A Biaxial Propeller Current-meter System for Fixed-mount Applications[1]

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ABSTRACT

A biaxial propeller current-meter system for use in shallow water, where instrumentation can be attached to rigid bottom-mounted towers, has been developed at the Chesapeake Bay Institute. The use of two like sensors to measure the horizontal-velocity vector eliminates the problem of matching time constants in rotor-vane systems. The propellers have a noncosine response to the angle of attack of the flow. However, the data recorded by two propellers mounted at right angles are sufficient to correct for the noncosine response.

Introduction. The Chesapeake Bay Institute (CBI) during the past several years has been using Eulerian sensors to measure the characteristics of the velocity field in estuarine waters. Because the frequencies of naturally occurring fluctuations in velocity span such a wide range, no single instrument is capable of measuring throughout the total range. One of the objectives of the program has been to develop suitable instrumentation when commercially available instrumentation was either nonexistent or inadequate. A doppler-shift current meter was developed to study high-frequency fluctuations (Wiseman 1969), and commercially available current meters that use Savonius rotors to sense speed and vanes to sense direction were used to study lower frequency fluctuations (Cannon 1968). The frequency ranges of these studies did not overlap.

This paper describes a current-meter system that has been designed to sample the frequency range not included in the above-mentioned studies, i.e., motion with scales in the interval between the tidal and the surface-wave frequencies. This description is presented separately from the results because of the possible applicability of the techniques in studies of motion in estuaries and on the continental shelf. In addition, the techniques of using propeller sensors and achieving

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the proper reduction of the data from noncosine responding propellers have not been completely stated previously.

The measurement of motion at the scales of interest has involved the problem of averaging the high-frequency fluctuations in the motion, which in this case included fluctuations due to surface waves, to prevent or minimize aliasing of the record. Further, because velocity is a vector, this averaging should be done vectorially. A propeller sensor, i.e., two propellers mounted at right angles to each other, was preferred to a rotor-vane system because of the problem of matching time constants of the rotor and the vane.

Description of the Instrument. The current meter consists of two propellers, each approximately 38 cm in diameter, mounted one above the other at right angles (Figs. 1, 2). Each propeller has six asymmetric plastic blades, three of which face forward and three backward in a symmetric fashion; they are held in place with hexagonal polypropylene plates. The asymmetry of the blades combined with the symmetry of their distribution makes the propeller sensitive to the direction of flow. The symmetry of the entire propeller assembly is a necessity to preserve the symmetry in the angular response of the propeller. The propeller is almost neutrally buoyant in water.

The propeller shaft consists of a 0.635-cm aluminum rod, with tungsten carbide rods of a smaller diameter set coaxially in both ends to form the stud parts of the bearings. The carbide rods are free to turn in the bearing assemblies, which are screwed into 1.27-cm-diameter bronze rods in the frame. Ordinary copper tubing has been used for the remainder of the frame. The bearing assembly is made up of a hollowed Delrin AF rod (composite of acetal resin and teflon) at the opening, a synthetic sapphire ball at the back, and a gum-rubber pad behind the ball, all of which are contained in a threaded bronze casing.

Twelve pulses per revolution of the propeller are generated by a conductivity technique (described below), using the two pairs of copper electrodes protruding from either side of the frame and the two round Delrin disks with 12 slots equally spaced around their rims. The leads to the electrodes are placed inside the frame until they reach the junction between the pair of propellers, and from there they run along the outside of the supporting rod to the tower.

For our specific experiments, a sampling interval of 10 sec was chosen. The number of pulses from each propeller was counted during each 10-sec interval; thus, in effect, an average speed over 10 sec was determined. The twelve pulses per revolution and the 10-sec sampling interval resulted in a precision in speed of approximately ± 0.5 cm/sec.

Response Characteristics. The response characteristics of the propellers were determined in the CBI circulating test flume. The test section of the flume is 3.0 m long, with a cross section 0.91 m wide by 0.91 m deep. The speed of flow can be controlled within ± 0.05 cm/sec or $\pm 0.5\,^{0}\!/_{0}$, whichever is greater,

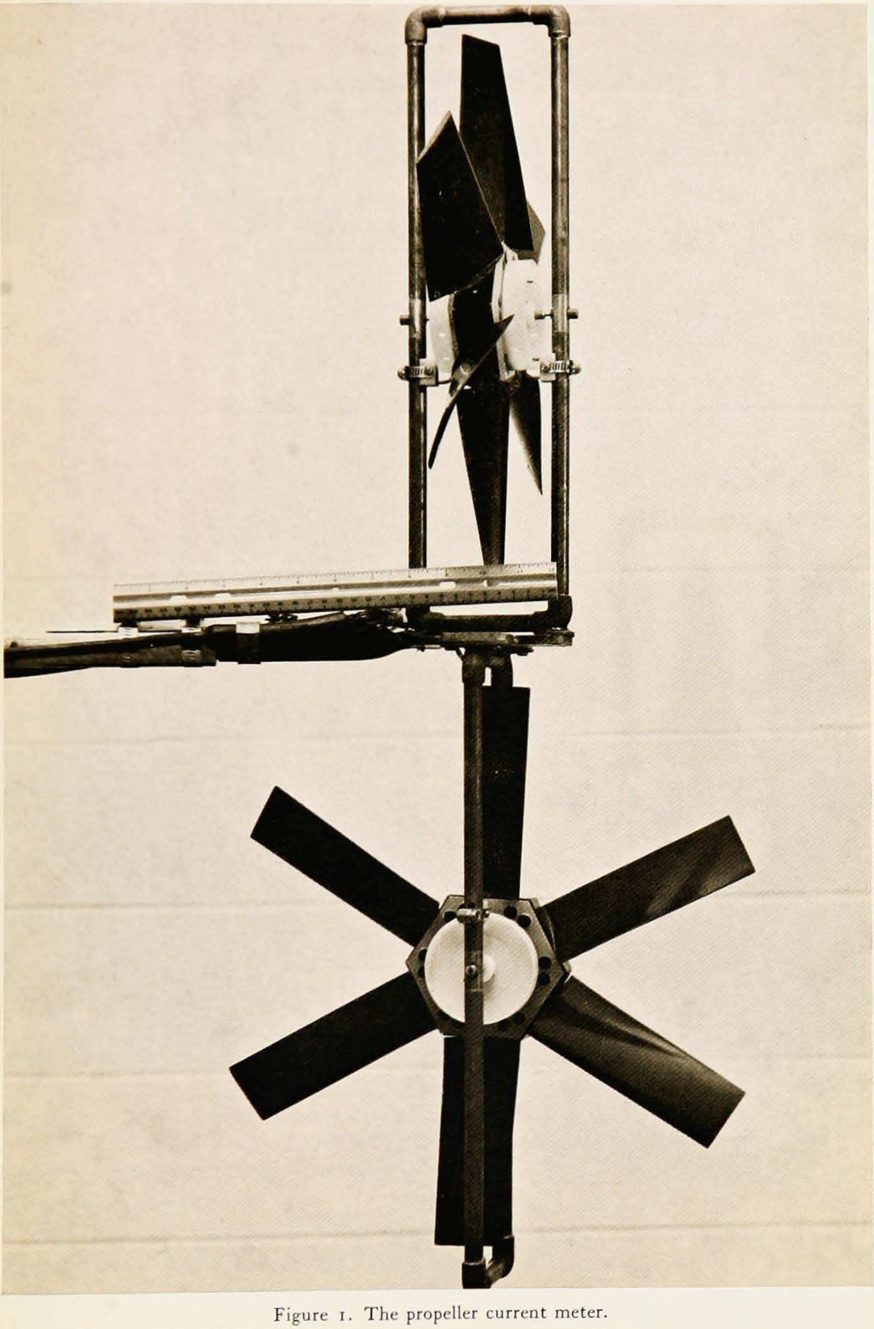

Figure 1. The propeller current meter.

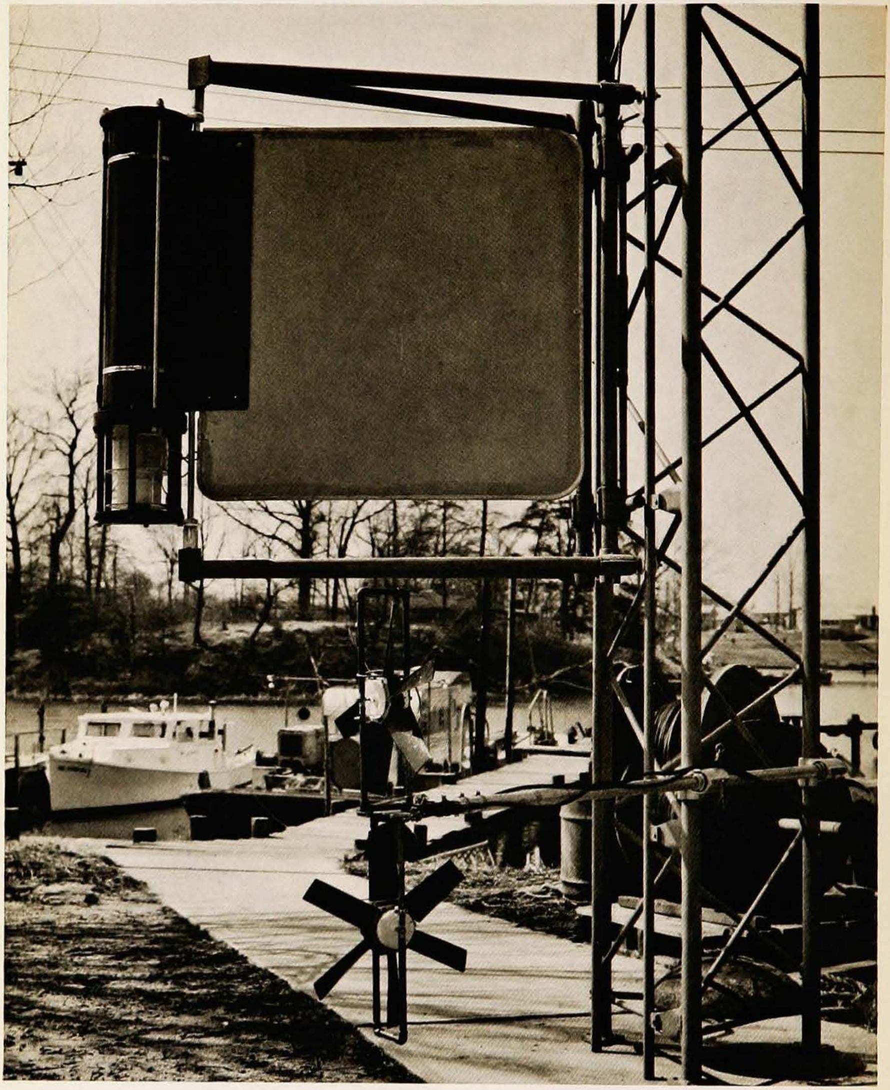

Figure 2. A propeller current meter and a Savonius-rotor current meter showing the method of attachment to a tower. In the actual field experiments the meters were well away from the bottom.

for speeds ranging from less than 1 cm/sec to about 50 cm/sec. One propeller was calibrated in detail to determine its head-on and angular responses; the remaining propellers were compared with it.

Preliminary angular calibrations showed that the response of the propellers was not cosine, but some other function, $f(\theta)$, of the angle between the velocity vector and the propeller axis. However, if $f(\theta)$ is known, the recorded speeds (u_r, v_r) from two propellers mounted at right angles are sufficient to determine the true components of velocity (u_t, v_t) parallel to the axes of the two propellers. To illustrate this, consider a current of speed $|\vec{V}|$ incident on the propellers at an angle θ to the axis of the propeller facing in the x direction. The true components of the current are

$$u_t = |\vec{V}| \cos\theta, \tag{1}$$

$$v_t = |\vec{V}| \sin\theta = |\vec{V}| \cos(90^\circ - \theta). \tag{2}$$

The recorded values of speed are

$$u_r = |\vec{V}| f(\theta), \tag{3}$$

$$v_r = |\vec{V}| f(90^\circ - \theta). \tag{4}$$

A tangent-like function, $g(\theta)$, from whose inverse function the angle of flow can be determined, is defined by

$$g(\theta) = \frac{v_r}{u_r} = \frac{f(90^\circ - \theta)}{f(\theta)}. \tag{5}$$

Because of the symmetrical properties of $f(\theta)$, $g(\theta)$ need to be defined for only $0^\circ \le \theta \le 45^\circ$. The inverse of $g(\theta)$ can be used directly to determine θ when $(|v_r|/|u_r|) \le 1$ or by using $(|u_r|/|v_r|)$ when the former term is > 1. The true components of the current are given by

$$u_t = u_r \frac{\cos\theta}{f(\theta)}, \quad v_t = v_r \frac{\cos(90^\circ - \theta)}{f(90^\circ - \theta)} \tag{6}$$

or by

$$u_t = u_r \frac{\cos(90^\circ - \theta)}{f(90^\circ - \theta)}, \quad v_t = v_r \frac{\cos\theta}{f(\theta)}, \tag{7}$$

when $(|v_r|/|u_r|) \le 1$ or > 1, respectively. This simple scheme is dependent on only the requirement that the angular response function of the propellers be independent of speed.

The threshold speed of the test propeller was in the range 0.65–0.70 cm/sec for increasing flume speeds and in the range 0.60–0.65 cm/sec for decreasing flume speeds. All other propellers rotated at flow speeds of less than 1 cm/sec.

The head-on response of the propellers as a function of speed was deter-

Table I. Linear least-squares fit to head-on calibration data for the test propeller. The regression equation is $u_{10} = 0.17 + 0.4714 P_{10}$, with a standard error of estimate of 0.06 cm/sec.

P_{10} (pulses/10 sec)	u_{10}-actual (cm/sec)	u_{10}-calculated (cm/sec)	(u_{10}-calc.) – (u_{10}-act.) (cm/sec)	(%)
1.89	1.	1.06	.06	5.73
3.89	2.	2.02	.02	1.11
10.28	5.	5.02	.02	.32
20.75	10.	9.95	–.05	–.49
42.00	20.	19.97	–.03	–.16
63.06	30.	29.90	–.10	–.35
84.54	40.	40.02	.02	.05
105.84	50.	50.05	.06	.13

mined at 0° and 180°, and then averaged. A linear least-squares fit was made between the number of pulses/10 sec (P_{10}) and the corresponding flume speed (u_{10}, cm/sec) (Table 1). Within the precision of the flume, the head-on response of the test propeller was linear throughout the speed range for which is was used. Because the regression equation fitted the data best at speeds 2, 5, 20, and 40 cm/sec and because a least-squares fit to these points alone gave a regression equation that is identical to the original equation, the remaining propellers were calibrated at only these four speeds.

The angular calibrations were determined by first forcing the responses at 75° and 105° to be equal and by ascertaining that the values at 255° and 285° were equal to this common value. Speeds were determined every 3° from 0° to 180° at a flume speed of 20 cm/sec, and the values at angles θ and $180° - \theta$ were averaged to decrease further the error in alignment. The angular-response function for $0° \leq \theta \leq 84°$ (Fig. 3) was obtained by normalizing all values to the value obtained at 0°. The function shows a marked change in curvature at 57° and a less-noticeable change at 75°. The propeller does not respond, at any speed, to flow incident at angles greater than 84°. The differences in speed obtained by using the response function for 20 cm/sec instead of the response finction for the actual speed were less than the ± 0.5-cm/sec resolution of the meter. The differences in the angular-response functions for the various propellers were negligible, provided that the individual head-on calibrations were used. Greater uniformity could probably be achieved if the entire propeller was manufectured from a single mold.

The average acceleration of a propeller from rest was determined (Table II); approximate steady state was reached following one-quarter revolution (three pulses) at all speeds. This rate corresponds to a passage of 19 cm of water. Reliable data could not be obtained for the deceleration. Qualitative observations showed that the propeller came to rest in a time that was of the same order-of-magnitude as that required for acceleration. Note that this is not meant to imply that acceleration and deceleration have the same characteristics.

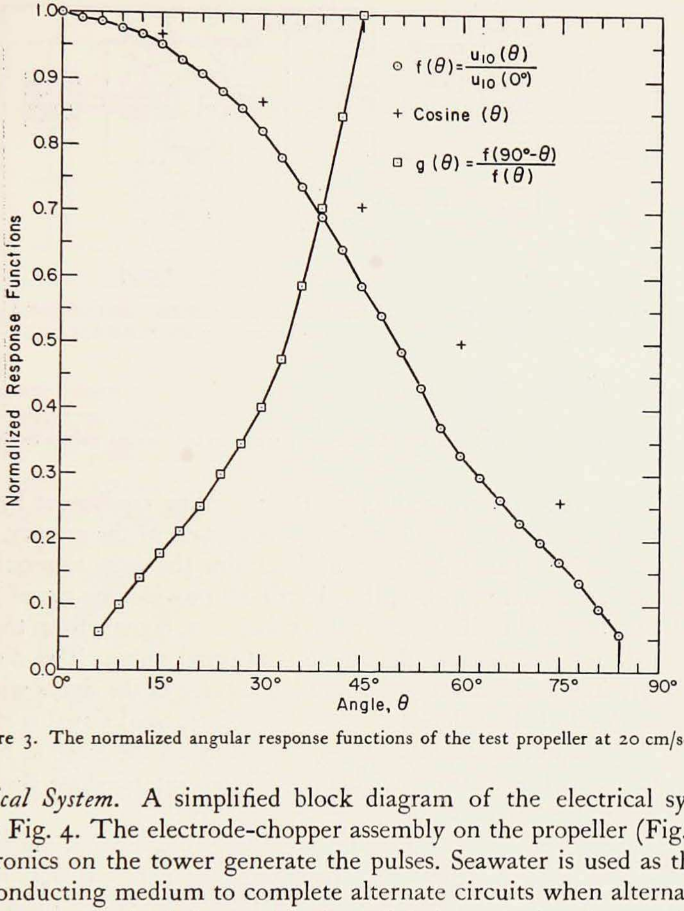

Figure 3. The normalized angular response functions of the test propeller at 20 cm/sec.

Electrical System. A simplified block diagram of the electrical system is shown in Fig. 4. The electrode-chopper assembly on the propeller (Fig. 5) and the electronics on the tower generate the pulses. Seawater is used as the electrically conducting medium to complete alternate circuits when alternate electrode pairs are opposite holes on the rims of their respective chopper. Because the holes on the two choppers are slightly offset, the sense of rotation can be determined from the alternate forms of the signal for the two senses of rotation

Table II. Average times (sec) for successive pulses for a propeller accelerating from rest.

	Flume speeds (cm/sec)		
Pulse	20	10	5
1	0.42	0.83	1.58
2	0.25	0.57	1.14
3	0.26	0.52	1.03
4	0.25	0.52	1.05
5	0.25	0.51	1.00
Steady-state average times	0.25	0.51	0.98

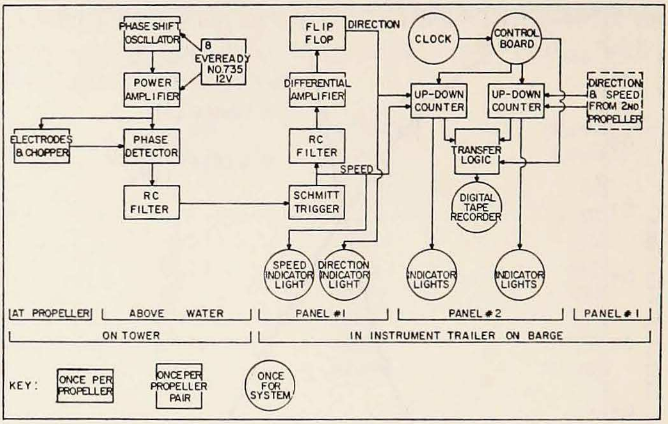

Figure 4. Simplified block diagram of the electrical system from the current meters to the recorder.

(Fig. 6). The signals are transmitted to the recording equipment by standard # 18-3 neoprene armored wire laid along the bottom of the estuary.

The electronics on panel # 1 (Fig. 4) determine the sense of rotation of the propellers and, for each propeller, the electronics provide one signal for direction and one for speed to the counters on panel # 2. Signals from the Schmitt triggers (Fig. 6) go directly to the counters as speed pulses. The direction of flow is determined by calculating the running average of the signal with respect to the mean level of the Schmitt triggers. This integrated signal is either plus or minus with respect to the mean level, depending on the sense of rotation of the propeller. A pair of indicator lights provides an intermediate check on the signals leaving panel # 1 for one propeller at a time.

The electronics on panel # 2 count, according to direction, the number of speed pulses for each propeller; the electronics, every 10 sec, also record the numbers in binary in a compact format on IBM compatible magnetic tape.

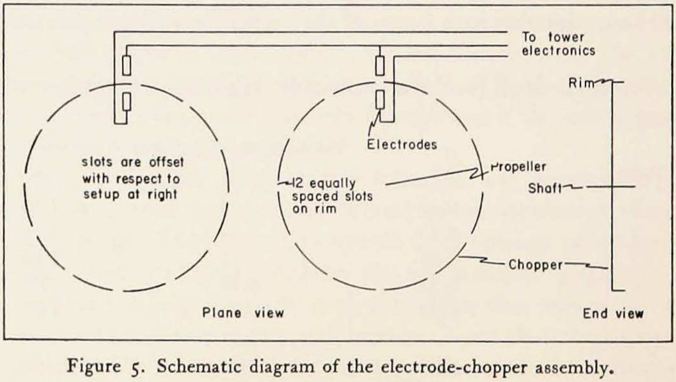

Figure 5. Schematic diagram of the electrode-chopper assembly.

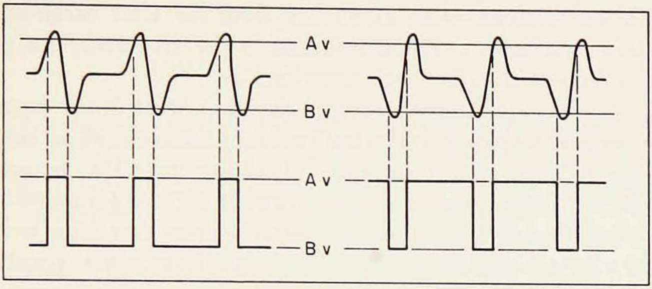

Figure 6. Schematic diagram of the pulses generated for the two senses of rotation of the propeller (upper) and the respective signals from the Schmitt triggers A and B (lower).

The up-down counters, with a capacity for 256 pulses (8 binary digits) plus sign, are stopped, recorded, and reset in rapid succession. The provision to hold (count) only one pulse during the small, yet finite, recording time limits the system to current speeds of less than 85 cm/sec. It is only close to slack water that the counters count up and down during any 10-sec interval; thus the resulting errors in $g(\theta)$ are small. For ease in data handling, a gap is generated on the magnetic tape following every 100 sets of numbers. Two sets of indicator lights provide a check on the counters for one propeller pair at a time. The clock is a crystal-control oscillator and is stable to less than 0.001 sec in 10 sec.

The copper electrodes on the propellers become corroded with time, and the amplitudes of the signals decrease by about 50% during a 50-hr experiment. Thus, the signals must be monitored during the experiment, and the voltage levels of the Schmitt triggers (Fig. 6) must be adjusted from time to time as the signals decay. Additionally, the electrodes must be cleaned and polished prior to each experiment. There have been no other operational or maintenance problems. The corrosion problem could be alleviated by replacing the electrode system with a photocell system (Nece and Smith 1970; Smith, personal communication).

Support Equipment. Four of these propeller current meters have been used in estuarine waters where they could be attached to rigid bottom-mounted towers, thus minimizing contamination of the data by mooring motion. Two kinds of towers have been used. The current-meter frames were attached to the towers with standard Nu-rail *t*-fittings (Fig. 2), and all connections have keys and slots to maintain proper alignment. The propellers were oriented with the predominant flow at an angle of 45° to each propeller. This arrangement minimizes the times of occurrence of the flow angle in the interval from 84° to 90° (Fig. 3).

A catamaran 6.0 m long and 2.5 m wide was designed and built at CBI to transport one kind of tower so that experiments could be made with various arrays. Field experiments were monitored from the CBI barge anchored on station. Thus, data tapes could be returned to the University for preliminary processing and checking after each experiment.

For our specific experiments, a record duration of 50 hours (approximately four lunar semidiurnal tidal cycles), a sampling interval of 10 sec, and four propeller pairs yielded eight time series of 18,000 points to be processed for each experiment. Preliminary processing required about 45 min. of IBM 1401 time, and it consisted of reading the compactly written data tape, writing a new data tape in a format that can be read by normal FORTRAN programming, and listing the data. Additional processing depends on the investigator's interest in the time series, but it can be done entirely with FORTRAN. We have been particularly interested in (i) the characteristics of the mean velocity averaged over the tidal cycles, (ii) the characteristics of the tidal velocity, and (iii) the statistical characteristics of the velocity fluctuations (Cannon 1969). In the analysis of the last of these, we found that the 12 pulses per revolution and the 10-sec averaging interval result in a least-count (corresponding to the ± 0.5-cm/sec resolution) noise density in the spectra of kinetic-energy density which is not negligible and that the spectra have to be corrected. In our case this problem resulted in only extra computations, but it should be carefully considered in the design stage of the experiments.

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