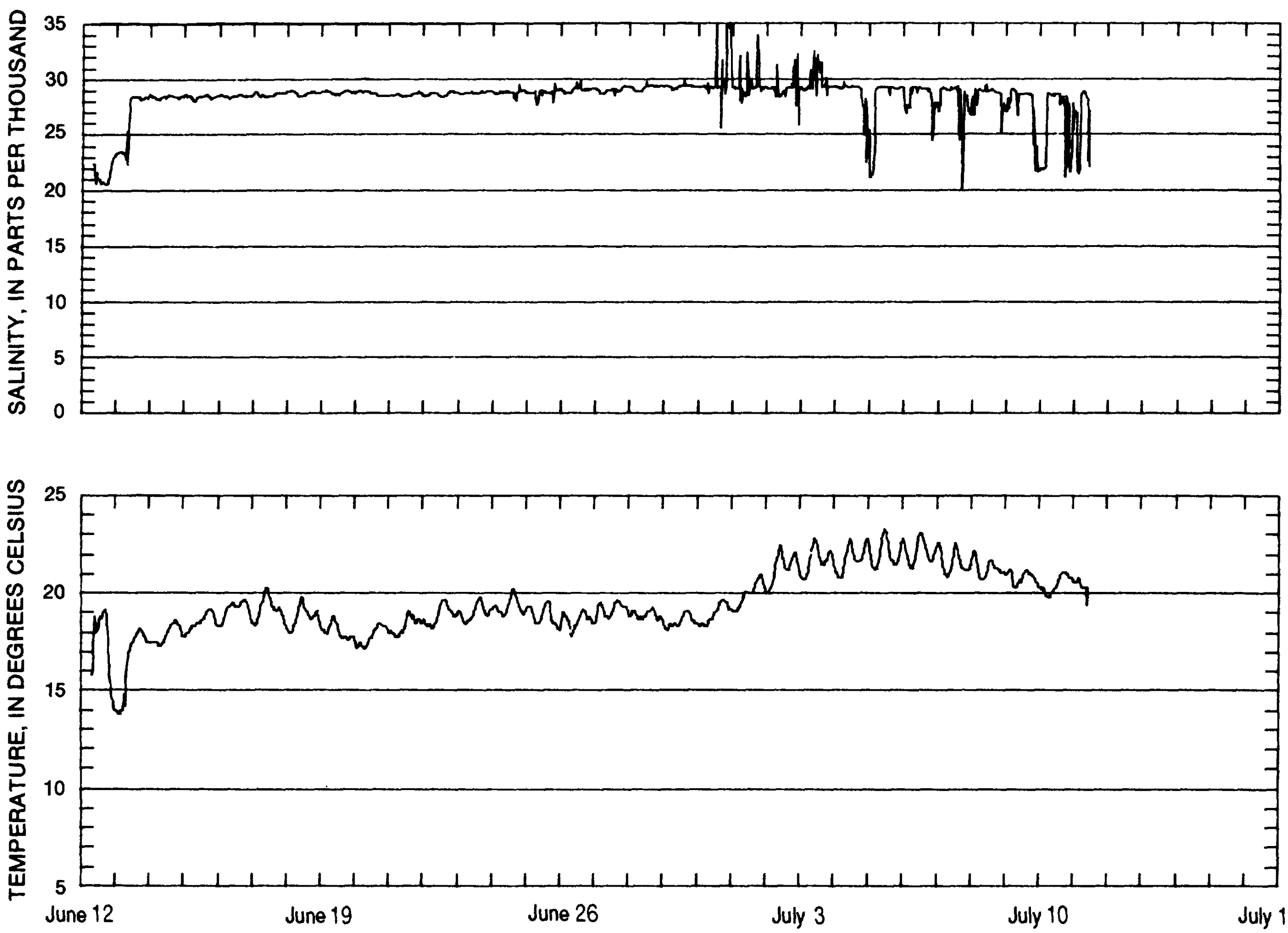
Time-series plot of water level



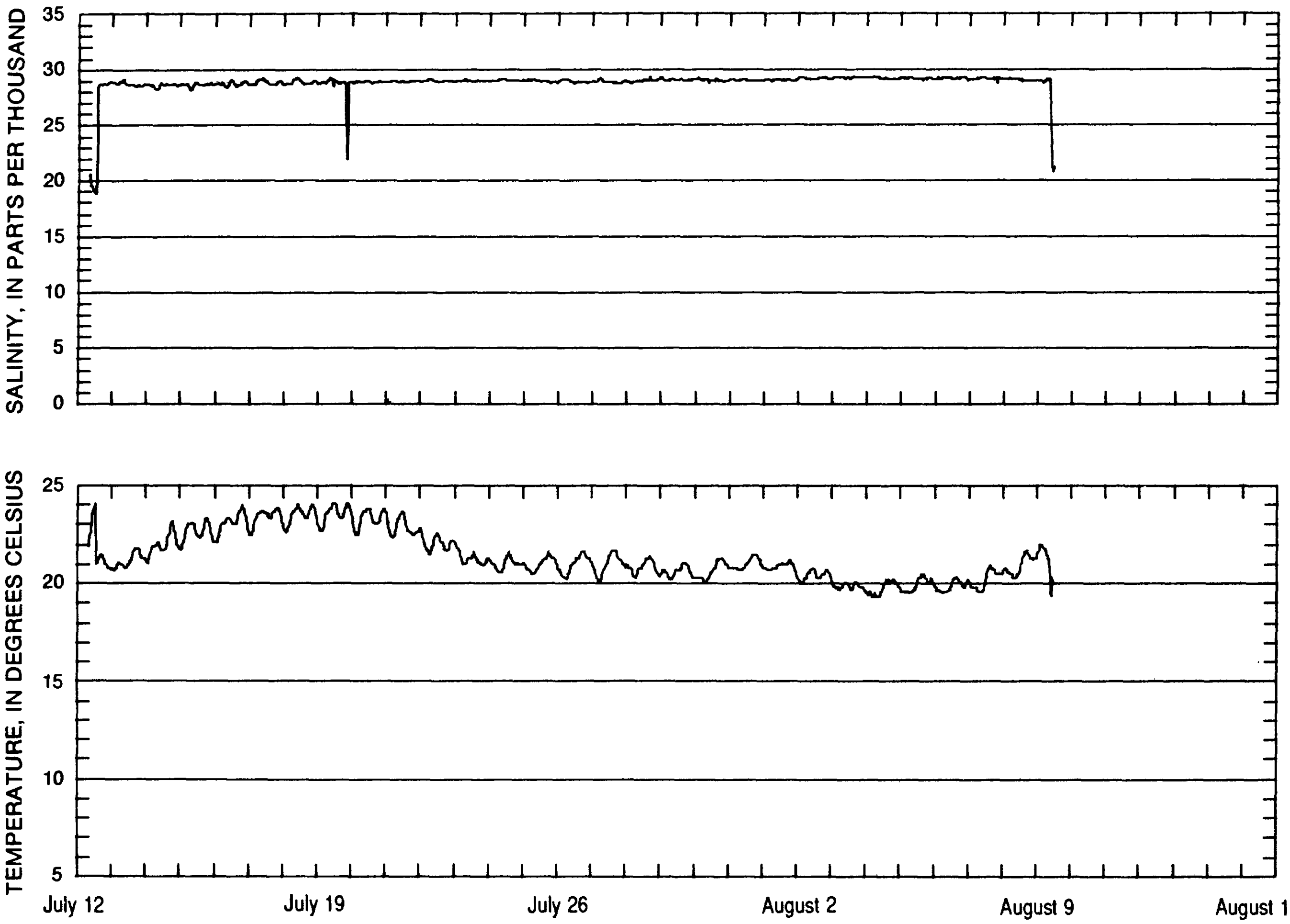
SUPPLEMENTAL DATA C

Time-series Plots of Temperature and Salinity

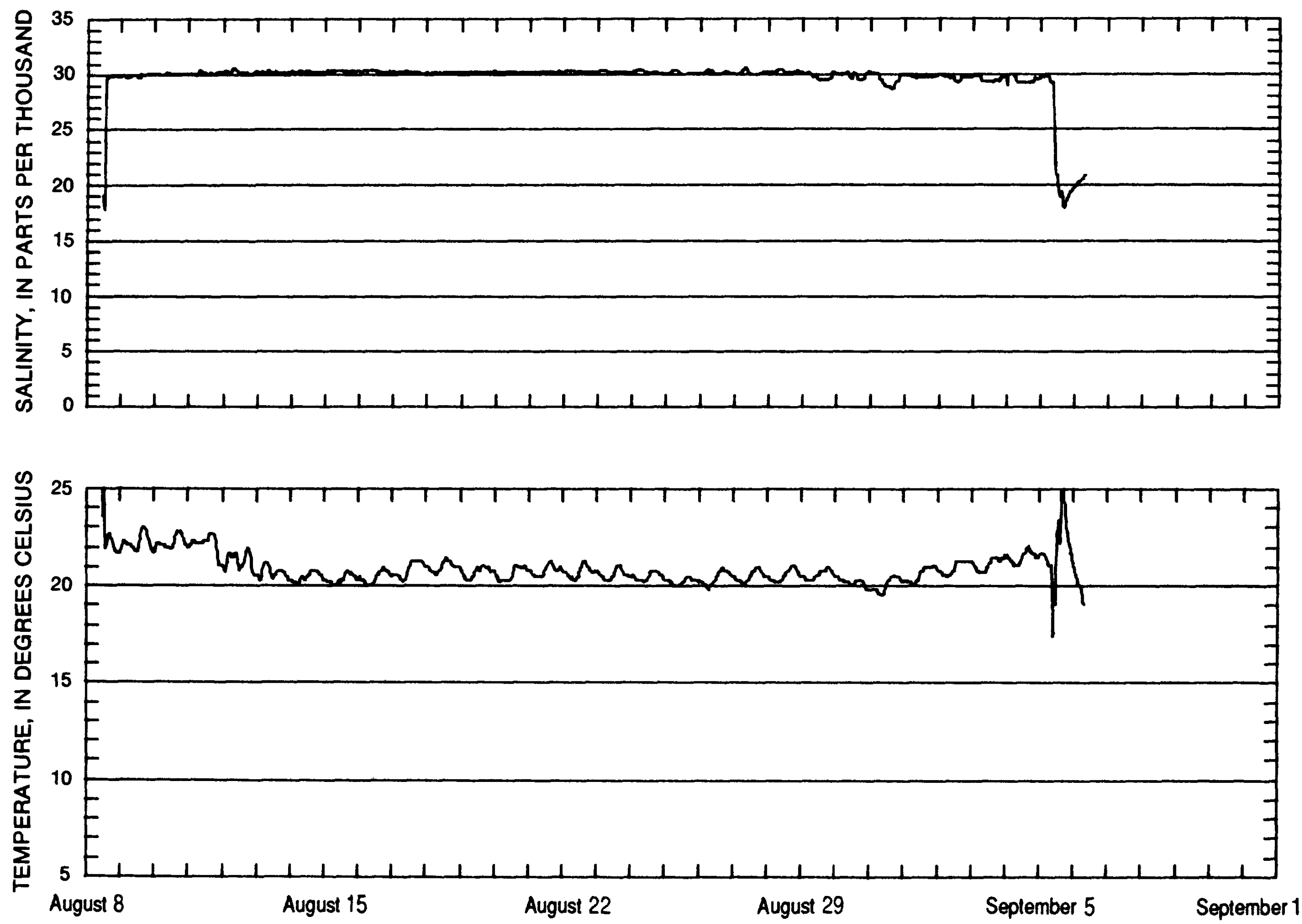
Time-series plots of temperature and salinity



Time-series plots of temperature and salinity



Time-series plots of temperature and salinity



SUPPLEMENTAL DATA D

Time-series Plots (stick diagrams) of Wind Velocity

Time-series plots of wind velocity