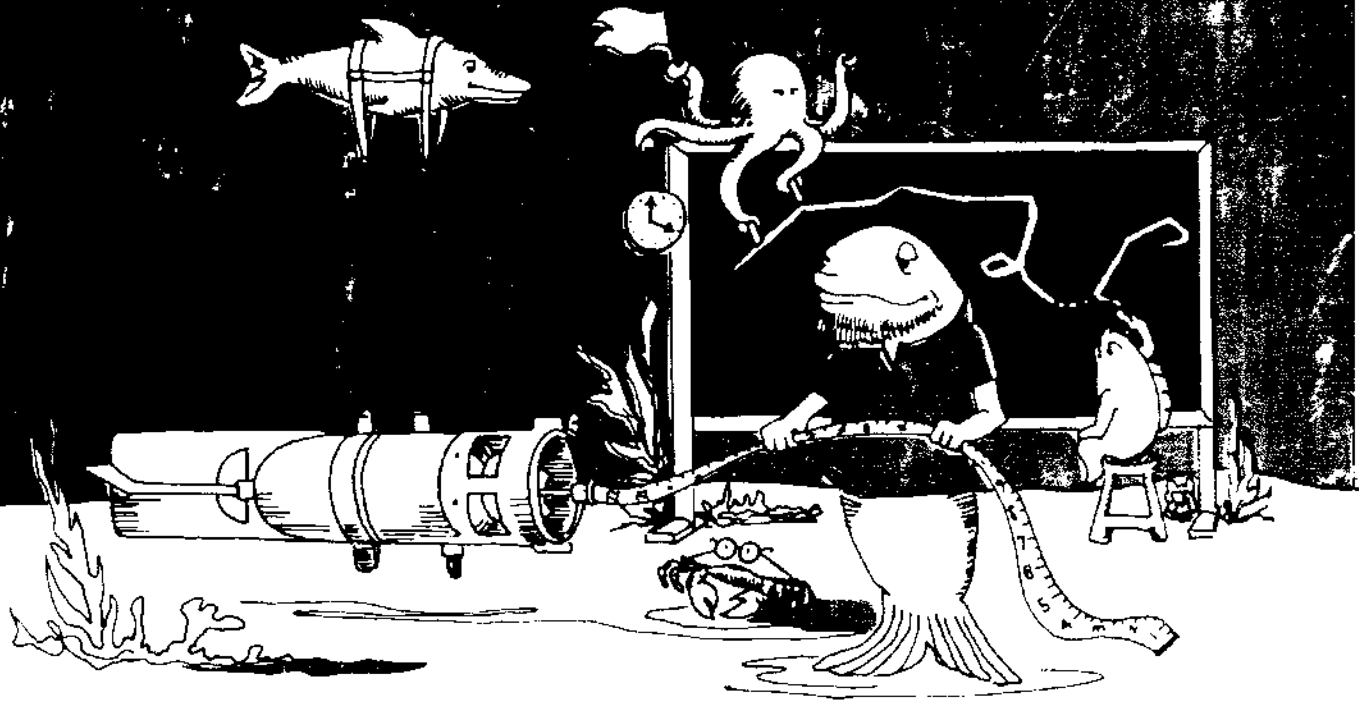
PROCEEDINGS OF A WORKING CONFERENCE ON

JANUARY 11-13, 1978



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Proceedings of a
Working Conference

on

C U R R E N T   M E A S U R E M E N T

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BACKGROUND AND CONFERENCE OBJECTIVES

There is concern within the marine community about the ability of existing current measurement systems to provide accurate and reliable flow velocity information when subjected to the full range of marine environmental conditions. Despite a significant amount of activity, instrument development, testing and applications are not fully documented. There is particular concern about the insufficient knowledge of the dynamic response characteristics of many sensors and systems, and thus the uncertainty of data collected with them.

The Office of Ocean Engineering (OOE), NOAA's initial response to numerous external recommendations citing the need for advances in ocean engineering and for a federal entity to foster civilian ocean engineering, feels that the area of current measurement technology is of sufficient importance to take a special initiative. The recently established office, existing organizationally in NOAA under the Assistant Administrator for Research and Development, has the mission to deal with this type of technology problem that is widespread throughout the community yet has no single agency dedicated to solving it. To stimulate a responsive approach to the technology problems, a working conference was convened for those in the community involved in the measurement of currents. The Working Conference on Current Measurement was sponsored by OOE in conjunction with the University of Delaware Sea Grant College Program and held in Newark, Delaware on January 11, 12, and 13, 1978.

The Conference was convened to help determine who has the need to measure currents and why, what technology is presently being used and for what reason, and what technology problems and needs exist. Additionally, it was hoped that solutions to specific technology problems could be recommended.

The overall conference objective was twofold: first, to provide a focus for technical information exchange among those in the marine community involved in current measurement and second, to provide guidance for action by OOE and others in defining and promoting realistic initiatives directed toward improving the national current measurement capability.

CONFERENCE STRUCTURE

The first two days of the conference were separated into four sessions by current measurement applications. The four categories, covering the spectrum of users, included:

- Scientific Research
- Ocean Engineering
- Environmental Impact Assessment
- Operational Surveys

The 3 to 8 invited speakers in each session were chosen as representatives of the "user" community as opposed to technologists per se. The speakers were asked to discuss in general their current measurement needs, the technology they are presently using to satisfy their needs, their perception of problems with existing technology and the impact of these problems, if any, on their programs. In addition, two invited presentations and a luncheon address were devoted to technology.

The third and final day of the conference was devoted to a working session designed to:

- provide expert opinions on the effectiveness of and deficiencies in existing current measurement technology relative to the needs of the community

- identify specific limitations in technology

- recommend appropriate tasks that should be undertaken to address the identified limitations.

SUMMARY OF INVITED PRESENTATIONS

As expected, the needs, the philosophies and the perception of the measurement problems varied among the different segments of the community.

The scientific research community, in describing their studies directed toward understanding ocean circulation, made it clear that their technology needs are, in general, not being satisfied by the commercial instrument manufacturers (understandable because of the limited and varied market). Driven by somewhat open-ended and pioneering research goals and a resource climate conducive to in-house efforts, many researchers (though not all) are inclined to invent, build and determine the performance of their own devices to support their measurement activities.

The ocean engineering/construction community, on the other hand, is applications-driven and has no choice but to rely on off-the-shelf technology, some of which may in fact have been developed initially by the scientific research community. Schedule and resource constraints impose real deadlines on their measurement programs and they cannot afford, in time or money, the "luxury" of building their own equipment.

Their immediate problem thus translates into how they can understand and improve upon the performance/reliability of commercially available technology.

The problems of the environmental impact assessment community differ slightly. Although they, too, must rely on commercially available instruments, the uses to which their data are put impose unique requirements on the type and accuracy of the sensors. Because the measurements may become the object of legal proceedings, the accuracy and representativeness of the data must be known and documented. The determination of instrument performance and traceability of testing or calibration procedures, techniques and facilities, thus become critical issues.

The operational survey community typically uses commercially produced technology and usually in large quantities. Although measurement accuracy is a primary concern, ease of handling, reliability and overall life cycle costs are of considerable importance when dealing with relatively large volumes of instruments.

Although there are current measurement problems that affect virtually all users, the impact of or concern about the technical problems varies with the particular application. Jim McCullough from Woods Hole Oceanographic Institution highlighted the existing technical problems in his presentation. These ranged from large vane and improper sampling rates, to zero stability and mooring motion. He emphasized that, although we have complicated measurement problems in the water, the weights attached to the components in the error equation vary with application and the environmental operating conditions. That is, one person's signal is another's noise.

Many common requirements for measurements were outlined. The researchers and the surveyors work in both shallow and deep water, making measurements throughout the water column. The engineers and environmental impact community are most active at coastal and continental shelf depths from the surface to the bottom.

The scientific researchers are trying to understand the turbulent mixing processes of the boundary layers of the ocean, coastal regions and estuaries. They want to understand the vagaries of the intense Gulf Stream or equatorial currents, and the energy levels of internal waves and ocean eddies. This involves measurements of natural fluctuation with periods of a few tenths of a second to weeks, months and years.

The ocean engineers explain that they must determine all those features of the currents which will impact intended engineering activities or structures. Although measurements at surface wave periods are necessary, for the engineers the longer-term, maximum or severe (perhaps storm-driven) and average currents are most important. Because the current speeds are typically high, system accuracy, although very important, is preempted by reliability and cost in trade-off considerations for system selection. Also, real-time measurement (including telemetry, processing and display) is becoming important for applications such as facility installation.

Because pollutants ejected into the environment will cause an impact depending on where they are carried and their dilution along the way, the environmental impact people want to know about potential trajectories and the variations in the currents that might affect dilution. They must measure variations of sometimes very low currents over periods of seconds to hours, yet provide averages over many weather cycles to obtain appropriate long-term mean currents. (Periods of extensive flow stagnation can be important to document in this application.) This wide range dictates that the instruments must record rapidly and unattended over periods of several months.

The varied applications of surveys (estuarine tidal current surveys to large area surveys for ASW operations) imply requirements in line with all of the above.

The measurement technique used to satisfy the majority of these requirements is Eulerian in nature and includes the rotor/vane inertial devices, electromagnetic and, in some cases, acoustic methods. Lagrangian methods have some unique capabilities for the research and environmental impact communities. The need was voiced for commercially available Lagrangian sensors for measurement of the probability of impact of pollutants expelled into the environment.

The future of current measurement technology might best be summed up by excerpting from Jim McCullough's presentation--"McCullough's crystal ball:"

In the future we might expect to see:

- Revival of the surface mooring
- Much activity in the upper and bottom boundary layer
- Rapid growth of doppler technology (laser, acoustic)
- Solid-state memory advances leading to flashlight-sized current meters
- Development of current sensor strings or pods
- More telemetry and real-time control of data acquisition
- Roving moorings
- Better funding.

An issue that was raised and discussed vigorously at the conference was the apparent failure of the scientific community to explain why they were doing their science. This issue has prompted a response by Chris Mooers of the University of Delaware. The response is in the form of an "Essay on the Basic Research Goals of the Physical Oceanographic Community Engaged in Current Measurement." The essay is included in the appendix to these proceedings.

SUMMARY OF WORKING SESSION AND RECOMMENDATIONS

The working session was originally organized to address some specific questions that were selected before the conference. During the conference, however, it became apparent that there were some important issues over and above the preselected questions that should be discussed. A full report of the session is provided in these proceedings (p. 305) and a summary discussion of the highlights is given below.

A. A handbook or compendium of current measurement would be useful. The handbook would contain a summary of manufacturer's information on the operational characteristics of their current measurement systems. Additionally, the handbook would include results of independent performance evaluations with subjective yet credible opinions from users based on experiences with particular system applications. The objective would be to have an easily revised document for use in choosing appropriate technology.

B. Community-sanctioned standardized testing methods and procedures are needed. Although there exist many good and useful testing procedures throughout the community, their lack of commonality makes difficult comparison of test results for different or even the same instruments. The important result of having standardized testing procedures sanctioned by the measurement community would be that every current meter could be tested against them with credible and comparable results.

C. Suggestions for an appropriate mechanism to implement the above procedures and to fill the void created by the disestablishment of the National Oceanographic Instrumentation Center stimulated much discussion. The idea of some sort of government-sponsored central testing capability, perhaps open to all who have a need, was proposed as a cost-effective service to the nation. The rationale behind this idea is based on the large capital investment needed for current meter testing facilities, which manufacturers in a small volume market cannot afford individually, and because the federal dollar is directly or indirectly associated with the purchase of the majority of current measurement instruments. A central capability of this type would ultimately save the taxpayers money by assuring that good quality instruments are used to support measurement programs.

D. It was agreed that there is a need for both hardware and software "standards" applicable to the measurement of current. The discussion focused on laboratory standards, in situ hardware standards and data recording standards: both technique and format.

Laboratory testing requires a knowledge of the relative water motion past an instrument undergoing test. A device or combination of devices of known accuracy, responsive to a broad range of time and spatial scales (for steady and non-steady conditions) is needed as a standard for laboratory measurements.

For field applications, there is a need for some type of device of known accuracy or perhaps a calibrated flow field along with which or into which an instrument could be deployed and its absolute performance determined.

The problem of the lack of data recording format and technique standards is significant. Adoption of existing standards of this type would eliminate the costly and unnecessary duplicate magnetic tape processing facilities required by the several recording methods and formats available in existing current measurement instrumentation.

An important consideration relative to the whole issue of standards is that current measurement technology is continually evolving technically. Because of this, it may not be feasible or even correct to develop a standard. Perhaps a class of evolving standards of standard systems would be more appropriate.

E. It was proposed and agreed that an ad hoc committee be formed at the conference. Committee members representing each segment of the community were elected at the working session and were given the charge to be the initial community mechanism responsible for addressing the issue of current measurement standards. During its one-year lifetime, the committee will focus its efforts on considering development of standardized testing methods and procedures and investigate the possibility of creating a permanent committee affiliated with one or more professional societies.

F. The establishment of a library or "reading room" open to everyone at which all pertinent current measurement literature would be available for reference was recommended. The library would maintain close liaison with the community and actively seek new published or unpublished information or data pertinent to current measurement technology.

G. Who should underwrite the cost for research and development of new current measurement technology ideas--industry or the federal government? Because the market is small and uncertain, investment in current measurement R&D is risky, and industry typically tries to maintain a low dollar level input. To industry, federal government support of the risky R&D phase is appealing for obvious reasons. The issue, however, is whether it is appropriate for the government to support the development of technology that may ultimately compete with existing technology that was developed with money invested by industry. The feeling is that when it can be demonstrated that specifications for a particular piece of technology required for a government project cannot be met by existing technology, R&D may be necessary and government support on a competitive basis is appropriate. However, since we lack accepted current meter test procedures and standards, demonstrating an instrument's adherence to certain specifications may be difficult if not impossible. Thus, the lack of testing capability complicates this issue and makes it difficult in many cases to judge the appropriateness of government-sponsored development.

GENERAL SESSION

NEAR-SURFACE OCEAN CURRENT SENSORS: PROBLEMS AND PERFORMANCE

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ABSTRACT

When current meters are used to measure mean horizontal currents in the presence of surface gravity wave motions, immunity to the vertical component of flow is important, even though the net vertical flow averages to zero and is normal to the desired horizontal components. A technique is presented for estimating the magnitude of the errors introduced by imperfect rejection of the off-axis flows (cross-talk) from laboratory measurements of the current meter "vertical-cosine-response." The predicted dynamic response is shown to compare favorably with laboratory measurements. The measured steady state vertical-cosine-response functions for several practical current sensors are summarized and used to estimate the magnitude of wave induced errors in horizontal mean current measurements. A new dye technique for evaluating near-surface current meter performance in waves is shown.

WORKING CONFERENCE ON CURRENT MEASUREMENTS, JANUARY 1978. SPONSORED BY THE NOAA OFFICE OF OCEAN ENGINEERING AND THE DELAWARE SEA GRANT COLLEGE PROGRAM.

INTRODUCTION

Ocean currents can now be measured routinely in all but the strongest flows and in the surface wave zone. In the wave zone, the orbital velocities require greater sensor linearity than has, until very recently, been available. McCullough (1978), Davis and Weller (1978), Smith (1974) and others describe acoustic and propeller sensors which show considerable promise for wave zone measurements.

It may seem strange that flow measurements in waves are difficult to make, when both time and distance can be measured with extraordinary accuracy. The difficulty arises naturally from the broad-band nature of wave zone flow. There is no single speed present, but rather a mixture of speeds and length scales characterized by their broad frequency and wave-number spectra. Implicit then in the concept of fluid "velocity" is knowledge of the averaging processes (time and space) used in making the measurement. The nature of errors introduced by improper averaging in the presence of surface gravity waves and/or wave-driven mooring motion is the subject of this paper.

THE SIGNAL

Figure 1 shows the nature of the near-surface flow signal as inferred from photographic and pressure measurements and as measured directly by current meters. Wave flow in a "sea" is seen to be very complex, quite unlike the periodic linear motions traditionally used to model it. In (b) and (c), note the similarity of wave shape over a wide range of wave scales [from 0.5 m waves in (c), to 10 m waves in (b)]. The v and w (horizontal and vertical) speeds shown in (d) give some feeling for the signal at 2 m as seen from a rigid platform. In other records of this type, Shonting (1967) shows that even the approximate 90° phase relation between v and w is not always maintained.

Figure 2 shows a typical frequency distribution of flow energy near the ocean surface. The term ocean "currents" is conventionally used to describe motions such as those of the tidal, inertial and lower frequency processes shown at the left. To measure these currents in the presence of the large wave energies shown at the right, some form of frequency separation (usually vector averaging) is used to reduce the current meter band-width. The separation is made practical by the low energy "gap" at frequencies of roughly 1 to 10 cycles per hour. To limit the scope of the discussion here, current meters are assumed to register only the mean horizontal component of current below wave frequencies, i.e., the part of the signal to the left of the wave energy in Figure 2.

VECTOR AVERAGING

Figure 3 further illustrates the importance of low-pass velocity component filtering (vector averaging) in the wave zone. Note that the

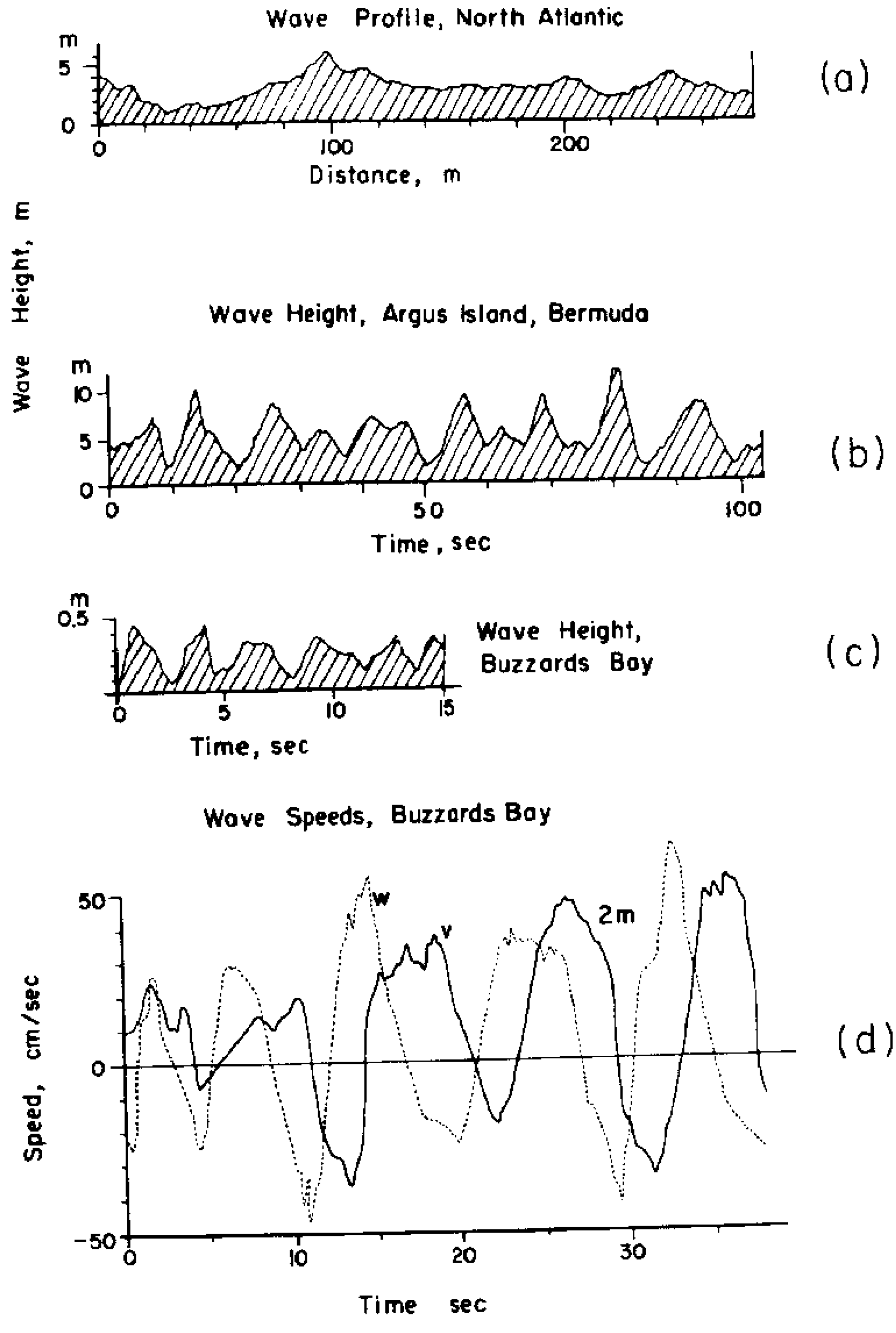


Figure 1. Measured wave signals from stereoscopic photographic measurements (a); tower-mounted pressure gauges (b) and (c); and direct propeller speed observations from a fixed tower at 2 m depth in small waves (d). "Sea" waves are seen to be highly irregular in space, time and speed. (Frames (a-c) after Neumann and Person, 1966; frame (d) after Shonting, 1967).

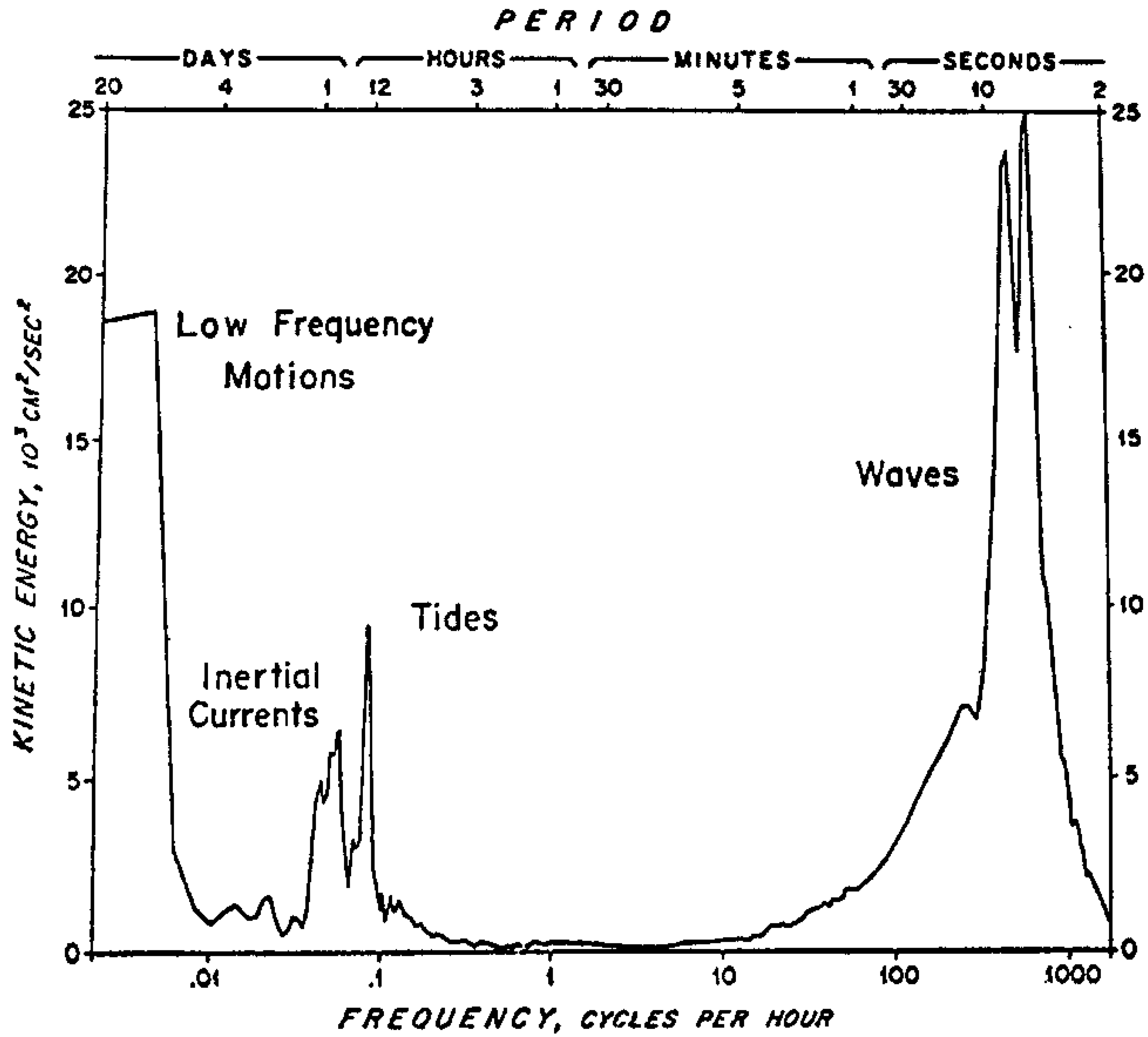


Figure 2. Typical distribution of energy near the ocean surface as a function of frequency (and period). The data are scaled so that equal areas under the graph represent equal energies, a "variance preserving" plot. To measure the lower frequency tides, etc. (at left), it is necessary to follow the wave motions (right) even though they average to zero (after Webster, 1967).

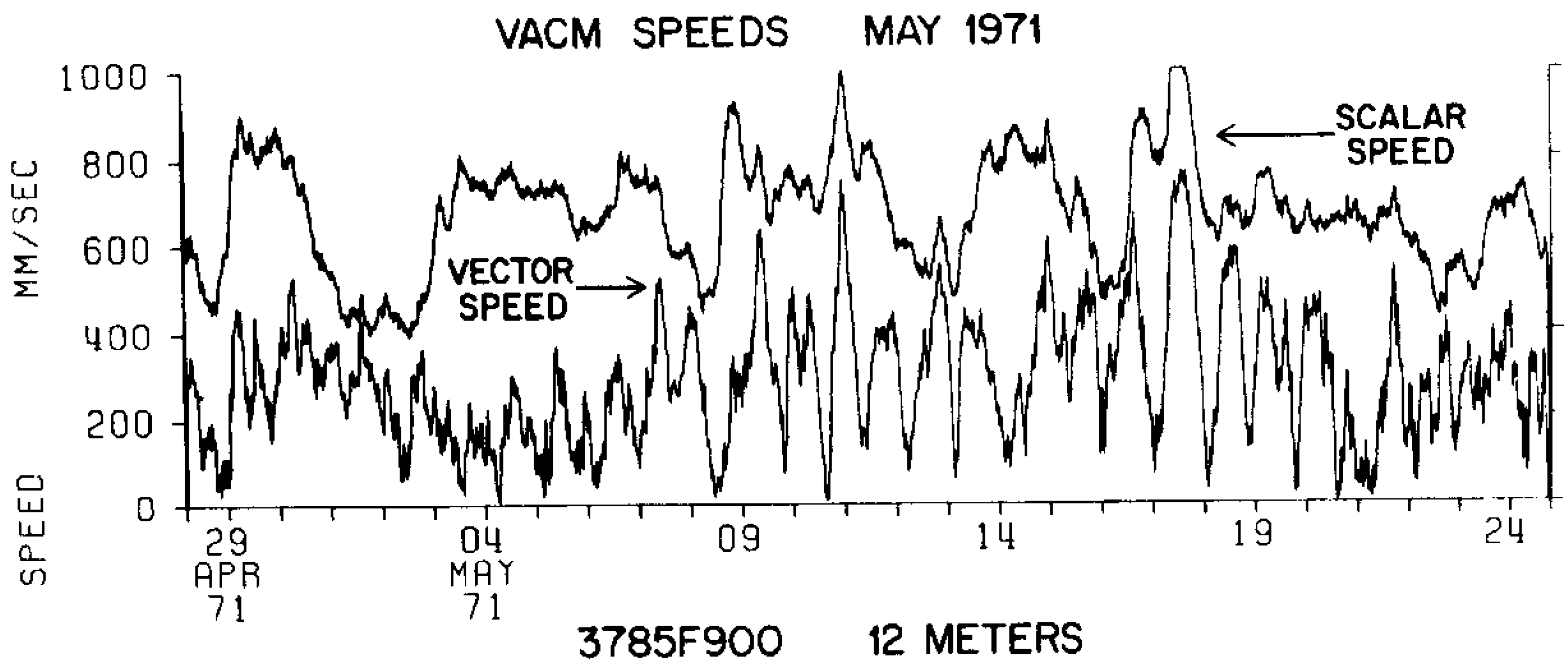


Figure 3. Vector averaging current meter (VACM), rotor speed and vector magnitude at 12 m depth below a surface-following toroid float in 2665 m of water at W.H.O.I. Site D, May 1971. Note that the rotor speed from one 15-minute sample to the next is nearly constant (the rotor curve is relatively smooth from hour to hour). Also note that the vector speed found by including several thousand compass-vane samples each 15 minutes is often much smaller than that of the rotor value. On 10 May, for example, the indicated vector average goes to zero even though the rotor is being turned at about 80 cm/sec (after McCullough, 1975).

rotor (scalar) speeds of the vector averaging current meter (VACM) are large, while the magnitude of the vector-averaged velocity varies from nearly that of the rotor on May 1, to two (or more) orders of magnitude less on May 10. For this reason, current meters that use separate speed and direction averaging schemes (Aanderaa, Alexaev, Hydro Products, etc.) are generally not considered suitable for measuring mean velocity in the wave zone.

SENSOR RESPONSE

Figure 4 illustrates the improvement in sensor response that can be expected with acoustic-travel-time-difference sensors as compared with rotors. Laboratory measurements of rotors have for some time shed doubt on the validity of all rotor-vane measurements in waves. As will be suggested in the discussion of Figure 13, such reservations may be overly conservative since the laboratory tests may inadequately model broad-band wave flows seen from moving moorings.

A KINEMATIC MODEL OF VERTICAL-COSINE-RESPONSE

The importance of curent meter "vertical-cosine-response" is illustrated in Figures 5 through 9. The term "vertical-cosine-response" is used to describe a current meter's ability to reject vertical components of flow while making horizontal flow measurements, i.e., to measure only the component $V \cos\theta$, of flow V at an angle θ to the horizontal plane. Figure 5 introduces the simulation model concept. The model is used to estimate mean horizontal dynamic response from steady flow measurements of vertical-cosine-response. The analysis treats only the kinematics of the problem and does not include important dynamic considerations such as sensor wakes and response in turbulence.

At the top of the figure, the modeled circular wave orbit velocities ($a\omega$) are added to mean speeds (V_0). The speeds S are then numerically integrated to find the average velocity ($\overline{V}$) of meters with imperfect vertical-cosine-response. Since the direction errors introduced by inaccurate vertical-cosine-response are generally small ($\sim 5°$ or less), only the speed component of $\overline{V}$ is treated here.

The model results are parameterized by the response ratio $\overline{V}/V_0$ (the ratio of measured to true mean speed), and the "signal-to-noise ratio" $V_0/a\omega$ (the ratio of the steady to the oscillatory speeds). The three circular diagrams at the top of Figure 5 give example flows to help visualize the ratio $V_0/a\omega$. The assumed departures from ideal vertical-cosine-response are shown at the top right. The bottom graph gives the modeled mean response of the meters in single-frequency, circular-orbital waves which are coplanar with the mean velocity V_0. For signal-to-noise ratios less than one ($V_0/a\omega < 1$), reversing flows are indicated.

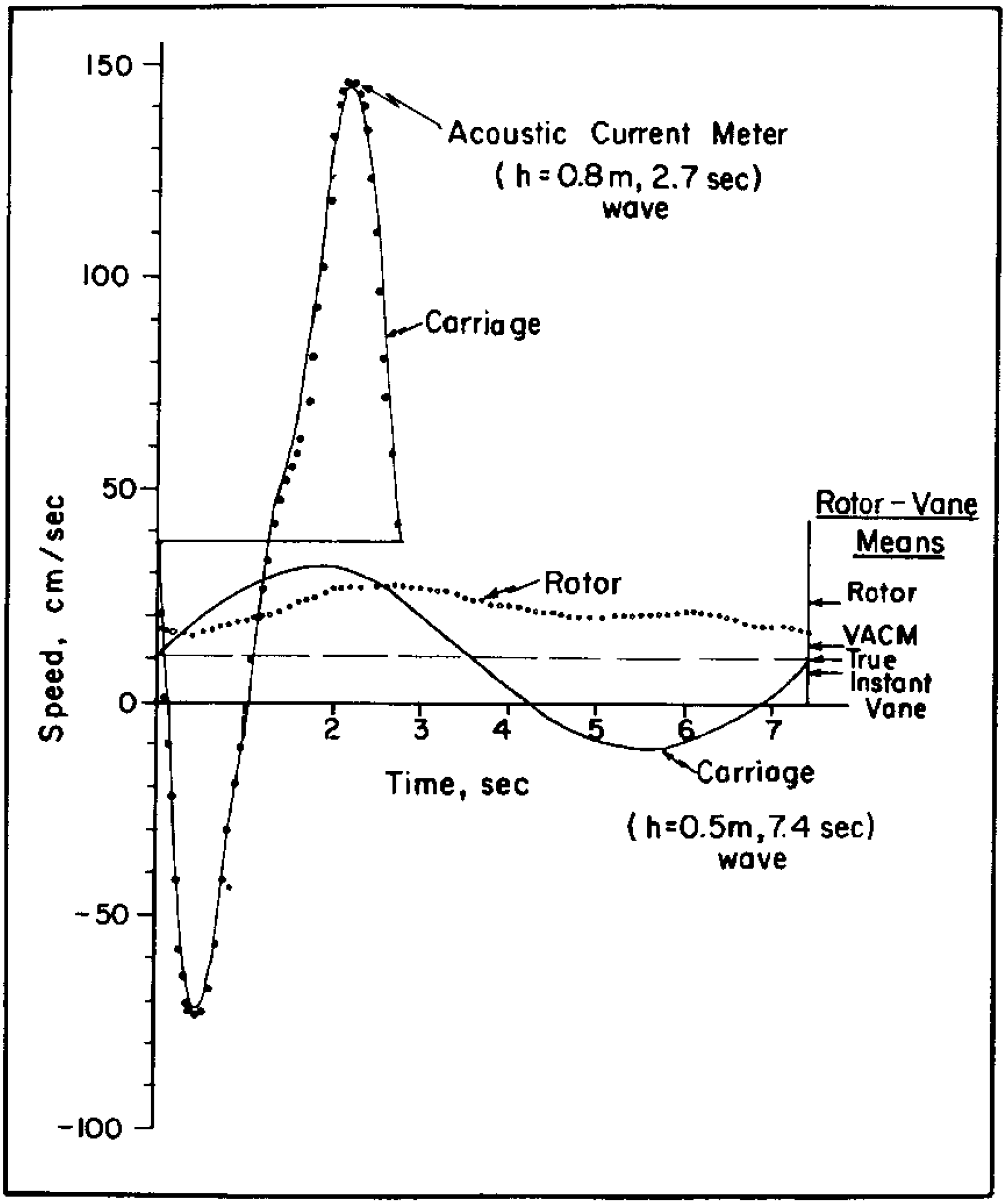
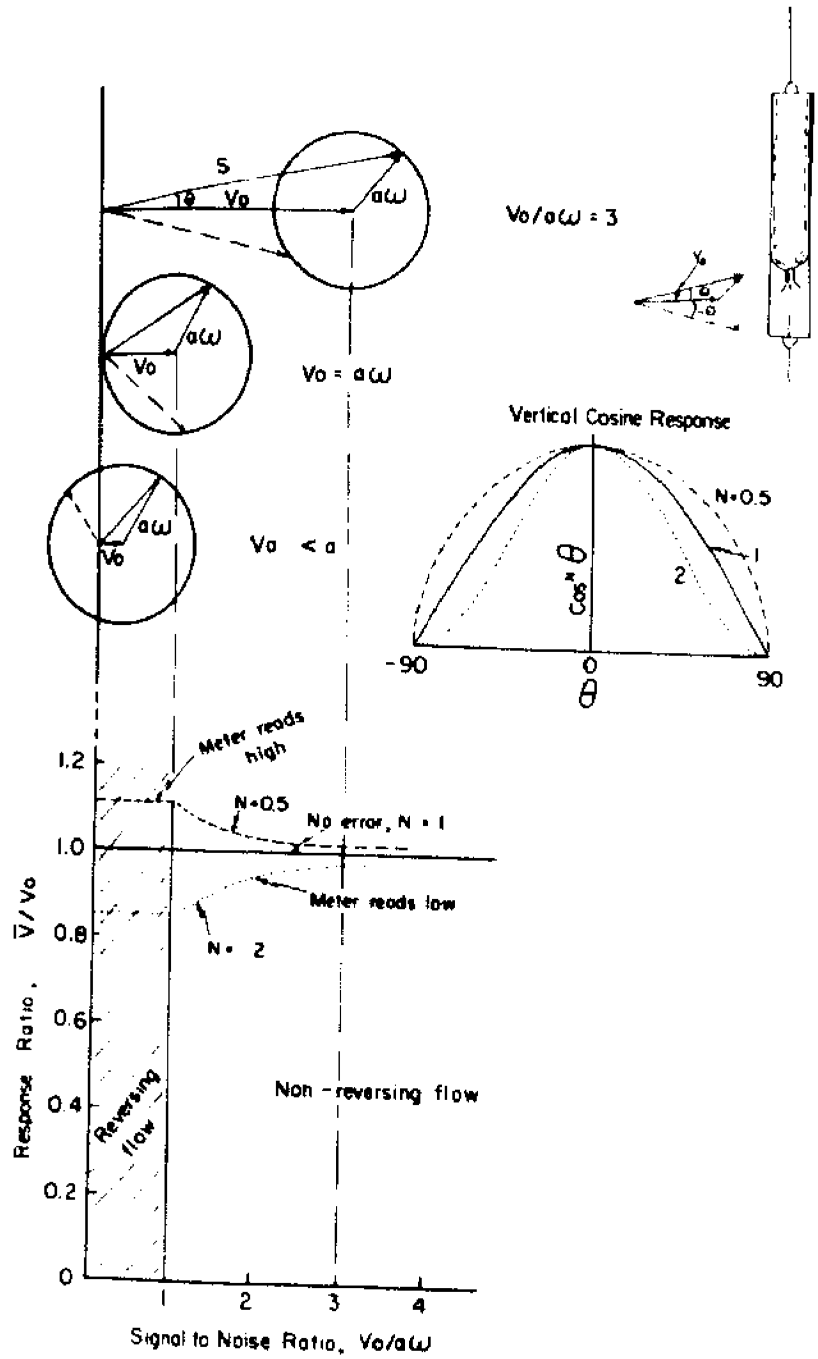


Figure 4. Dynamic tow tank data from an acoustic-travel-time-difference current meter and a VACM. The acoustic meter (upper dotted curve) follows the carriage coplanar sloshing motion almost exactly, while the rotor (lower dotted curve) runs nearly twice as fast as the true mean value shown at the right. Also at the right, if the vane response were instantaneous (no lag), the mean value would be too small. The mean found by the lagged vane of the VACM, however, is somewhat too large. If the vane had not reversed, the mean would be that of the rotor which is too large by about a factor of 2. (After McCullough, 1974 and more recent unpublished data.)



gure 5. Effects of imperfect vertical-cosine response in an otherwise ideal (no errors) current meter. The three circular figures at the top represent different ratios of steady flow V_o to the coplanar circular velocity $a\omega$. As shown in the lower figure, the flow is reversing for the ratio $V_o/a\omega < 1$. Three different assumed values of vertical-cosine-response are shown in the insert (upper right). High, correct and low response values are indicated by $\cos^N\theta$ for N = 0.5, 1 and 2, respectively. In the lower graph, the ratio of the modeled current meter mean-flow $\bar{V}$ to the true mean V_o is shown as a function of the signal-to-noise ratio, $V_o/a\omega$, for each of the three cases. In the reversing flow region, the response ratio is constant at 1.12, 1 and 0.85, respectively. As the signal-to-noise ratio increases beyond one, the response improves (approaches $\bar{V}/V_o = 1$). For ideal cosine response (N=1), the response ratio is always unity.

Critical values of the response ratio and signal-to-noise ratio exist at values of ONE. The line $\overline{V}/V_0 = 1$ represents the locus of all correct readings. As will be shown next, $V_0/a_\omega = 1$ separates regions of high and low dependence on wave orbit characteristics.

Figure 6 extends the coplanar circular-motion of the previous figure to more general cases including elliptical motion (such as seen from a surface following mooring) and orbital motion at an angle to the mean flow (the usual case).

A collection of various calculated responses is shown in Figure 7a and b. For signal-to-noise ratios less than "one" (to the left of the vertical dash-line), a wide range of error conditions exists depending on the wave and mean current geometries. For values greater than "one," such considerations are of little importance. Figure 7b shows that typical near-surface ocean conditions place high demands on rigidly mounted current meters. The actual moored situation modeled in Figure 11 is more complex but at shallow depths is less demanding.

Figure 8 shows measured vertical-cosine-response functions of four practical ocean current sensors tested at the David Taylor Model Basin (now called DTNSRDC for short). The functions have been used as input to the model to predict the error components due to improper vertical-cosine-response. From the 12 curves labeled n, c and ℓ (for normal, coplanar and linear-normal oscillations respectively), it is clear that the predicted errors are complex functions of the signal-to-noise ratio and can be large at low signal-to-noise ratios. This complexity may help account for some of the puzzling response variability frequently noted in *in situ* wave zone intercomparisons. Halpern (1977 and 1978) reviews such *in situ* intercomparisons. Note that low values of V_0/a_ω do not necessarily imply small (insignificant) mean speeds V_0.

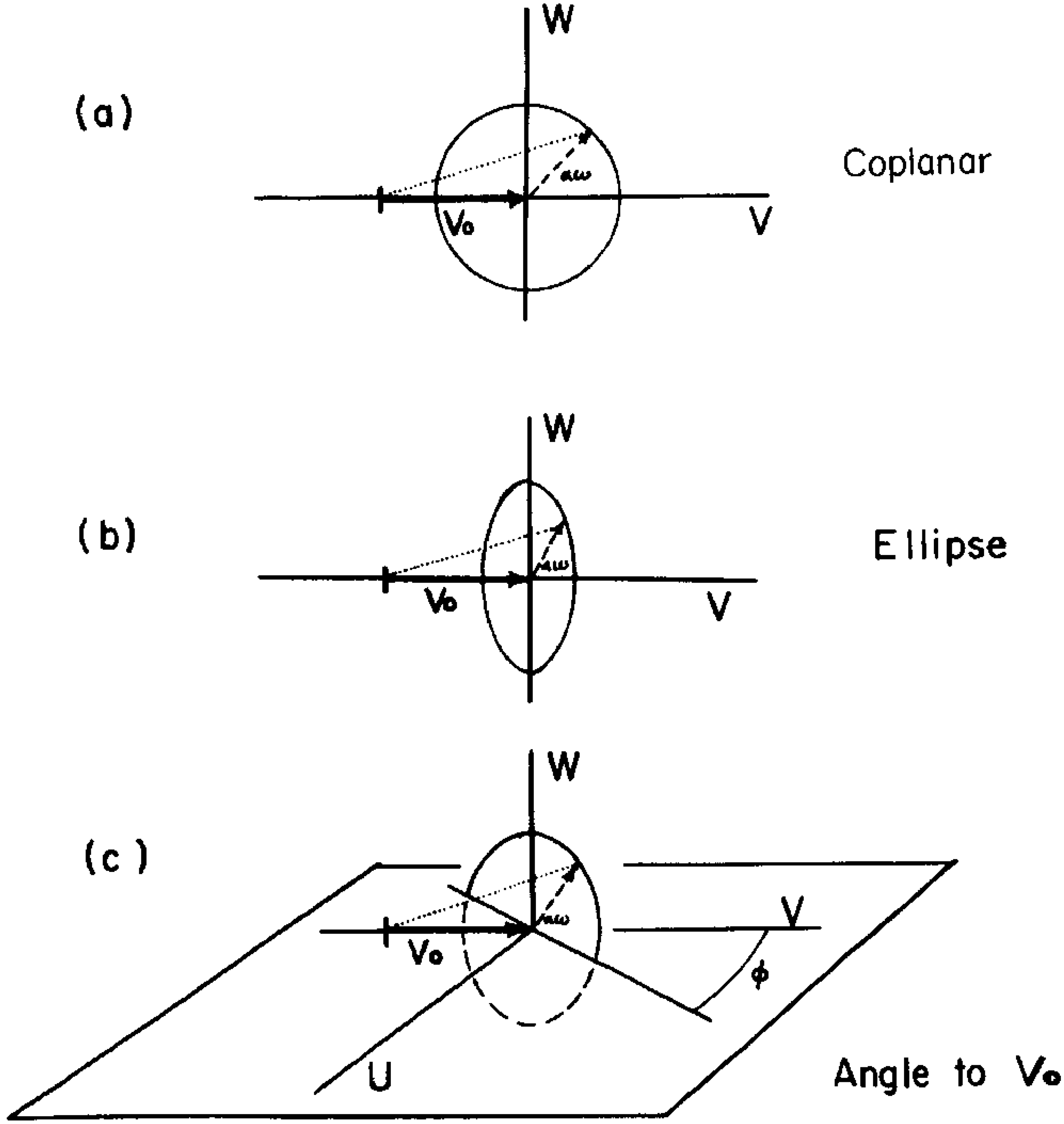
Figure 9 shows the general agreement between predicted and measured dynamic response for a prototype acoustic-travel-time-difference meter. The agreement with the model suggests the importance of vertical-cosine-response in such meters.

SOME MEASURED DYNAMIC RESPONSE FUNCTIONS OF CURRENT SENSORS

Figure 10 compares the measured dynamic response of four popular types of current sensors, plotted in the same coordinates used in the previous figures. At low signal-to-noise ratios, the particular electromagnetic and rotor-vane systems shown (top) overestimate speeds, while the propellers and acoustic sensors (bottom) tend to underestimate the mean.

ERRORS DUE TO MOORING MOTION

Figure 11 (top left) shows the Stokes-drift and error due to surface following vertical-mooring-motion as a function of depth, for the long



gure 6. Three cases of orbital and steady motion are considered in the following four figures: (a) Coplanar V_0 and circular $a\omega$; (b) Elliptical motion as might be seen at moderate or mid-depths on a surface-following mooring; (c) Orbital motion (circular or elliptical) at an angle ϕ in the horizontal plane to V_0.

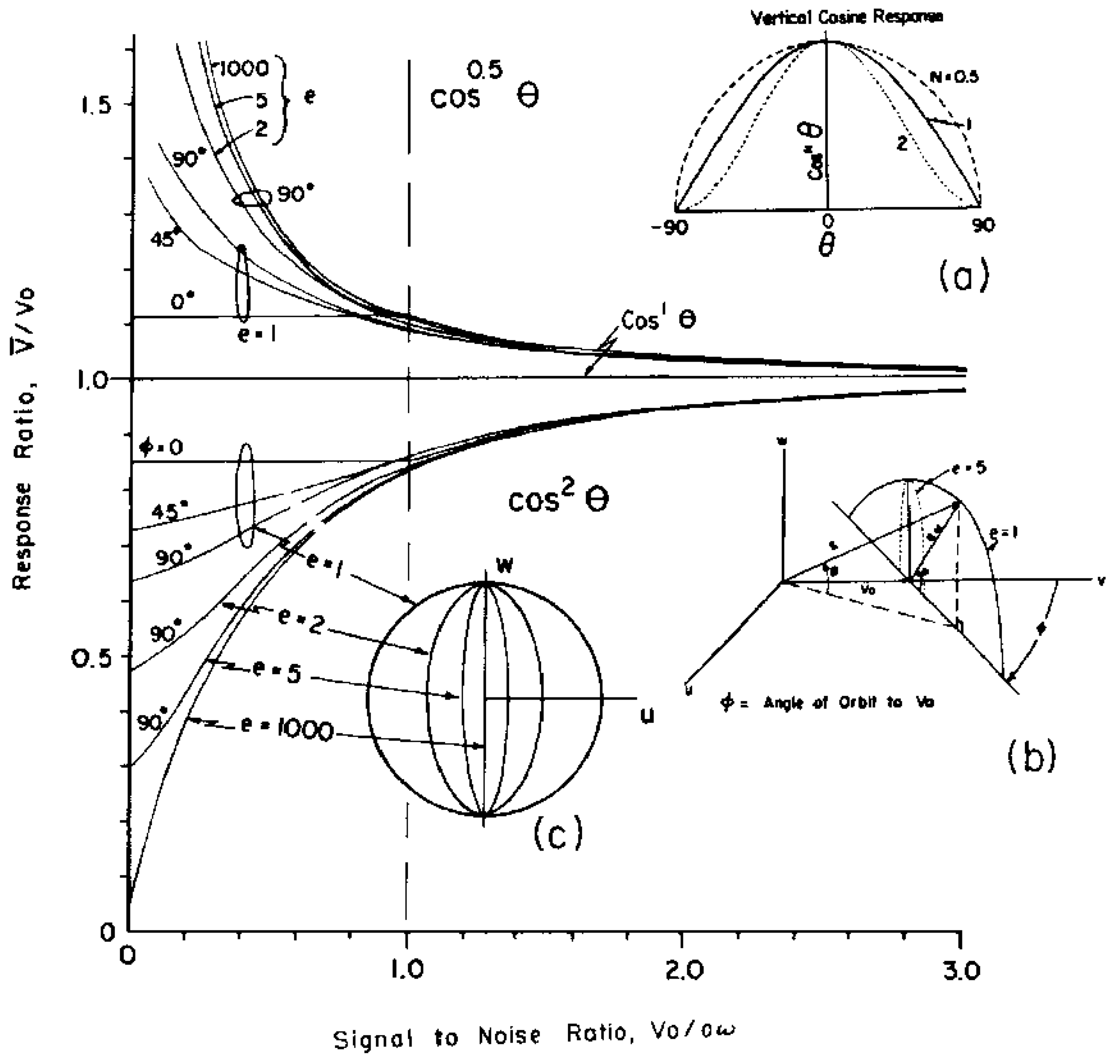


Figure 7a. Modeled dynamic response for the three assumed analytic vertical-cosine-response functions ($\cos^{1/2}\theta$, $\cos\theta$ and $\cos^2\theta$) shown at (a). The angle ϕ of the oscillatory flow $a\omega$ to the mean flow V_o is shown at (b). Effects of reducing the size of the horizontal component of the oscillatory flow are shown at (c). In the upper half of the figure, it is seen that the particular nature of the oscillatory flow is of little importance to the right of the vertical dashed-line through $V_o/a\omega = 1$. The errors continue to converge and diminish (approach the $\bar{V}/V_o = 1$ horizontal line) as the signal-to-noise ratio improves. To the left of the vertical $V_o/a\omega = 1$ dashed-line, however, the response errors are larger and are strongly dependent on the wave and mean-flow conditions.

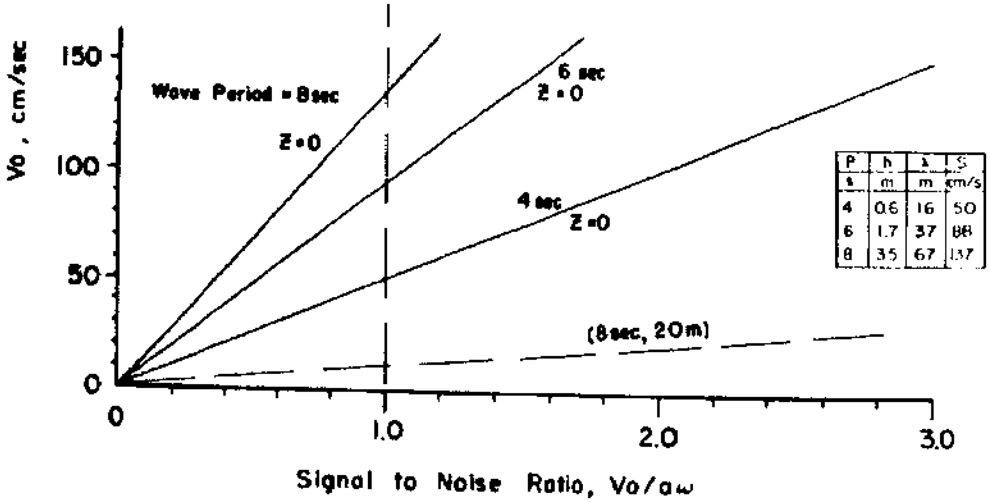


Figure 7b. This graph indicates for four wave-depth conditions, the relation between the signal-to-noise ratio, and the mean current V_o. Note that for typical open sea conditions (4-8 sec waves and mean currents below 50 cm/sec) the near surface signal-to-noise ratio is less than one (i.e., is to the left of the vertical dashed line). Deeper conditions (such as indicated by the 8 sec, 20 m depth line) on rigid platforms are less severe. (A quite different situation, modeled in Figure 11, exists, however, on conventional surface-following moorings.) The insert table gives the assumed single-frequency wave parameters. (P = period, h = height, λ = wavelength and S = orbital speed.

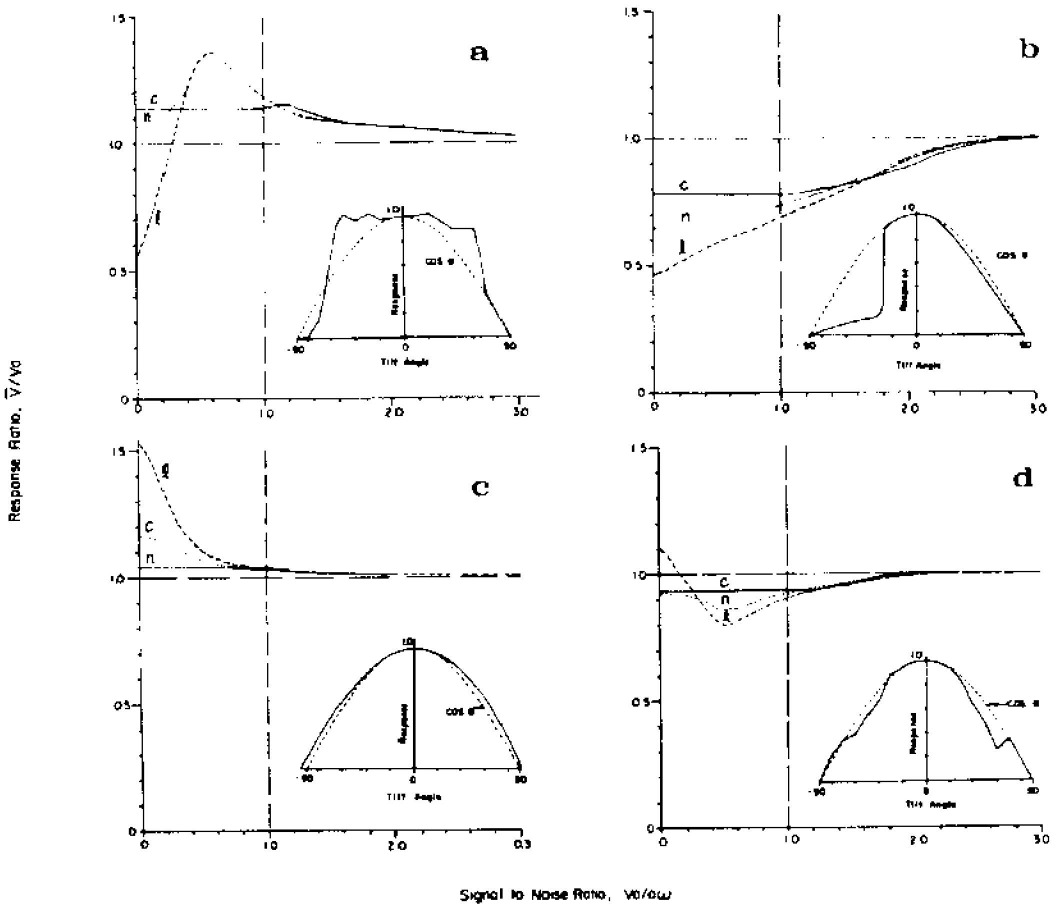


Figure 8. Modeled dynamic response calculated for four measured steady-state vertical-cosine response functions. a) A one-inch diameter cylindrical electromagnetic probe between flat circular end plates. b) Disc-shaped electromagnetic sensor. c) Same probe as in a) less the end plates. d) An acoustic-travel-time-difference probe of the mirror type. The measured static response functions are shown in the insert of each frame. The curves labeled n, c and ℓ represent normal (ϕ = 90), coplanar (ϕ = 0) circular orbits, and linear (large e) normal sinusoidal motion respectively. As before, the vertical dashed lines separate regions of high (left) and low (right) sensitivity to the orientation and shape of the oscillatory flow (a, b and c after McCullough, 1974; d after Appell, 1977a).

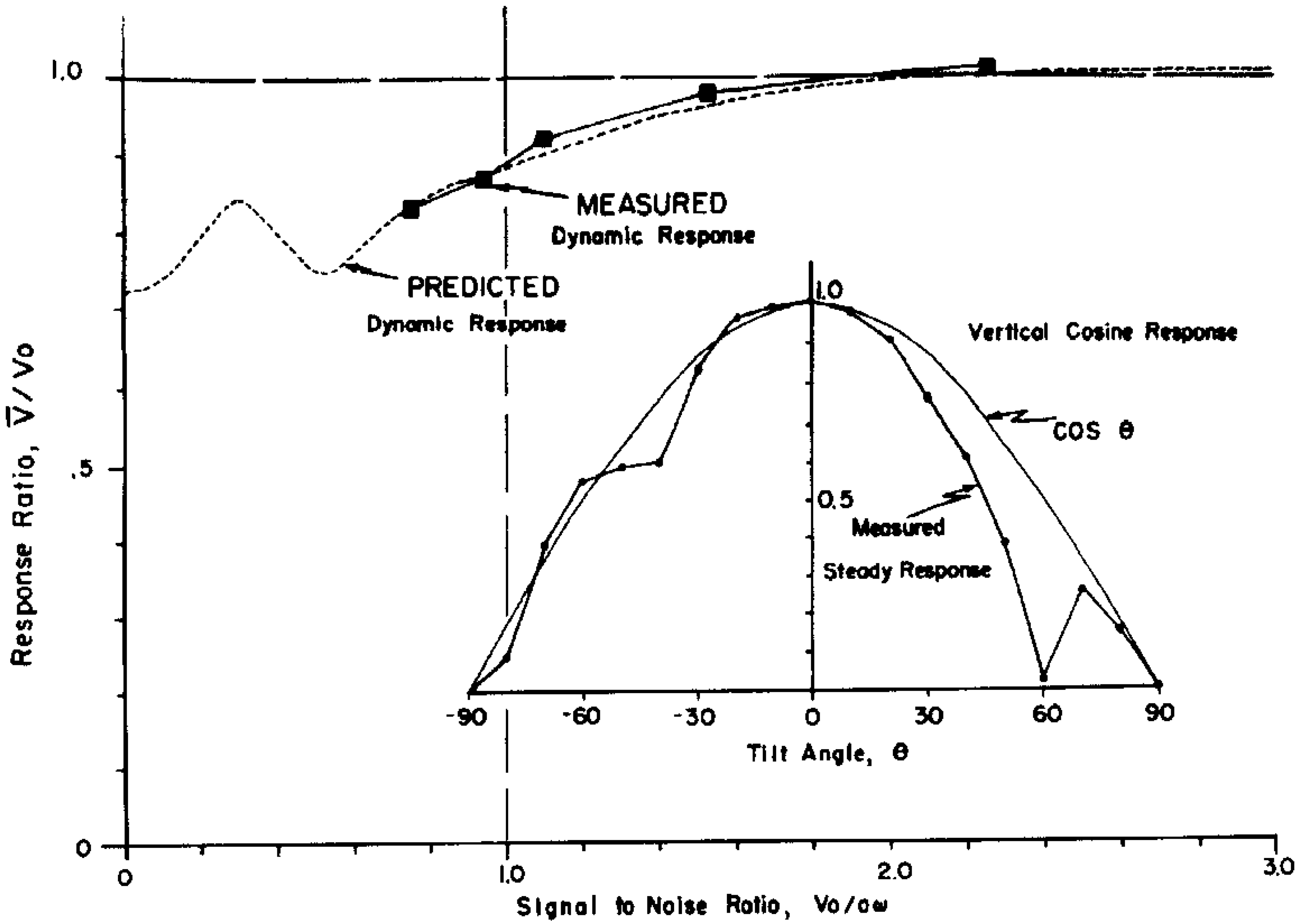


Figure 9. Model verification is demonstrated by predicted and measured dynamic response of an experimental mirror-type acoustic-travel-time-difference current meter. The measured steady-flow vertical-cosine-response used to calculate the predicted dynamic response is shown in the insert. (The low response at plus 60^{0} is caused by the wake of the acoustic mirror.) The good agreement between the measured and predicted dynamic response suggests that the main source of dynamic errors in this type meter is traceable to the static vertical-cosine-response. (Measured data after Appell, 1977a.)

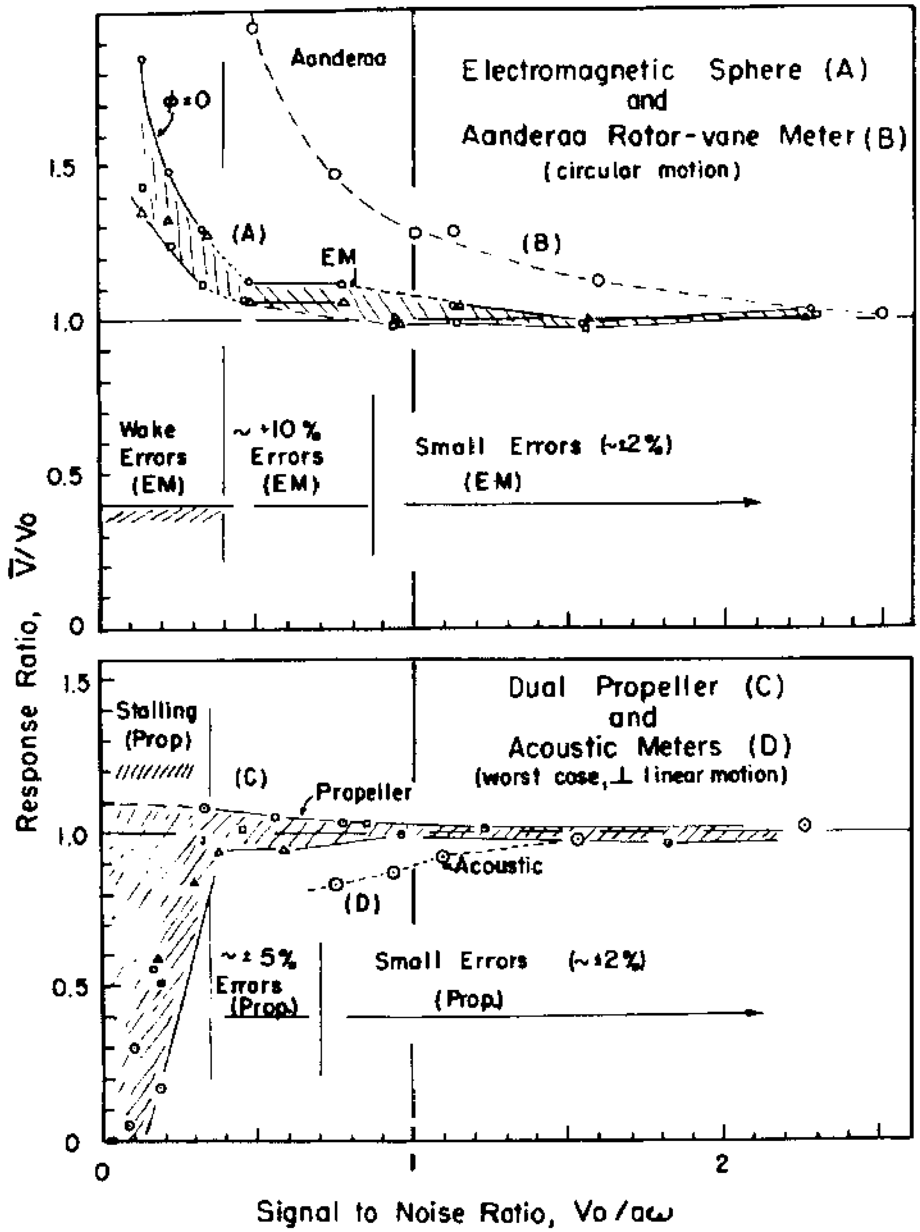
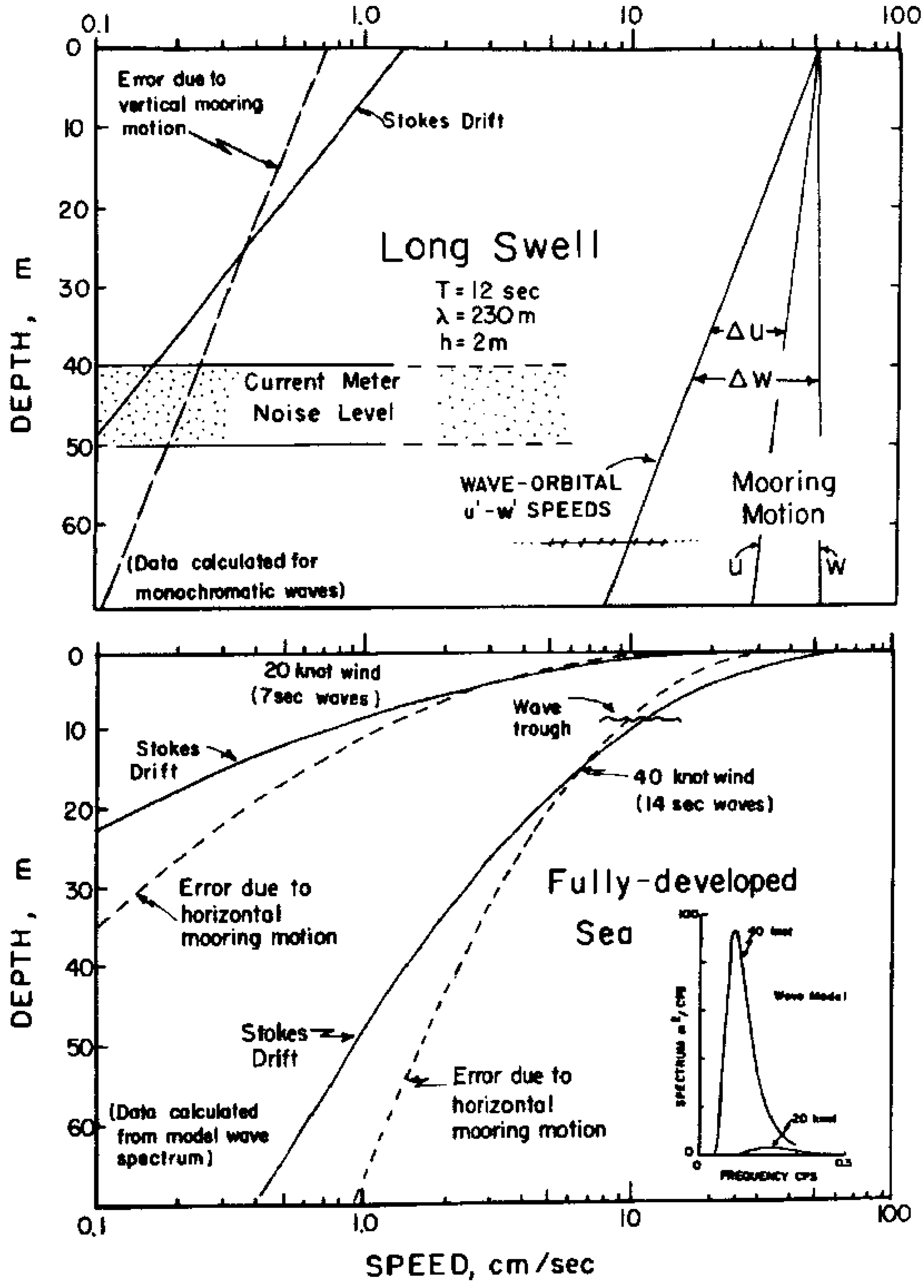


Figure 10. Measured dynamic response functions from four types of moored current sensors used in wave-zone studies. Measurements are plotted in the coordinates used previously. At the top, the response of an electromagnetic sphere (A) and an Aanderaa rotor-vane current meter (B), are shown for coplanar-circular-orbital motion (1.22 m diameter, three periods) superimposed on selected linear tow carriage motion. In the lower frame, performance of dual propellers (C) and acoustic-travel-time difference (D) flow sensors are shown for linear-sinusoidal motion normal to the tow. In a) note that for $\phi = 0$, the measured dynamic response function is not constant as predicted by the kinematic model of Figure 5. This suggests that additional and dominant, dynamic effects exist. (Data in (a) after Kalvaitis, 1977; (b) after Appell, 1977b; (c) after Davis, 1978a; (d) is the same as shown in the previous figure.)

Figure 11. (facing page) Schematic representation of mean errors caused by mooring motion in waves. Perfect current meters (no error in measuring relative flow) are assumed. In the top left figure, the magnitude of Stokes-drift and errors caused by vertical mooring motion in the wave conditions indicated, are shown as a function of depth. The stippled "current meter noise level" block indicates for this condition of swell that the mooring-induced errors are relatively small.

At the right, a simple exponential-decay mooring model is used to illustrate the increase of both the horizontal and vertical oscillatory relative-motions (ΔU and ΔW) seen by moored instruments with depth. The wave "noise" seen by the meters increases with depth.

In the lower figure, the Stokes-drift and horizontal mooring-motion-induced current meter errors are shown for the modeled wave spectra shown in the insert (after Kenyon, 1969). The curves at the left are for fully developed seas of 20 knot (10 m/sec) winds, the pair at the right are for fully developed seas of 40 knot winds.



0.1
1.0
10
100
Error due to vertical mooring motion
Stokes Drift
Long Swell
T = 12 sec
λ = 230 m
h = 2m
Δu
Δw
Current Meter Noise Level
WAVE-ORBITAL u'-w' SPEEDS
Mooring Motion
u
w
(Data calculated for monochromatic waves)
DEPTH, m
20 knot wind (7sec waves)
Wave trough
Stokes Drift
40 knot wind (14 sec waves)
Error due to horizontal mooring motion
Fully-developed Sea
Stokes Drift
Error due to horizontal mooring motion
(Data calculated from model wave spectrum)
Wave Model
40 knot
20 knot
FREQUENCY CPS
SPEED, cm/sec

Figure 11

swell condition indicated. Ideal current meters (ones with no errors), no lateral motion and monochromatic waves are assumed in this case. The predicted mooring-induced errors are seen to be relatively small. In other situations, particularly very near the surface in high seas or at mid-depths on surface-following moorings, the motion-induced errors may be dominant. (For further discussion of the Stokes drift and mooring motion effects see Kenyon, 1969; Pollard, 1973; Ianniello and Garvine, 1975; Carson and Collar, 1977, etc.).

The exponential decay of the wave-orbital horizontal and vertical speed components, u′ and w′ (upper right), are also shown as a function of depth. In typical deep-sea wire-moorings, the vertical-mooring-motion (w) is essentially undiminished with depth in the upper part of the mooring. The horizontal mooring motion component (u) is different, however, and can be modeled to first order as being equal to u′ at the surface with an exponential decay (but a slower rate than the waves) with depth. (The model of u shown is patterned after one developed by NDBO.) The oscillatory component of flow seen by current meters on the moving mooring is indicated by Δu and Δw in the figure. Note that the relative orbital motion typically increases, rather than decreases, with depth over the upper part of a surface-following mooring. Also, mean currents typically decrease with depth. These wave, mooring and ocean properties combine to produce favorable signal-to-noise ratios near the top and bottom of surface-following moorings, with generally less favorable signal-to-noise conditions at intermediate depths.

In the lower frame of Figure 11, errors caused by horizontal-mooring-motion in 20- and 40-knot fully developed seas (see spectrum in insert) are predicted. The Stokes-drift conditions are included since they represent a second reasonable approximation to the errors caused by mooring motion. The actual errors encountered will depend on both the mooring motion and its phase relation to the local wave flow. For this reason, error functions can not be predicted, even if the motion of the current meter is accurately known in space from other measurements such as pressure, acceleration, acoustic tracking, etc. The only hope, then, for a first order mooring motion correction in waves, is through modeled mooring response and/or through direct measurement of the mooring motion and the relative values of u, v and w at Nyquist frequencies high enough to resolve the wave motions. To reiterate:

a. Current measurement errors caused by mooring motion in waves exist even if ideal current sensors (ones with no errors) are used.
b. Knowledge of the mooring motion alone does not allow first-order correction since the motion relative to the wave is required.

HOW WELL CAN WE DO IN WAVES?

Figures 12 and 13 give some highlights of the CMICE-76 current meter intercomparison described by Beardsley et al. (1977). Figure 12 gives a

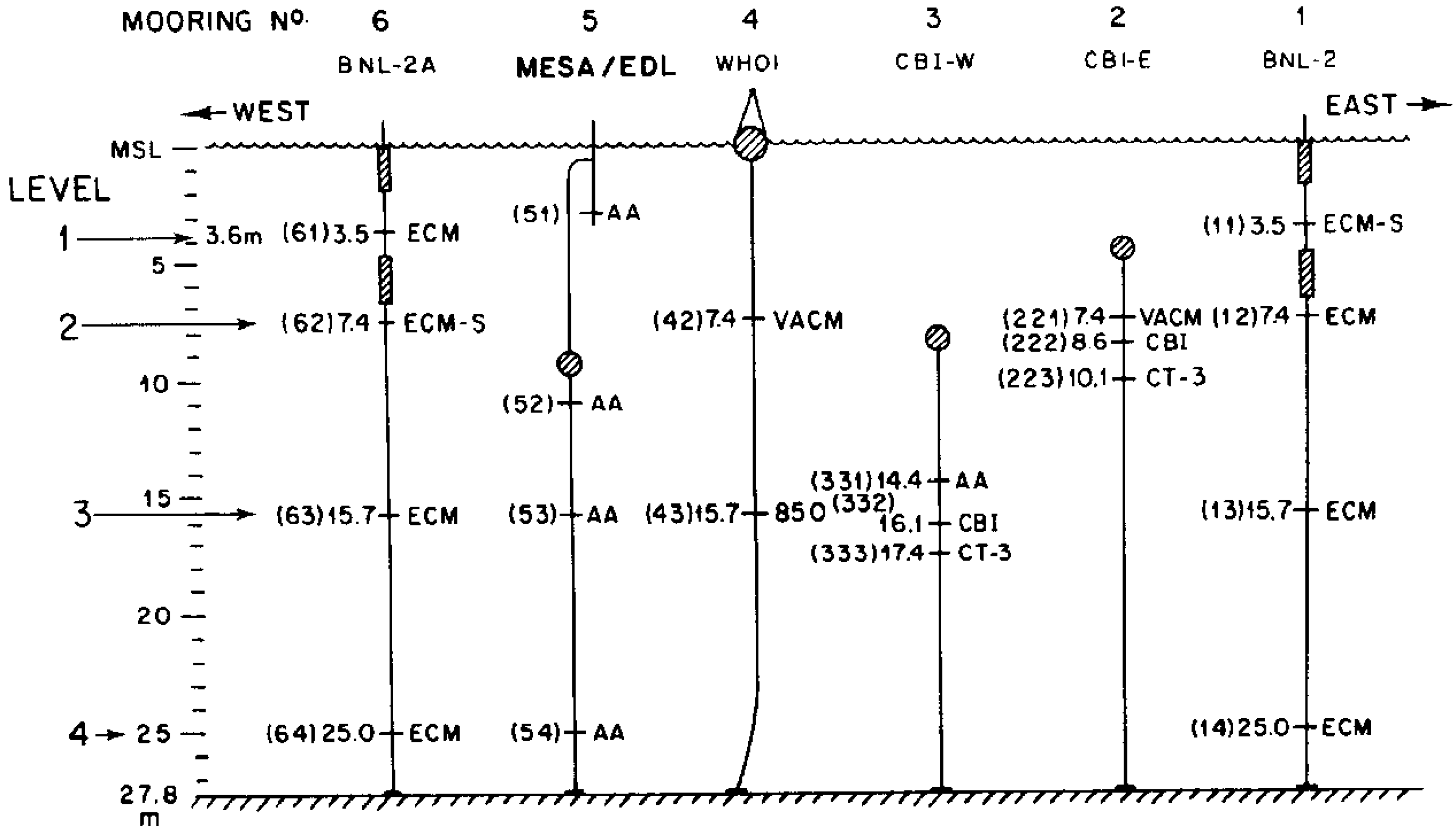


Figure 12. Mooring configuration of a recent near-surface current meter intercomparison, named CMICE-76. Moorings 1 and 6 are thin plastic spars rigidly attached to the bottom and equipped with in-line electromagnetic sensors. Moorings 2, 3 and 5 are conventional subsurface types, while number 4 is surface-following. Mooring 5 has a small spar loosely tethered to the subsurface float. The moorings are in a line 1.1 km long, parallel to shore, 5.9 km from shore in 27.8 m of water. (Some of the abbreviations are: CM = current meter, E = electromagnetic, S = spherical, AA = Aanderaa CM, CBI = modified Endeco CM, CT-3 = oriented electromagnetic CM, (---) = instrument numbers. For further details see Beardsley et al., 1977 from which this figure was taken.

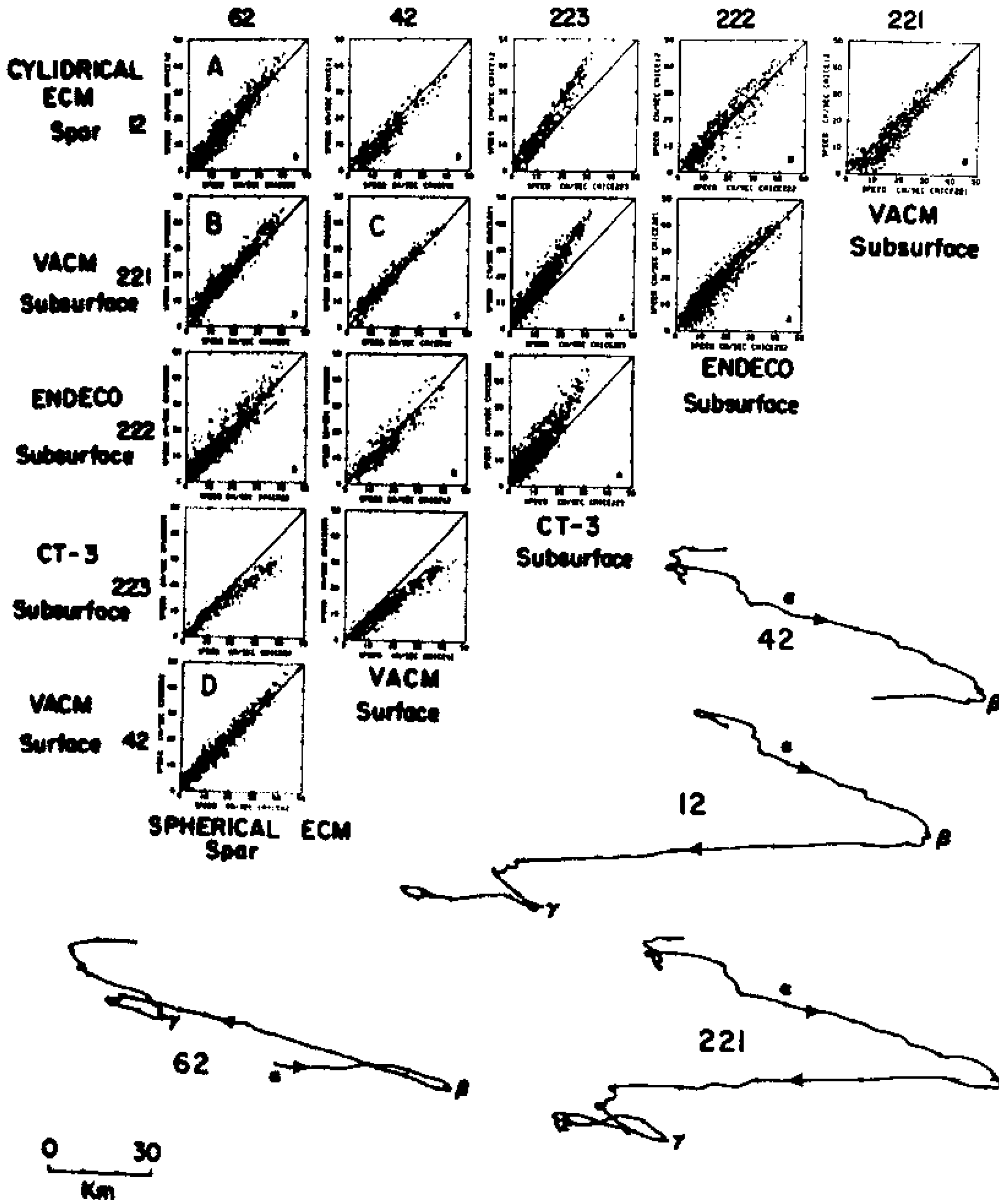


Figure 13. CMICE-76 hourly vector-mean-speed scatter plots (top) and progressive-vector plots (bottom). In the scatter plots, note the general agreement between electromagnetic cylindrical and spherical sensors (A), subsurface moored VACM and electromagnetic meters (B), surface and subsurface moored VACMs (C) and surface moored VACM and electromagnetic sphere (D). With the exception of the 5-frames involving the CT-3 data, the scatter plots show general speed agreement in the range of ± 10 cm/sec or better, in 1 to 4 m surface waves, for the six weeks of the comparison. The progressive vector plots at the bottom demonstrate that large mean direction differences can exist even in cases where the vector mean speeds generally agree. (i.e., note PROVECs 12 and 62, and the corresponding scatter plot (A).) (After Beardsley et al., 1977.)

side view of the line of six moorings set in February 1976, in 28 m of water, south of Long Island, New York.

Figure 13 gives comparative data from the 7.4 m level. Wave heights of 1 to 4 m were present during the experiment. The 15 scatter plots of one-hour vector-averaged current speeds (upper left) show (with the exception of the five CT-3 meter frames) a general agreement between the meters to within about ±10 cm/sec. Angular differences indicated by progressive vector diagrams (bottom right), however, may be large even when the speeds agree. Numbers 12 and 62 (Figure 13) and the corresponding scatter plot A illustrate the problem. The differences in this case are thought to arise from the fixed-orientation mooring system and zero-stability properties of the electromagnetic meters.

IN SITU TESTING

Moored intercomparisons of current meters at sea have been useful in identifying unanticipated *differences* between ocean current meter systems. Such tests, however, *have not* provided information on current meter *accuracy*, since the required *in situ* flow standards do not exist. Only *relative* performance is *directly observed*. Doppler current sensors on fixed platforms, acoustic ranges, etc., may one day provide the much needed standards for long-term *in situ* tests.

A short-term test technique described by McCullough (1977) is shown in Figure 14. The plan view (top) and section view (bottom) show a 20 m long, neutrally-buoyant boom, buoyed off horizontally at the desired test depth. One end of the boom is tethered to a moored boat, while the other end is free to swing with the current. Measurements of dye and drogue paths relative to the boom confirm that it aligns in waves to within a few degrees with the mean Lagrangian (Eulerian plus Stokes-drift) flow at its depth. The time of passage of dye past sensor stations at the middle and free end of the boom are used to measure the advection speed of the dye patch. The possibility of tracing the advection of the horizontal temperature variability in a similar manner is being investigated.

Figure 15 shows sixteen pairs of dye observations, starting at the upper left of the figure and ending at the lower right one hour later. For each trace pair, the mid-boom (station 1) signals are aligned vertically. The delay to the end-boom (station 2) trace gives the Lagrangian speed estimate. A single hose with openings at stations one and two was used with a pump and recording fluorometer on board the boat to detect the dye passage. Absolute Lagrangian speed estimates accurate to perhaps ±2 cm/sec may be possible with the technique. Boom motion, asymmetric dye injection, limited number of dye sensors and finite boom length are presently the major factors limiting accuracy.

Fundamental problems of relating the Lagrangian dye velocities to the Eulerian moored current meter observations exist, but as discussed earlier,

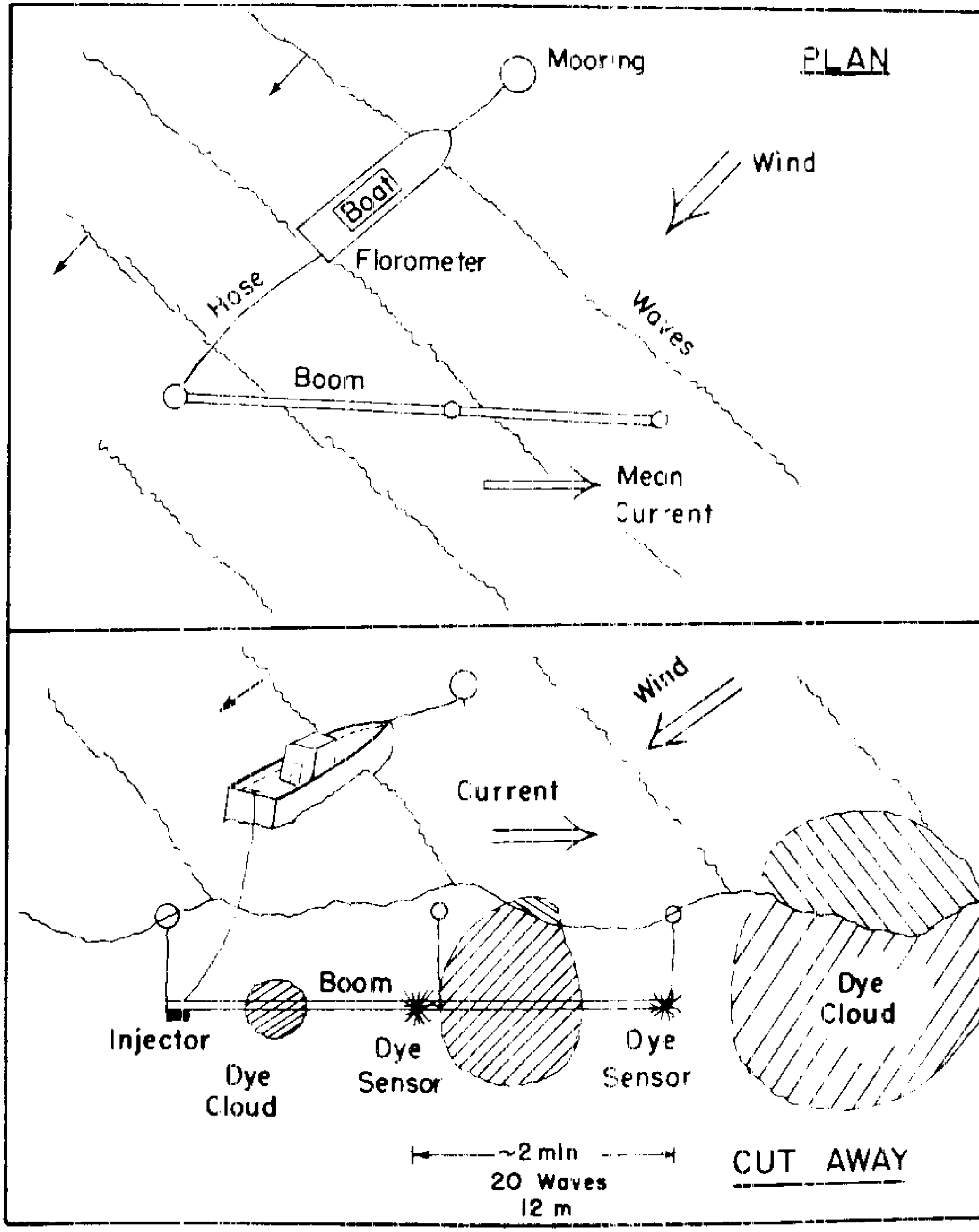


Figure 14. Sketch of an experimental dye technique used for *in situ* evaluation of moored current meters. A long, submerged boom is loosely tethered at one end to a moored boat. Dye injected at the tethered end is advected away by the mean current. Its progress is measured at two dye sensor stations on the boom. The far end of the boom (at right) is free to swing with the current. Observations of wave conditions allow first-order Stokes-drift corrections needed to estimate Eulerian currents from the Lagrangian mean speed of the dye. (After McCullough, 1977.)

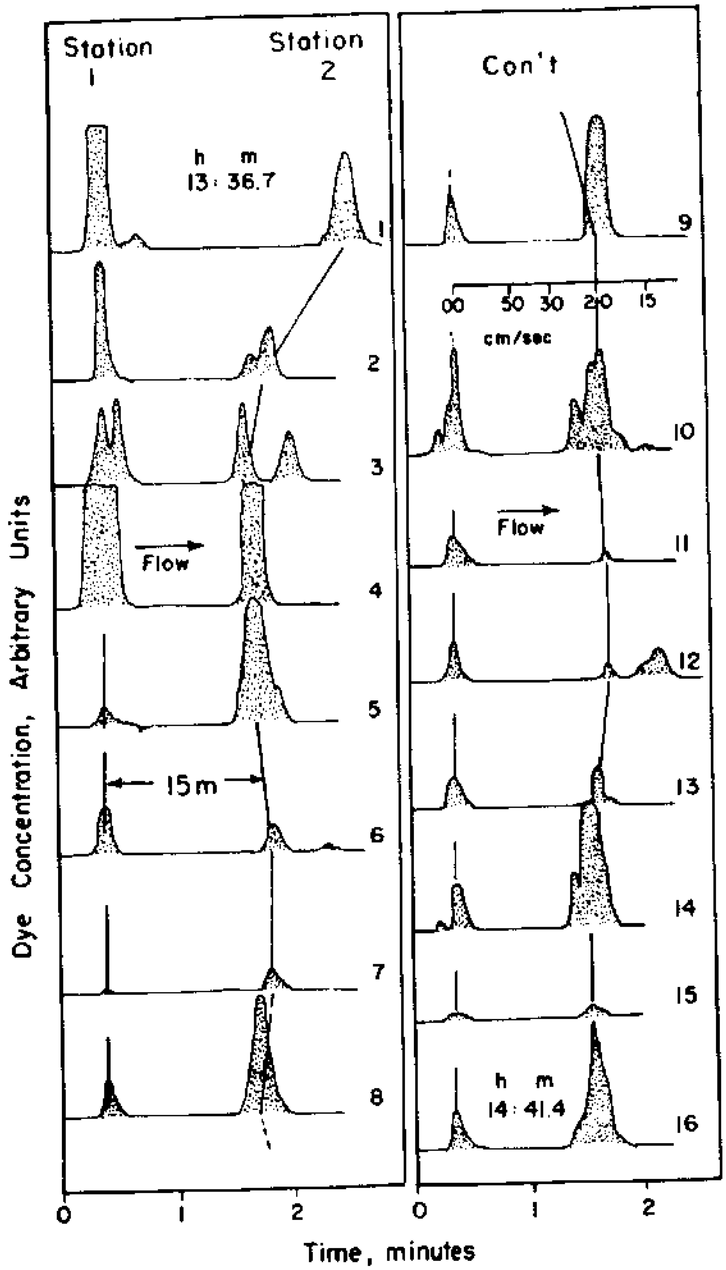


Figure 15. Dye concentration records from 16 dye injections over a period of one hour in small waves show the variation (wandering vertical line) in the mean tidal flow in Buzzards Bay, Mass. Flow in the figure is from left to right. The actual flow direction during the experiment is estimated by measuring the bearing of the line of boom floats. Separations of the sensors along the boom was 15 m. The time between passage of the dye at each station is given on the ordinate. Trace pairs are separated by roughly 4 minutes. As shown by the scale below trace-pair 9, the mean dye speed was about 20 cm/sec. The scale also indicates how speed sensitivity increases at lower speeds and becomes less as the speed increases. Variation of the dye intensity and multiple dye peaks are artifacts of the experimental procedure.

may not be critical in many practical situations. Since observations of currents from moving moorings are altered by effects similar to the Stokes-drift, intercomparisons of dye and moored current meter measurements may provide new insight into the accuracy of moored current meter observations from anchored but periodically moving platforms.

ACKNOWLEDGMENTS

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A REVIEW OF THE PERFORMANCE OF AN ACOUSTIC CURRENT METER

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ABSTRACT

The Test and Evaluation Laboratory of NOAA/National Ocean Survey (NOS) recently completed a limited performance evaluation of three Neil Brown Instrument Systems acoustic current meters (NBIS ACM-1's) for the NOAA Data Buoy Office. Steady flow calibrations were performed on the four cardinal measurement axes, as well as directivity response evaluation in both the horizontal and vertical planes. Calibrations were performed on the solid-state compass used for magnetic heading reference in the current meters. Environmental tests were conducted in accordance with MIL-STD-167B for vibration testing, and environmental temperature tests were guided by MIL-STD-810C. The methods and procedures for these tests are discussed, and evaluation results are graphically displayed.

WORKING CONFERENCE ON CURRENT MEASUREMENTS, JANUARY 1978. SPONSORED BY THE NOAA OFFICE OF OCEAN ENGINEERING AND THE DELAWARE SEA GRANT COLLEGE PROGRAM.

INTRODUCTION

The development of the acoustic phase shift velocimeter by Neil Brown Instrument Systems (NBIS), sponsored by the Office of Naval Research (ONR), has led to the production of the acoustic current meter designed specifically for oceanographic in-situ applications. The NOAA Data Buoy Office (NDBO) contracted development of three of these systems for use in their Continental Shelf Buoy Development Program, and requested that NOAA's Test and Evaluation Laboratory (T&EL) perform a series of limited evaluation tests to determine the performance and suitability of the three instruments (S/N 100, 200, and 300) for field deployment.

NBIS ACM-1

The Neil Brown Instrument Systems acoustic current meter (NBIS ACM-1) uses an acoustic phase shift detection method for correlating the time of travel of two acoustic beams to the velocity of the fluid medium along the beam path. Two orthogonal transducer pairs measure velocity components relative to the instrument, and their components can be resolved into a total velocity vector. The transmitted acoustic beams are focused on a reflecting plate which returns the signals to the receiving transducer. The reflecting-path technique permits physical design of the current meter to minimize fluid distortion generated by the transducers. (A technical paper by K. D. Lawson et al., details the theory of operation.)

An NBIS-developed solid-state compass provides geomagnetic reference to the velocity data which are vector averaged and recorded on magnetic tape.

TEST PROCEDURES

Test procedures, methods, facilities, equipment and analysis techniques are critical to the quality of performance data obtained from an instrument evaluation. The purpose of this discussion is to highlight the capabilities of T&EL and describe the general considerations for deriving quality test data.

Laboratory test procedures are designed to determine the performance of a current meter under controlled conditions, compared against known and accepted measurement standards. Test data sampling schemes are planned to yield statistically significant results. Test methods are designed to simulate the environment and maintain adequate control to ensure results traceable to standards. Assumptions and compromises made are documented and used in determining the overall uncertainty of measurement.

Current velocity tests were performed at the David Taylor-Naval Ship Research and Development Center (DT-NSRDC) number one tow carriage facility. The usable test length of the basin is 275 meters with a water depth of 6 meters and basin width of 15 meters. The basin is filled with fresh water from the Potomac River whose temperature follows ambient conditions. The measurement standard for velocity is the tow carriage speed readout system. This is a time-distance measurement whose output is a frequency which is proportional to carriage speed with respect to the stationary rails. The 95 percent confidence level in determining the mean carriage speed for a particular test run is on the order of 0.05 cm/s over a range of speeds from 2 to 250 cm/s. The estimated overall uncertainty in speed measurements made from tow carriage is 0.1 cm/s. The largest error source is the residual basin current, which can add or subtract from the tow carriage velocity. Basin currents are minimized by waiting between test runs and observing the currents with potassium permanganate dye traces. A miniature propeller meter that is calibrated as a secondary standard is towed parallel to the test instrument and is used to monitor gross disturbances in basin currents. In general, typical basin currents are less than 0.8 cm/s. Data are sampled and stored automatically with an HP 9825 programmable calculator. This data acquisition system samples carriage speed frequency, miniature propeller frequency, and the output of the test instrument. Thirty samples are acquired to define each test point. A statistical analysis is performed on the data for each test point, and a determination of the data quality is made before proceeding on to the next test speed (see Figure 1).

TEST RESULTS

Tests were performed on the +X, +Y, -X, and -Y (0°, 90°, 180°, 270° azimuth angles, +X max. output as 0° reference) for steady flow sensor calibration accuracy determinations. Three sensors were calibrated using the same basic procedures. Data were analyzed by several methods; the results displayed in this report were from a computed best fit straight line equation with 0 intercept. Calibration results are plotted in Figures 2-4 as residual sensor errors from the best fit straight line. Figures 5-7 show signal output noise levels converted to units of flow, versus actual tow speed that occurred during the calibrations.

Directivity response tests were performed in the horizontal and vertical planes of the sensors, and errors were computed from a true cosine response function. In this case, vectors were computed from the trigonometric relationship $\sqrt{X^2 + Y^2}$ and the resultant angle from tan Y/X. Horizontal response residual errors from a true cosine are plotted in Figures 8-10. The angle errors shown in Figures 11-13 represent the error from the true present angle. These tests were conducted at 13 and 51 cm/s. The vertical response residual errors

Run # 7 Meat Run # 90.0
NBIS ACM-1 S/N100 Date [illegible] Time 122538

30 Samples Taken at 0.97 Samples/Sec

Statistical Analysis

	CARRIAGE HZ	HETRPIC HZ	NBIS-X VOLTS	NBIS-Y VOLTS
Mean	4.031E 02	4.371E 01	-3.464E-02	3.620E-01
Std.Dev.	4.158E-01	1.002E-01	1.781E-03	2.588E-03
Min	4.023E 02	4.346E 01	-3.770E-02	3.588E-01
Max	4.039E 02	4.394E 01	-3.016E-02	3.681E-01
Range	1.610E 00	4.800E-01	7.600E-03	9.300E-03
S/R	9.690E 02	4.118E 02	1.945E 01	1.405E 02
95% conf.	1.518E-01	3.876E-02	6.505E-04	9.431E-04

Std Speed = 103.8 cm/sec Std.Dev.= 0.11 cm/sec
95% Confidence of Mean = 0.04 cm/sec

Hetrpic = 105.2 cm/sec Std.Dev. = 0.26 cm/sec
95% Confidence of Mean = 0.09 cm/sec

HETRPIC - CARRIAGE 1.5cm/sec

Vector Magnitude= 0.365 VOLTS Angle= 95.45 Degrees
95% Conf.= 0.001 VOLTS X Offset= 0.0000 Y Offset= 0.0000

Mea. Gain =284.58 cm/sec/volt
95% Confidence of Mean = 0.23 cm/sec

Figure 1

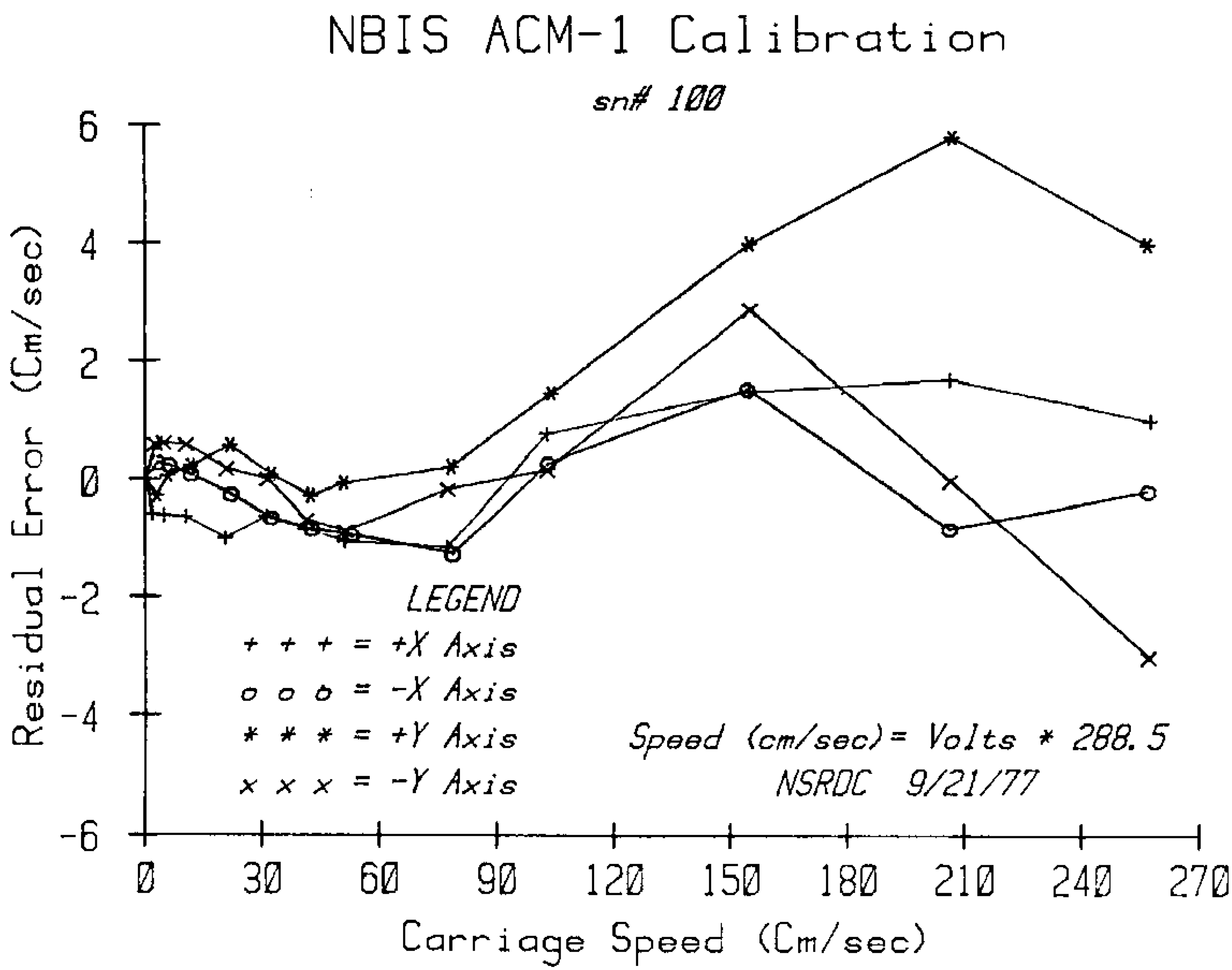

NBIS ACM-1 Calibration
sn# 100
Residual Error (Cm/sec)
6
4
2
0
-2
-4
-6
0
30
60
90
120
150
180
210
240
270
Carriage Speed (Cm/sec)
LEGEND
+ + + = +X Axis
o o o = -X Axis
* * * = +Y Axis
x x x = -Y Axis
Speed (cm/sec) = Volts * 288.5
NSRDC 9/21/77

Figure 2

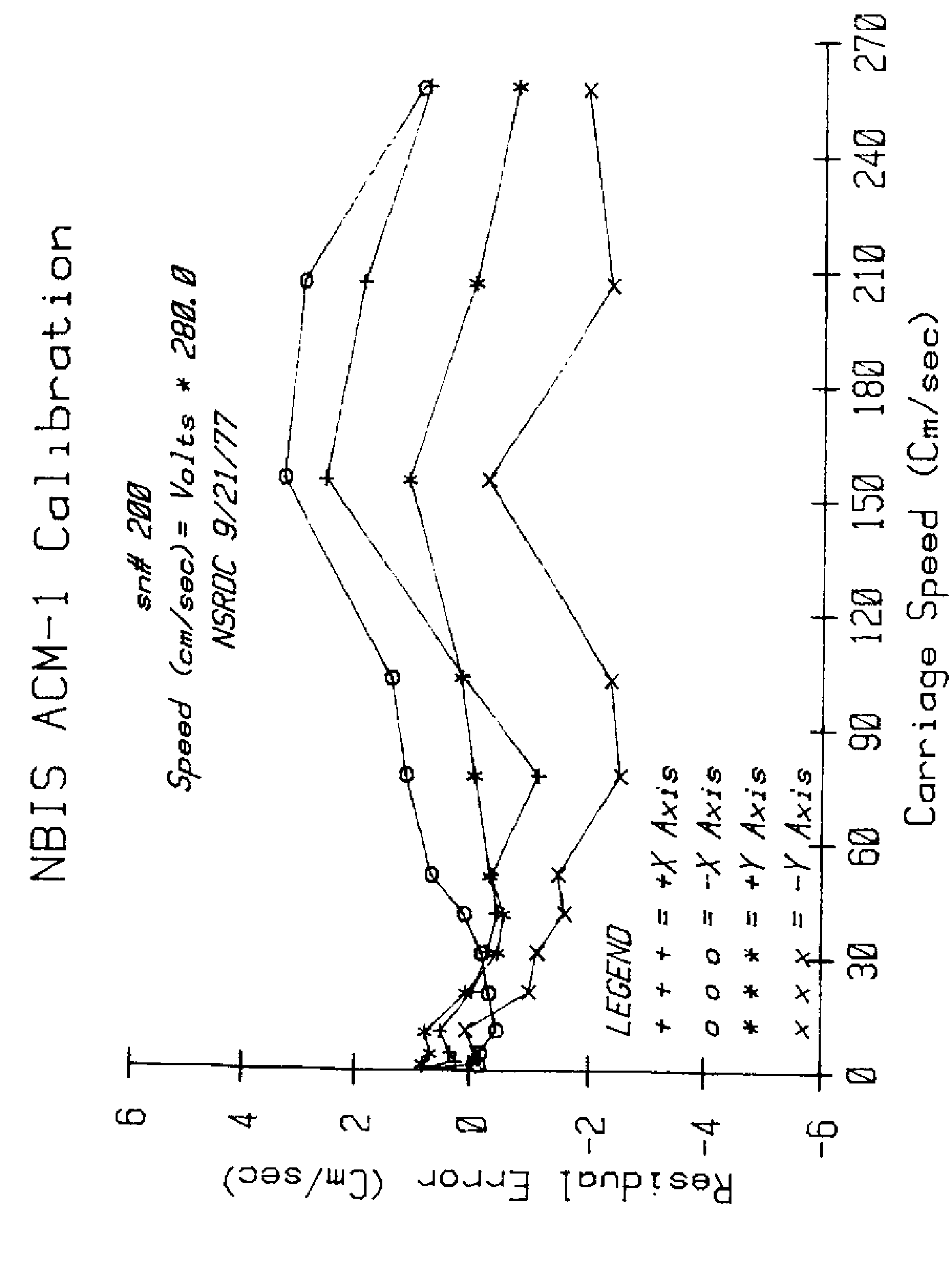

NBIS ACM-1 Calibration
sn# 200
Speed (cm/sec) = Volts * 280.0
NSRDC 9/21/77
LEGEND
+ + + = +X Axis
o o o = -X Axis
* * * = +Y Axis
x x x = -Y Axis
Residual Error (Cm/sec)
6
4
2
0
-2
-4
-6
0
30
60
90
120
150
180
210
240
270
Carriage Speed (Cm/sec)

Figure 3

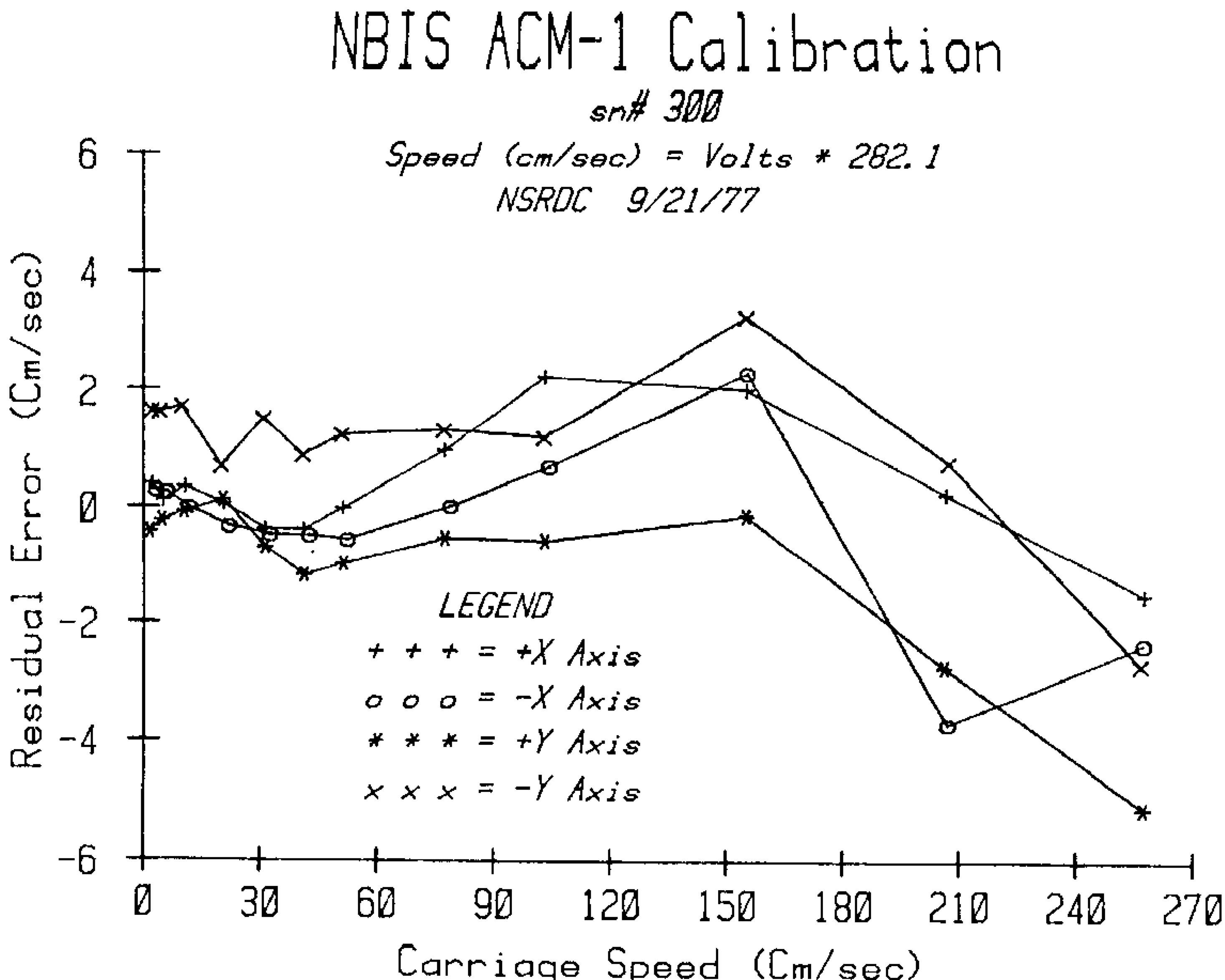

NBIS ACM-1 Calibration
sn# 300
Speed (cm/sec) = Volts * 282.1
NSRDC 9/21/77
LEGEND
+ + + = +X Axis
o o o = -X Axis
* * * = +Y Axis
x x x = -Y Axis
Residual Error (Cm/sec)
Carriage Speed (Cm/sec)
6
4
2
0
-2
-4
-6
0
30
60
90
120
150
180
210
240
270

Figure 4

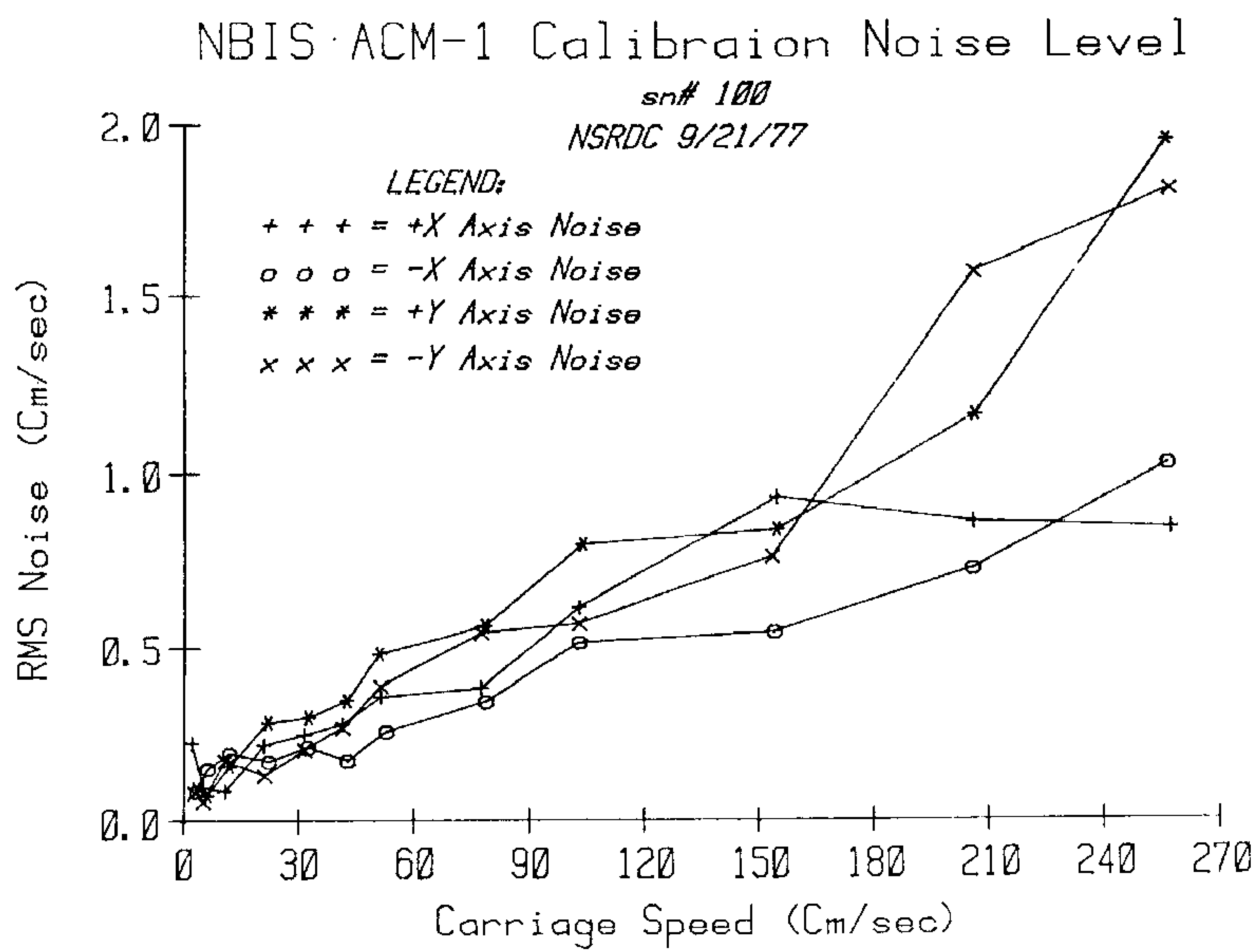

NBIS ACM-1 Calibraion Noise Level
sn# 100
NSRDC 9/21/77
LEGEND:
+ + + = +X Axis Noise
o o o = -X Axis Noise
* * * = +Y Axis Noise
x x x = -Y Axis Noise
RMS Noise (Cm/sec)
2.0
1.5
1.0
0.5
0.0
0
30
60
90
120
150
180
210
240
270
Carriage Speed (Cm/sec)

Figure 5

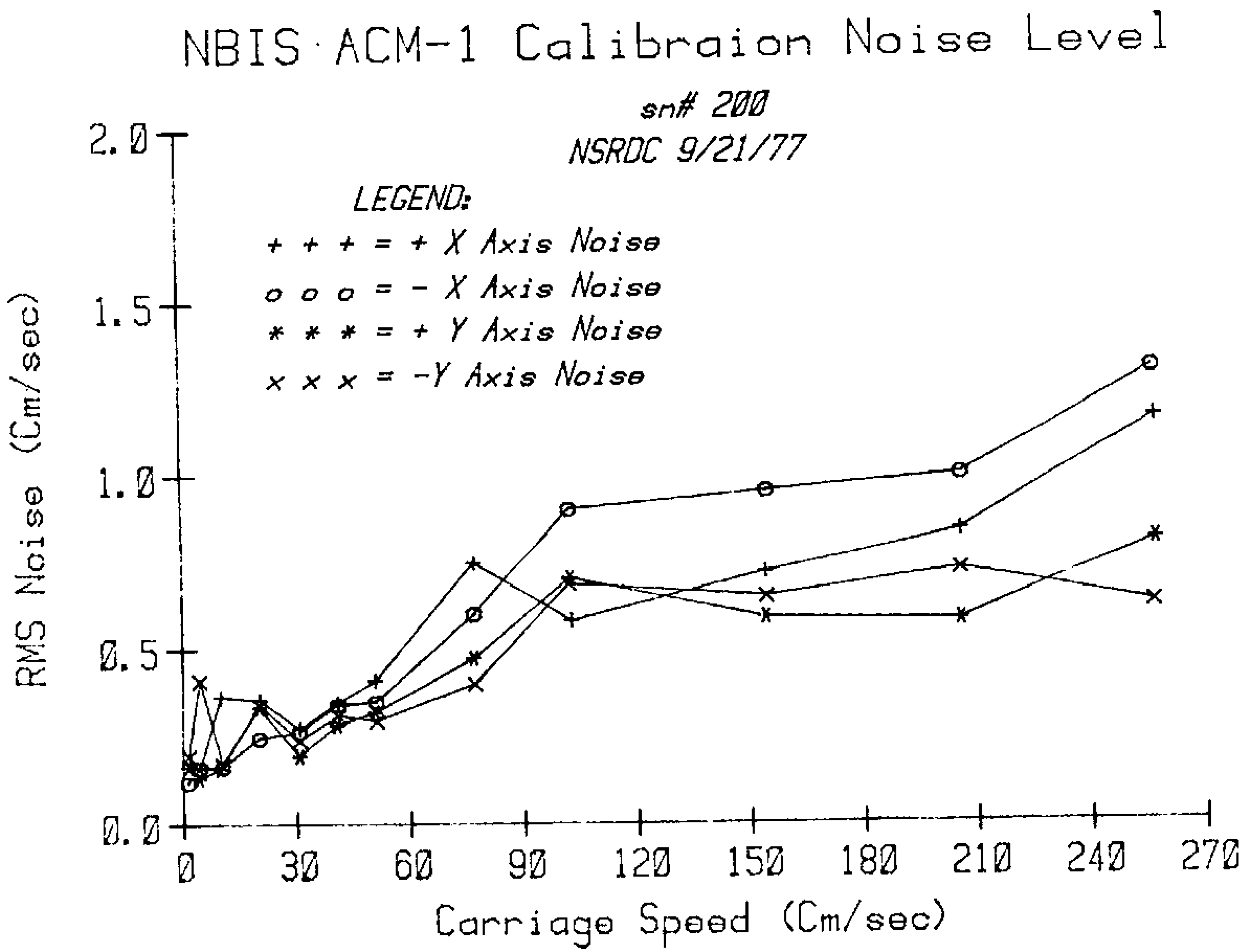

NBIS·ACM-1 Calibraion Noise Level
sn# 200
NSRDC 9/21/77
LEGEND:
+ + + = + X Axis Noise
o o o = − X Axis Noise
* * * = + Y Axis Noise
x x x = −Y Axis Noise
RMS Noise (Cm/sec)
2.0
1.5
1.0
0.5
0.0
0
30
60
90
120
150
180
210
240
270
Carriage Speed (Cm/sec)

Figure 6

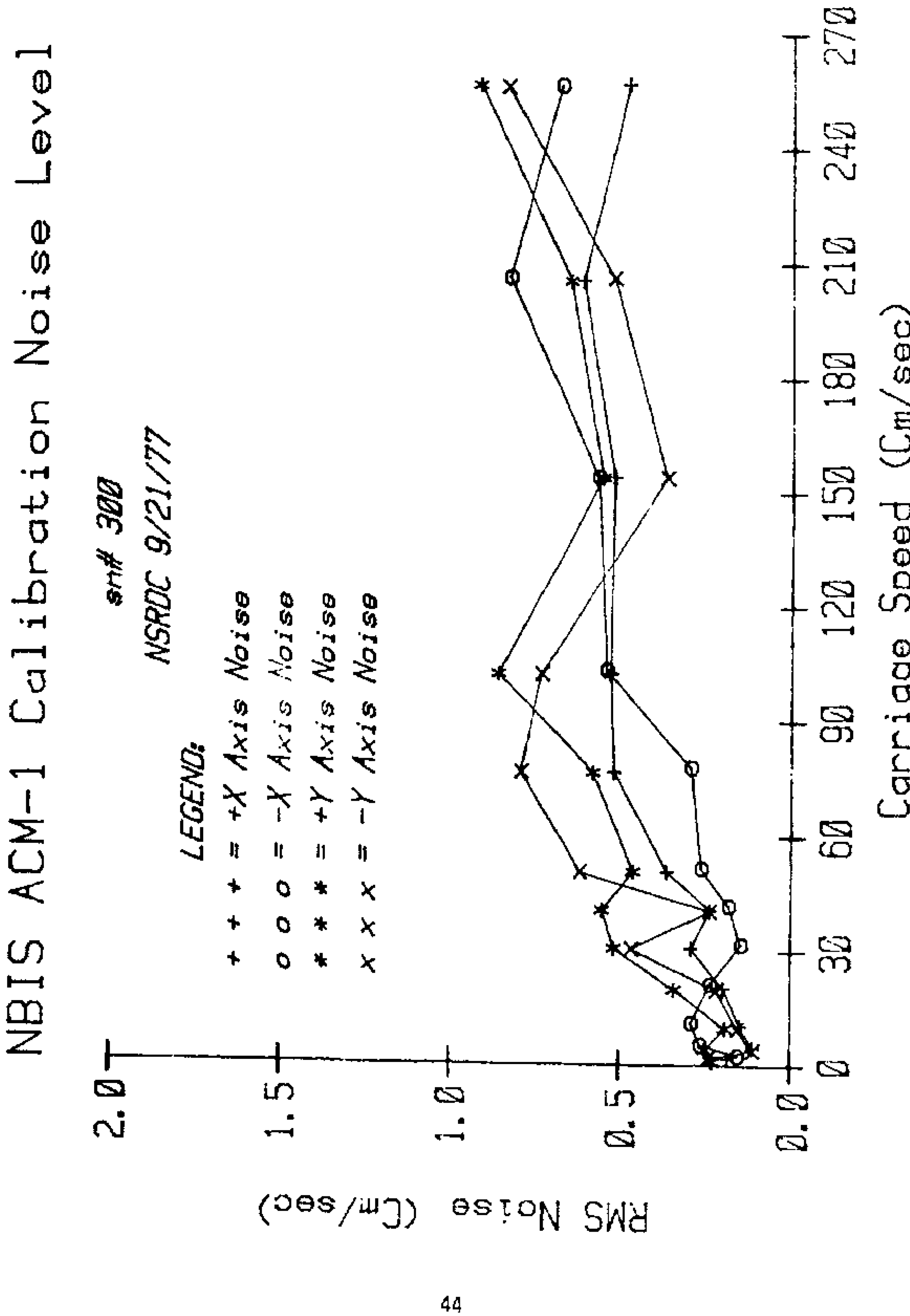

NBIS ACM-1 Calibration Noise Level
sn# 300
NSRDC 9/21/77
LEGEND:
+ + + = +X Axis Noise
o o o = -X Axis Noise
* * * = +Y Axis Noise
x x x = -Y Axis Noise
RMS Noise (Cm/sec)
2.0
1.5
1.0
0.5
0.0
0
30
60
90
120
150
180
210
240
270
Carriage Speed (Cm/sec)

Figure 7

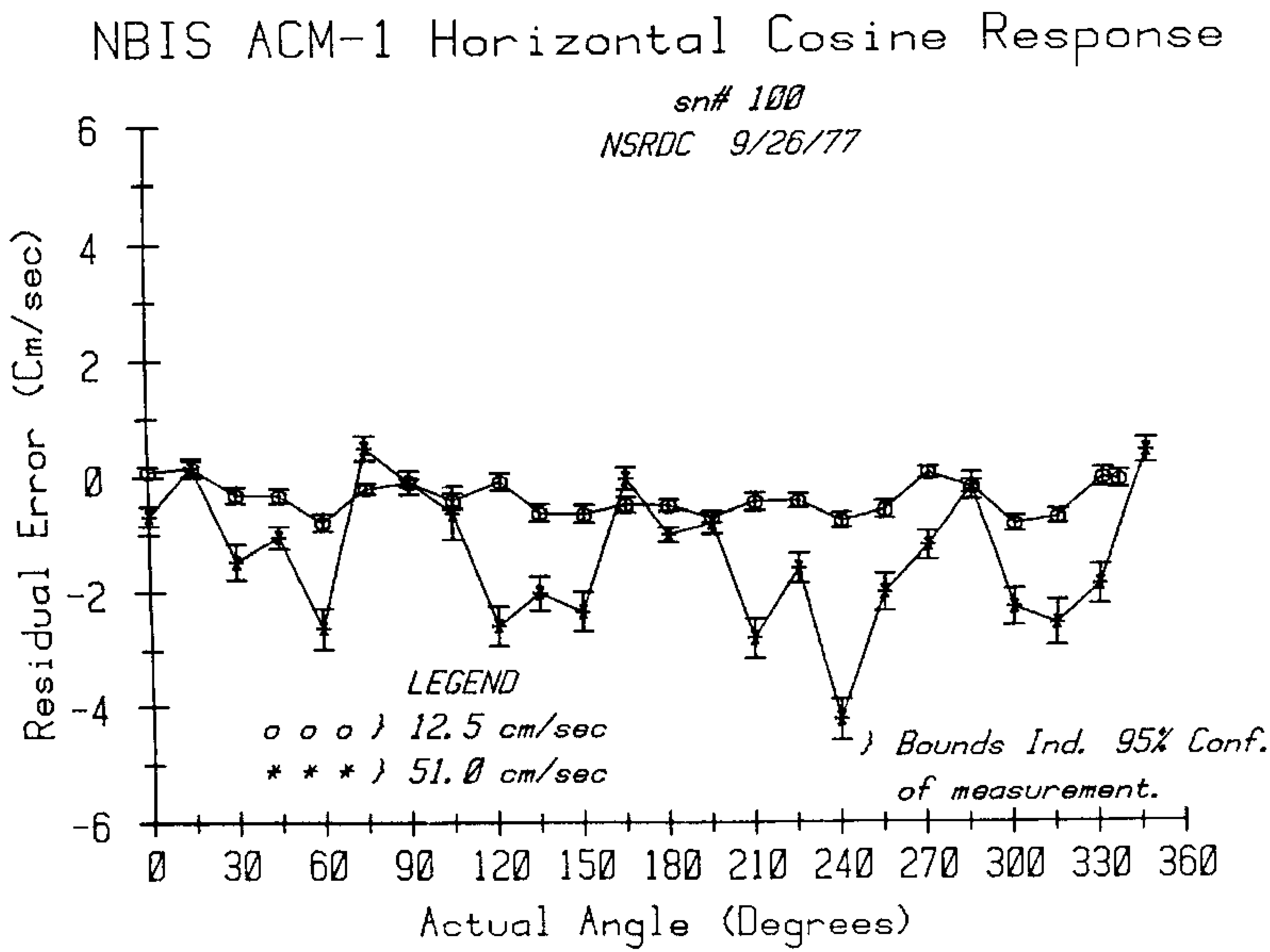

NBIS ACM-1 Horizontal Cosine Response
sn# 100
NSRDC 9/26/77
Residual Error (Cm/sec)
6
4
2
0
-2
-4
-6
0 30 60 90 120 150 180 210 240 270 300 330 360
Actual Angle (Degrees)
LEGEND
o o o) 12.5 cm/sec
* * *) 51.0 cm/sec
) Bounds Ind. 95% Conf.
of measurement.

Figure 8

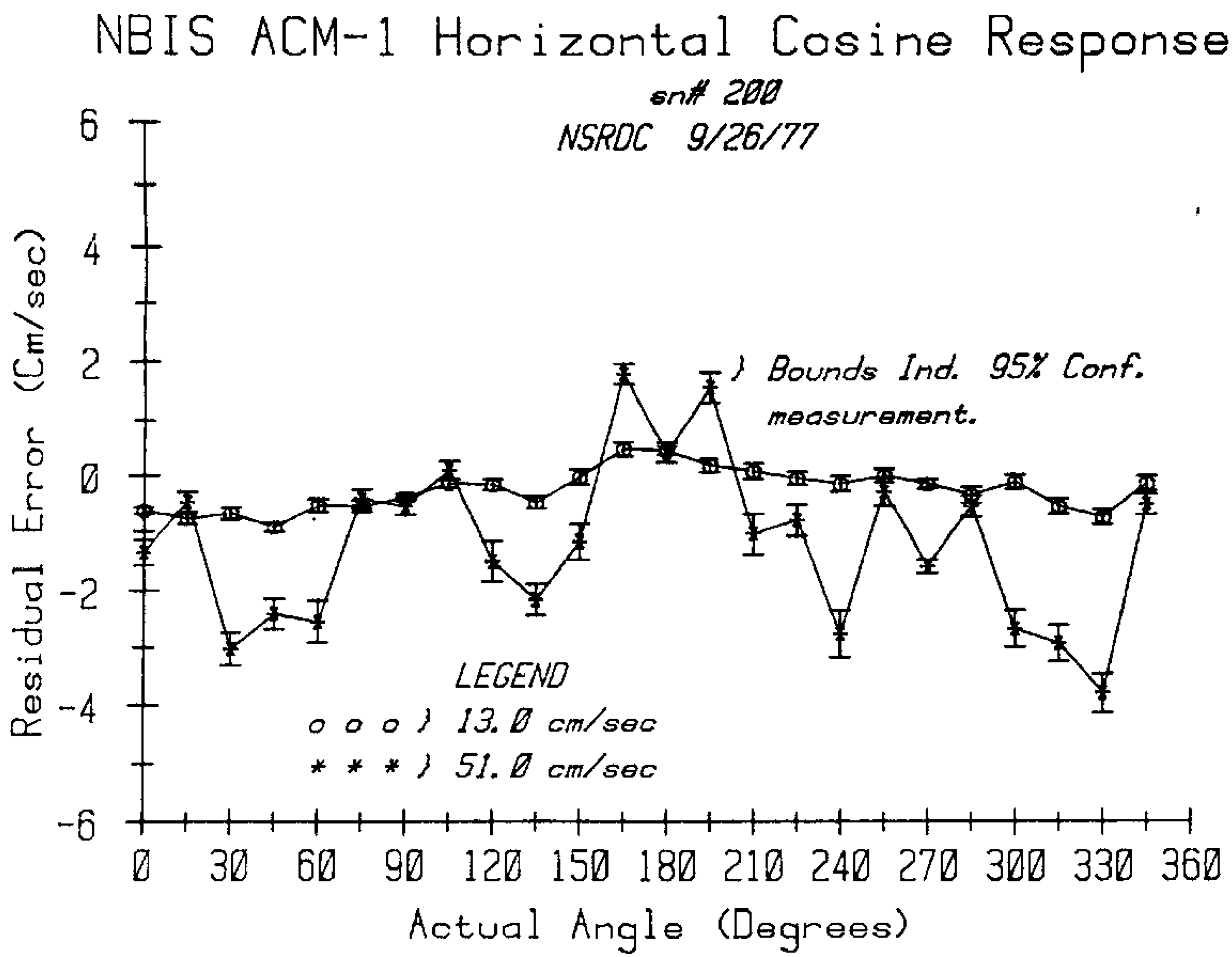

NBIS ACM-1 Horizontal Cosine Response
sn# 200
NSRDC 9/26/77
) Bounds Ind. 95% Conf.
measurement.
LEGEND
o o o) 13.0 cm/sec
* * *) 51.0 cm/sec
Residual Error (Cm/sec)
6
4
2
0
-2
-4
-6
0
30
60
90
120
150
180
210
240
270
300
330
360
Actual Angle (Degrees)

Figure 9

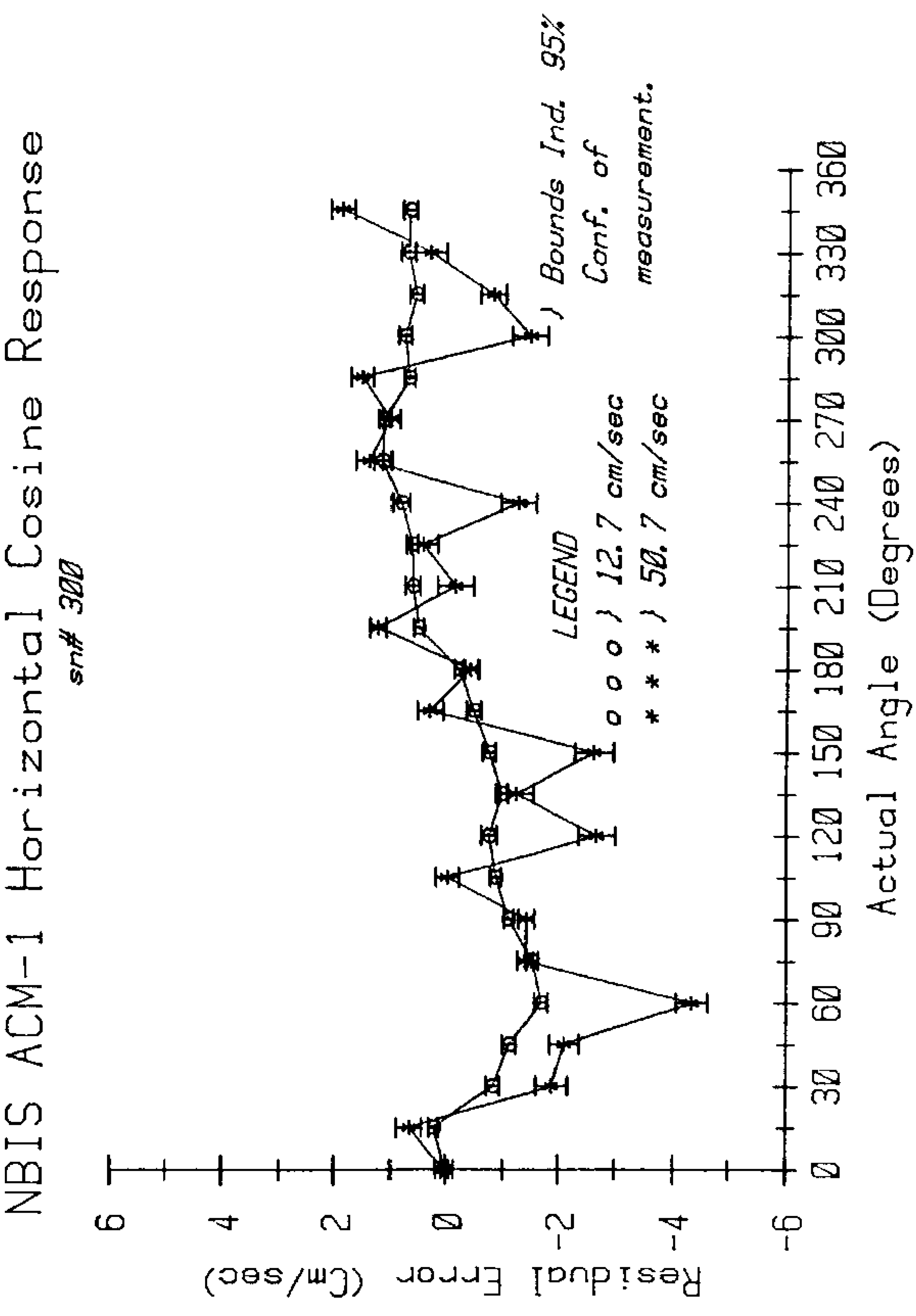

NBIS ACM-1 Horizontal Cosine Response
sn# 300
Residual Error (Cm/sec)
6
4
2
0
-2
-4
-6
Actual Angle (Degrees)
0
30
60
90
120
150
180
210
240
270
300
330
360
LEGEND
o o o) 12.7 cm/sec
* * *) 50.7 cm/sec
) Bounds Ind. 95%
Conf. of
measurement.

Figure 10

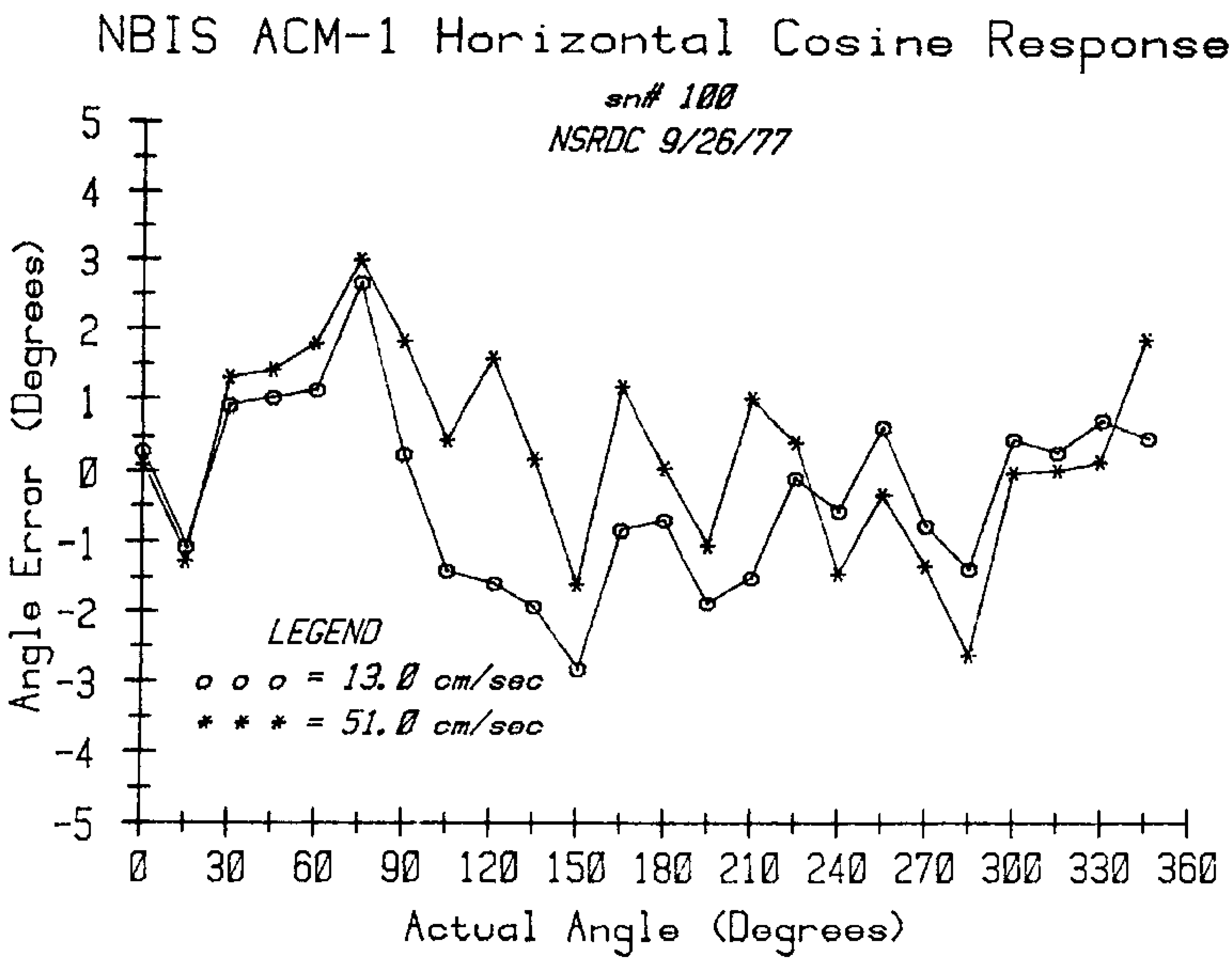

NBIS ACM-1 Horizontal Cosine Response
sn# 100
NSRDC 9/26/77
Angle Error (Degrees)
5
4
3
2
1
0
-1
-2
-3
-4
-5
LEGEND
o o o = 13.0 cm/sec
* * * = 51.0 cm/sec
0 30 60 90 120 150 180 210 240 270 300 330 360
Actual Angle (Degrees)

Figure 11

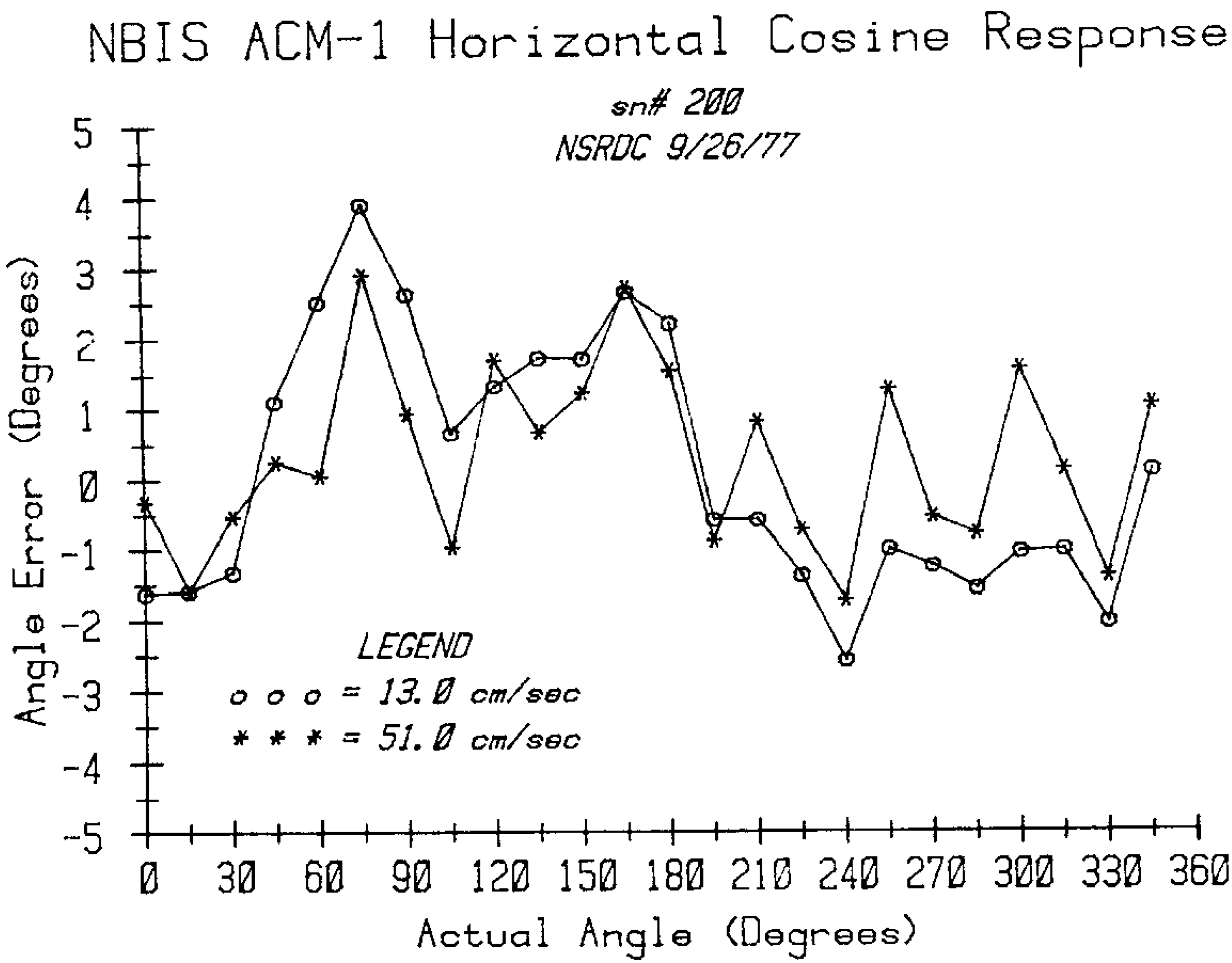

NBIS ACM-1 Horizontal Cosine Response
sn# 200
NSRDC 9/26/77
5
4
3
2
1
0
-1
-2
-3
-4
-5
Angle Error (Degrees)
LEGEND
o o o = 13.0 cm/sec
* * * = 51.0 cm/sec
0
30
60
90
120
150
180
210
240
270
300
330
360
Actual Angle (Degrees)

Figure 12

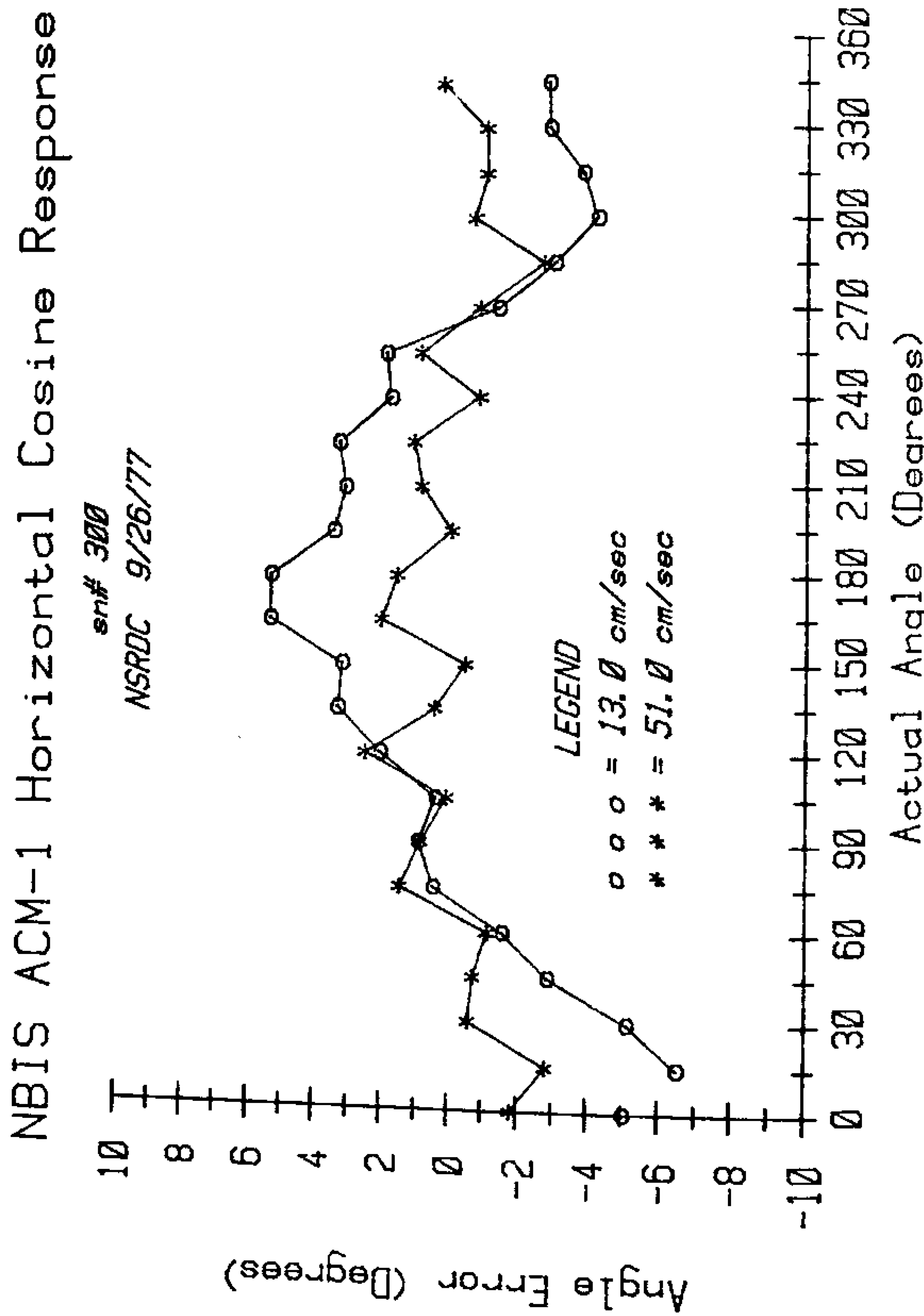

NBIS ACM-1 Horizontal Cosine Response
sn# 300
NSRDC 9/26/77
LEGEND
o o o = 13.0 cm/sec
* * * = 51.0 cm/sec
Angle Error (Degrees)
10
8
6
4
2
0
-2
-4
-6
-8
-10
0
30
60
90
120
150
180
210
240
270
300
330
360
Actual Angle (Degrees)

Figure 13

from a true cosine are plotted in Figures 14-16. In the vertical tests, the 0° reference is the normal attitude, with positive angles indicating counterclockwise tilt and negative angles clockwise tilt. The vertical response tests were also performed at 13 and 51 cm/s.

COMPASS

The three NBIS ACM-1's were calibrated for magnetic heading accuracy at Hyde Field, Maryland. The site is used for compass calibrations and has been determined to be magnetically stable and free of interference. The magnetic north reference standard is a LUTZ magnetic compass with 1° accuracy. The offset or bias uncertainty is in the order of ±1° of heading and the combined random uncertainty is approximately ±0.25°. Figures 17-19 show the sensor heading error as a function of true heading. Increments of 15° were performed in both clockwise and counter-clockwise rotational directions from magnetic north.

ENVIRONMENTAL TESTS

Vibration tests were performed on one of the three current meters in accordance with MIL-STD-167B. The meter was operational during the test and recorded data internally. Digital data were monitored externally with a "bit box" provided by NBIS to visually observe the binary information. The current meter was inspected and checked out after completion of the tests. There was no visual damage as a result of vibration, nor was normal operation impaired.

Temperature tests were conducted in air over the NBIS-specified range of -2° to 70°C, following procedural guidelines established in MIL-STD-810C. No deviation from normal operation resulted.

The last test was a combined pressure-tension test. A 10,000 pound tensile load was applied to the mooring attachments at each end of a meter while hydrostatic pressure was slowly increased to 3,000 psi. The combination of tension and pressure was maintained for one hour before being released. No leakage or observable defects occurred.

DISCUSSION

The graphical data presentations of the calibration and response tests of the three current meters provide an indication of the instruments' accuracy and performance that can be expected under ideal conditions. In-situ field conditions create a multitude of uncontrollable factors which may produce results with larger errors than indicated by laboratory tests. However, laboratory tests under

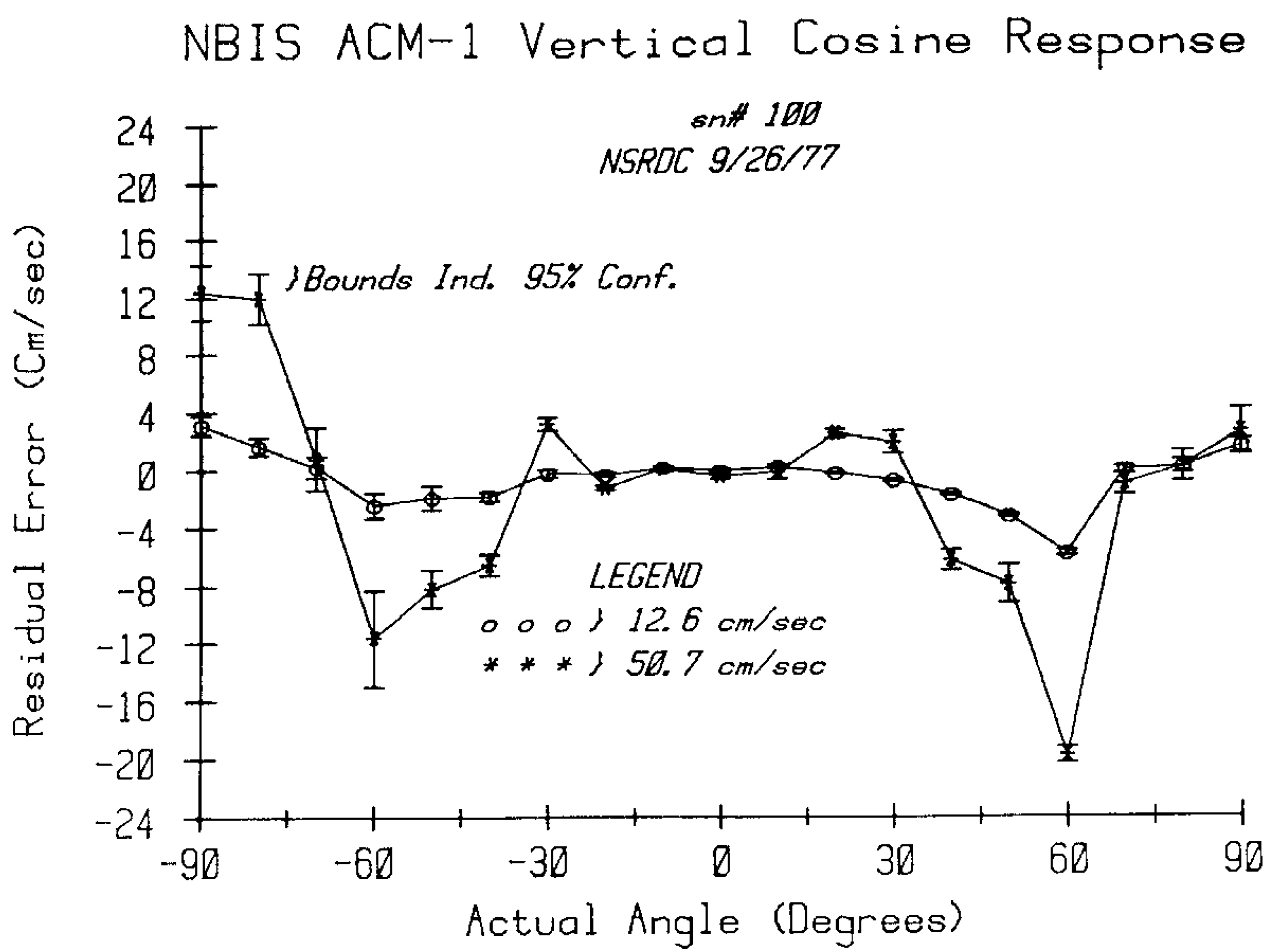

NBIS ACM-1 Vertical Cosine Response
sn# 100
NSRDC 9/26/77
}Bounds Ind. 95% Conf.
LEGEND
o o o } 12.6 cm/sec
* * * } 50.7 cm/sec
Residual Error (Cm/sec)
Actual Angle (Degrees)
24
20
16
12
8
4
0
-4
-8
-12
-16
-20
-24
-90
-60
-30
0
30
60
90

Figure 14

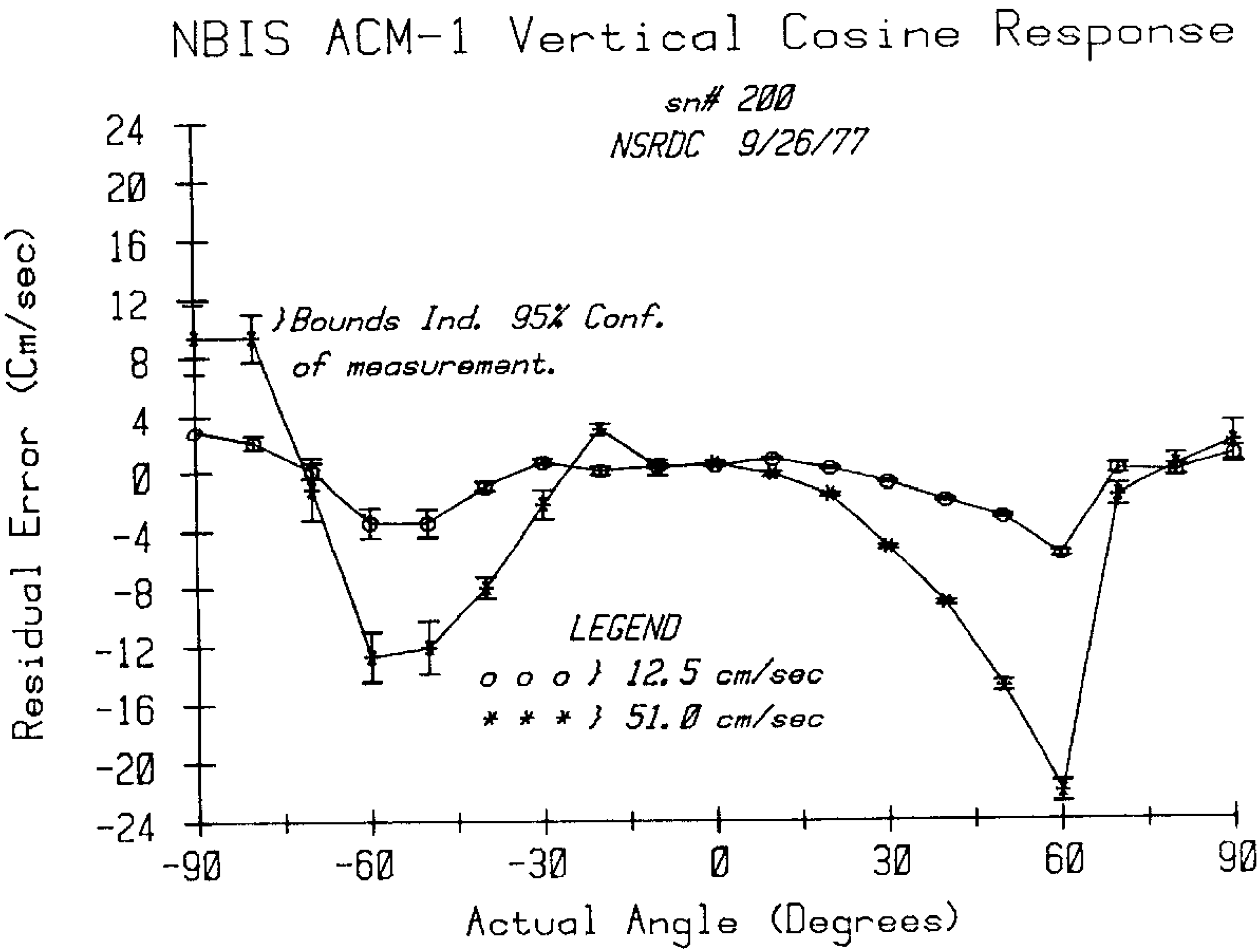

NBIS ACM-1 Vertical Cosine Response
sn# 2ØØ
NSRDC 9/26/77
}Bounds Ind. 95% Conf.
of measurement.
LEGEND
o o o } 12.5 cm/sec
* * * } 51.Ø cm/sec
Residual Error (Cm/sec)
Actual Angle (Degrees)
24
2Ø
16
12
8
4
Ø
-4
-8
-12
-16
-2Ø
-24
-9Ø
-6Ø
-3Ø
Ø
3Ø
6Ø
9Ø

Figure 15

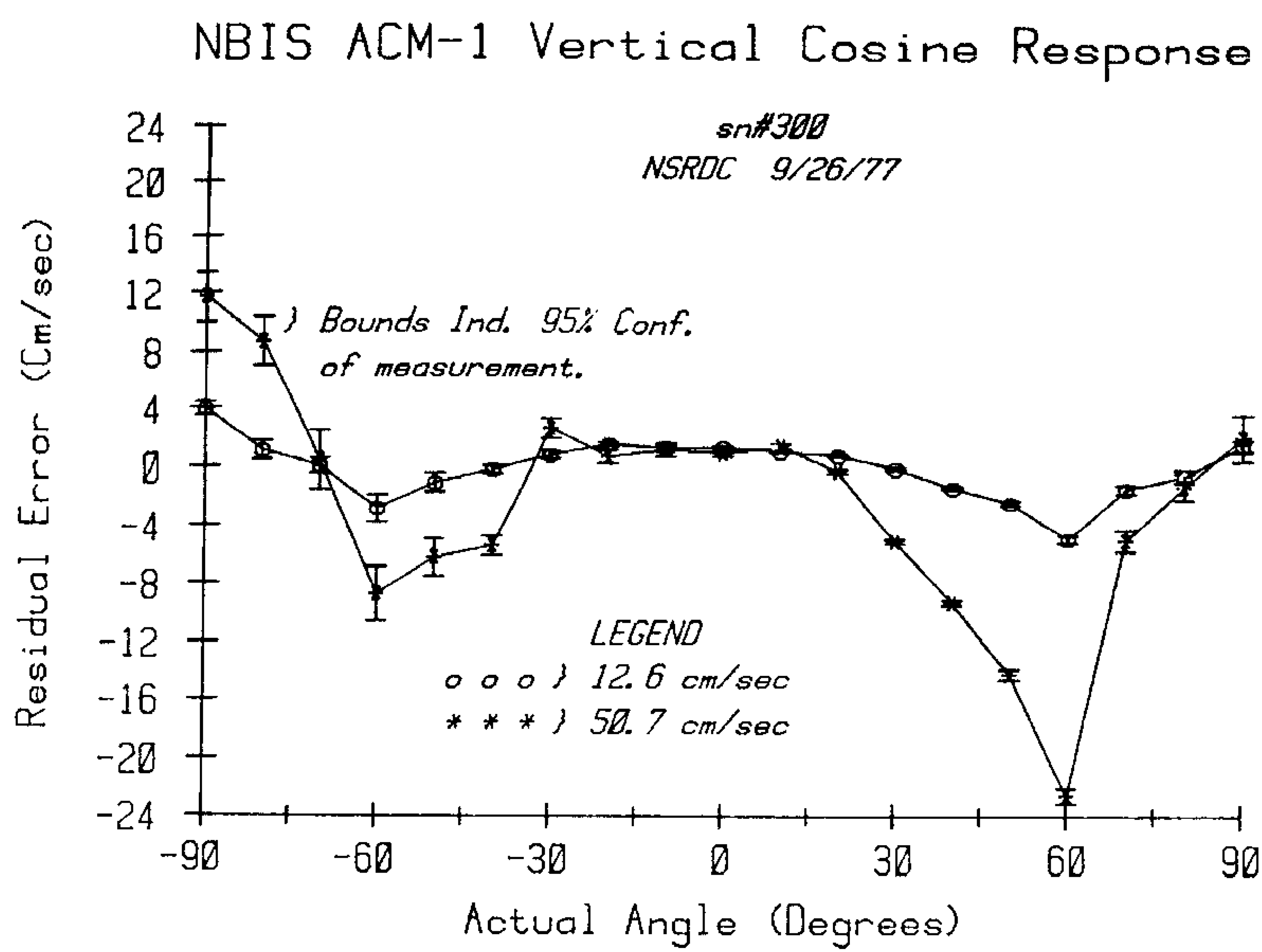

NBIS ACM-1 Vertical Cosine Response
sn#300
NSRDC 9/26/77
} Bounds Ind. 95% Conf.
of measurement.
LEGEND
o o o } 12.6 cm/sec
* * * } 50.7 cm/sec
Residual Error (Cm/sec)
24
20
16
12
8
4
0
-4
-8
-12
-16
-20
-24
-90
-60
-30
0
30
60
90
Actual Angle (Degrees)

Figure 16

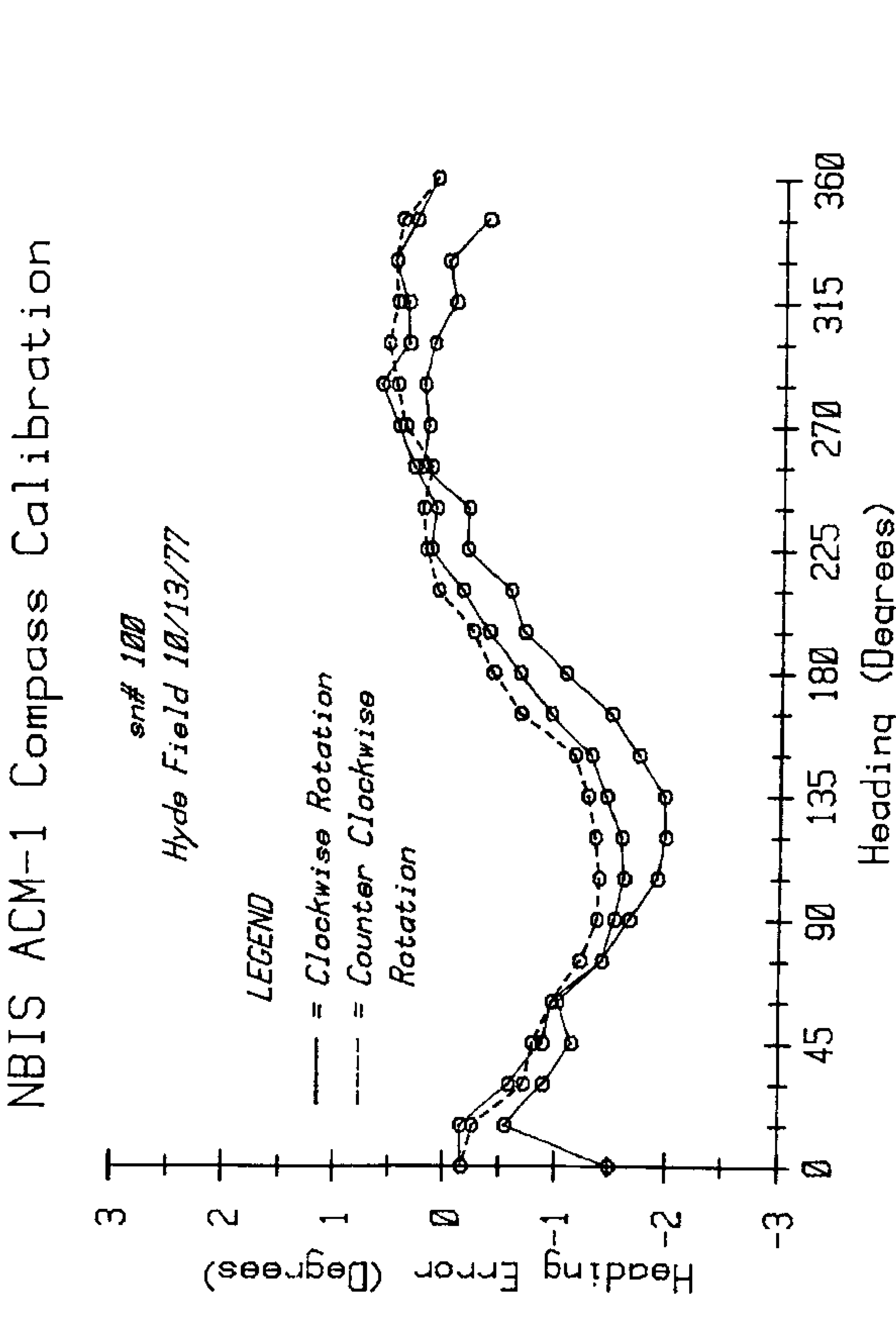
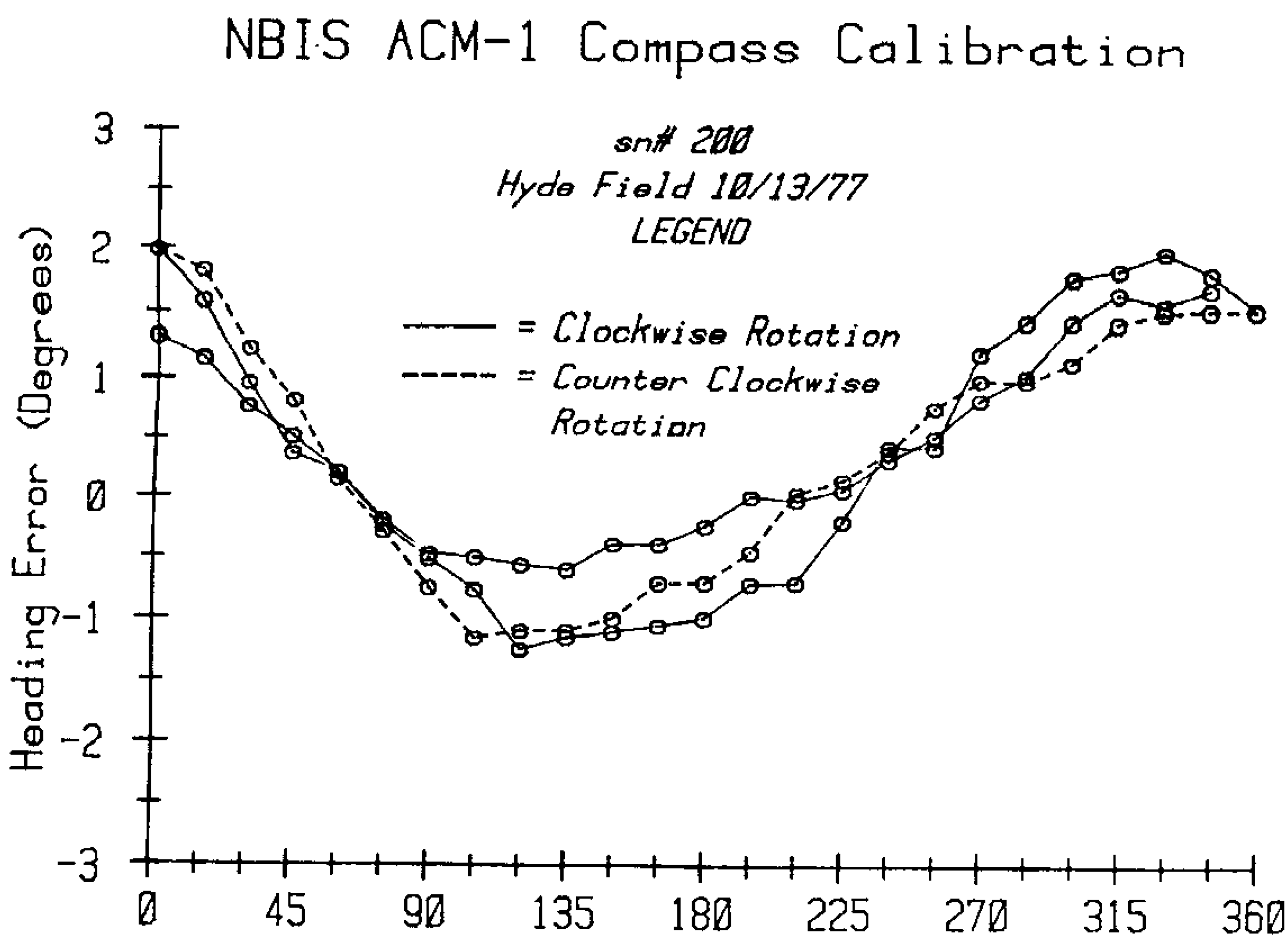
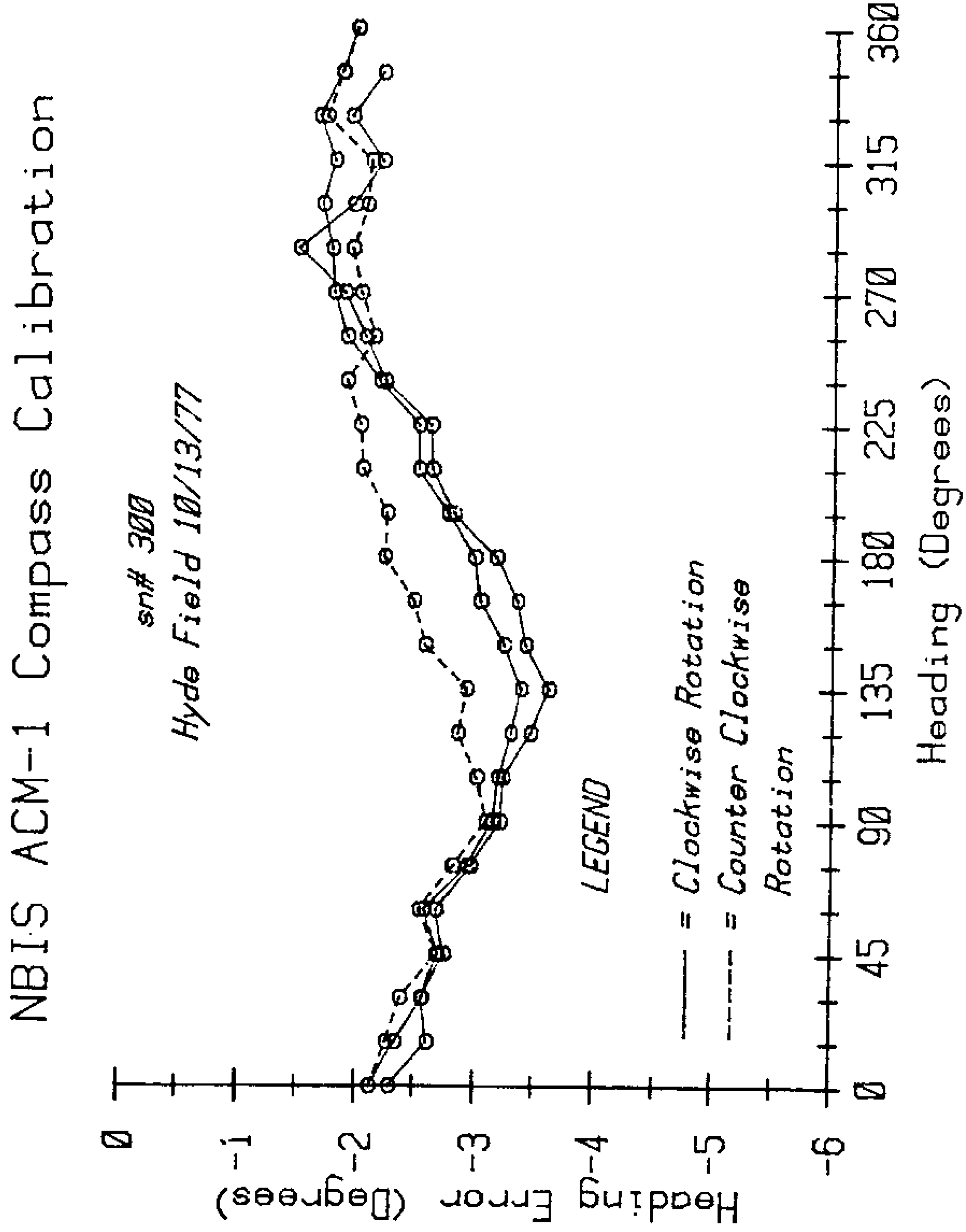

NBIS ACM-1 Compass Calibration
sn# 100
Hyde Field 10/13/77
LEGEND
—— = Clockwise Rotation
- - - = Counter Clockwise Rotation
Heading Error (Degrees)
3
2
1
0
-1
-2
-3
0
45
90
135
180
225
270
315
360
Heading (Degrees)

Figure 17


NBIS ACM-1 Compass Calibration
sn# 200
Hyde Field 10/13/77
LEGEND
= Clockwise Rotation
= Counter Clockwise Rotation
Heading Error (Degrees)
3
2
1
0
-1
-2
-3
0
45
90
135
180
225
270
315
360
Heading (Degrees)
Figure 18



NBIS ACM-1 Compass Calibration
sn# 300
Hyde Field 10/13/77
LEGEND
——— = Clockwise Rotation
- - - - = Counter Clockwise Rotation
Heading Error (Degrees)
Heading (Degrees)
0
-1
-2
-3
-4
-5
-6
0
45
90
135
180
225
270
315
360

Figure 19

controlled conditions establish a necessary baseline from which to assess data quality. Through modeling techniques (as described by McCullough in the preceding paper) and further testing for specific cause-effect relationships, an accurate prediction of field data quality can be developed before implantment and, through post-deployment calibrations, total error bounds may be established on survey data.

The NBIS ACM-1 performance excels in two categories: (1) fast time response to fluid velocity fluctuations, and (2) unlimited threshold with very low output noise levels relatively independent of velocity. Horizontal response errors are within the cardinal axis calibration error band accuracy. Vertical plane response is such that errors may be introduced by meter tilt and/or vertical velocities produced by mooring or water particle dynamics. The tests that T&EL have conducted yield an indication of sensor performance and show that the NBIS ACM-1 is an operational instrument capable of functioning in the environment. Field performance tests will indicate if the instrument is rugged enough to endure and if reliability, fouling, and corrosion problems exist. Additional laboratory tests should be performed to determine dynamic performance, directional response over a wider range of velocities, fluid characteristic effects, and long-term stability.

It is suggested that a coordinated evaluation approach be applied to all new instrument development. A major limitation to the use of new technology is the unknown characteristics of its performance. Field deployments and intercomparisons expose the instrument to a rather limited range of environmental conditions and generally are not cost effective in terms of knowledge gained. A coordinated program of laboratory and field testing should be performed before the operational use of instrumentation for scientific or engineering measurements. Data quality should be determined and be traceable to accepted standards and methods on each and every measurement program. To accomplish this, coummunity-wide communications must exist to allow interchange of information and establish a common data bank of knowledge to control the accumulation of unqualified measurement data.

REFERENCES

Lawson, K. D., N. L. Brown, D. H. Johnson and R. A. Matley. "A Three-Axis Acoustic Current Meter for Small-Scale Turbulence," ISA ASI, 1976, pp. 501-508.

REPRINTED with permission from the author and from Science magazine (198: 138-144, October 1977). The article has been revised, based on further radar system software improvements. The changes are in the results of comparison of the radar measurements with the drifter measurements, and are reflected in Figure 7 and its descriptive text.

Ocean Surface Currents Mapped by Radar

Mobile coastal units can map variable surface currents in real time to 70 kilometers, using ocean wave scatter.

D. E. Barrick, M. W. Evans, B. L. Weber

Currents within 1 meter of the ocean surface are highly variable, being driven by geostrophic forces and tides, but are strongly influenced by the local surface wind and wave fields. These currents transport floating matter and thus are of great importance in coastal areas, where considerable damage can be done by surface-borne pollutants and oil. In the case of the large oil spill by the tanker *Argo Merchant* off New England in December 1976, for example, catastrophic environmental damage was averted because strong offshore winds counteracted the normal surface-current drift toward shore. In a positive vein, the upper portion of the sea carries the zooplankton and phytoplankton, which are the dominant components at the bottom of the food chain and are responsible for production of most of the world's oxygen. Many types of fish eggs are borne by surface currents, which are therefore of concern to the fisheries industry. The transport of water with anomalous temperature differences is now believed to be responsible for unusual weather patterns affecting entire continents.

Near-surface current patterns, and how they respond locally to the relevant prevailing forces, are a subject that is largely unknown. Yet the subject is a crucial ingredient for the effective management of operations in coastal waters, and an increasingly important input for global resource monitoring and weather predictions.

Current Measurements

In conventional methods of measuring currents moored meters are used; the most recent types are referred to as vector-averaging current meters and the Aanderaa meter (*1*). These devices must be moored at depths exceeding 10 m, and thus provide little indication of the current at the surface, which is often different. Furthermore, data must be either recorded aboard the buoy (to be picked up later for analysis) or telemetered to shore; the instrumentation for the latter often restricts the operating range from the receiver to tens of kilometers. Surface currents have been measured by tracking floating objects. Qualitative estimates can be obtained by photographing the dispersal of dye packages from an aircraft, or by analyzing satellite infrared and optical imagery of suspended sediment (to a coarser area scale) (*2*). Quantitative measurements are made by photographically recording the positions of time-released floats dropped from the air, as described by Richardson *et al.* (*3*), or by tracking a drifting drogue buoy from a ship (*1*). In the latter case, a high-precision navigation system is required on the ship to accurately establish the drift of the buoy. Operations with aircraft or ships are both expensive and time-consuming for the meager amount of current data obtained (one vector over a period of about 1/2 hour). The velocity accuracy of these float-locating techniques appears to be of the order of 10 to 15 centimeters per second in magnitude and 5° in angle (*2*). The location of such drogues by triangulation, using high-frequency (HF) surface-wave emissions from the buoy, is described in (*3*); although such drogues are inexpensive ($175), the positional accuracy deteriorates with distance from shore, making this an unacceptable alternative near the edge of the continental shelf.

We discuss here a coastally located HF radar system that can measure and map near-surface currents to ranges about 70 kilometers from shore. This instrument deduces current velocity from the echoes scattered continuously from the ocean waves; buoys and drifters are not required. The radar units were built to be transportable and quickly deployable on a beach. A minicomputer controls the radar and processes the signals, permitting a current-vector map to be plotted in the field after 1/2 hour of operation. Two spatially separated radar units are presently employed, simultaneously

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but independently, in order to yield the total current vector at each map grid point.

The principles underlying the system have been studied theoretically and experimentally over the past several years. The motion of the waves is seen by the radar as a translation of the frequency of the received echo signal from that of the transmitted signal; this frequency translation is called the echo Doppler shift. The radar can thus resolve and measure the component of scatter velocity along the line between the scatterer and the radar, referred to as the radial velocity. Crombie (*4*) first showed experimentally—and it was later confirmed theoretically (*5*)—that to first order the scatterers at high frequency are ocean wave trains moving toward and away from the radar, having spatial periods precisely one-half the radar wavelength. Thus the scattering mechanism is the diffraction grating or Bragg effect used in holography or in x-ray analysis of crystalline structures. The spectrum of the continuous-wave transmitted signal is a narrow peak at the carrier frequency location, as shown in Fig. 1. In the absence of current, the received first-order sea echo appears as two symmetrically spaced peaks about the carrier, whose Doppler shifts are given by the lowest-order dispersion relation of the scattering gravity waves; that is

$$\pm f_B = 2v_{ph}/\lambda = 2(gL/2\pi)^{1/2}/\lambda = (g/\pi\lambda)^{1/2} \qquad (1)$$

where λ is the radar wavelength, $L = \lambda/2$ is the length of the ocean waves responsible for the first-order Bragg scattering, v_{ph} is the phase velocity of these waves, and g is the gravitational constant.

A current beneath the surface waves represents a transport of the water mass, and can be thought of as a translation of the entire coordinate frame for the waves with respect to the observer at the stationary radar on shore. Hence the two spectral peaks scattered from the waves will be shifted (with respect to the position of the carrier frequency) by a small amount proportional to the radial component of current velocity, as shown at the bottom of Fig. 1. This amount is $\Delta f = 2v_{cr}/\lambda$, where v_{cr} is the mean effective current velocity radial to the radar. In (*6*), radar-deduced radial current observations were compared with drifter measurements of currents at San Clemente Island; the narrow radar beam and short pulse kept the ocean patch size under observation to about 7 by 7 km. The agreement was about ± 10 cm/sec. In these investigations (*6*, *7*) the effect of a nonuniform current on the transport of the radar-observed surface waves was also analyzed as a function of depth.

Experiments such as those at San Clemente Island (*6*, *7*), resolving the sea echo from narrow azimuthal sectors at high frequency, require long permanent phased-array antenna systems (> 300 m) on the beach to form a narrow beam. When one considers typical current patterns and the various echo-signal Doppler shifts they would produce at different azimuths from the radar, one can conceive of much smaller, simpler antenna systems for determining the direction of arrival of the echo. For example, by comparing the phase between two noninteracting antennas separated by less than one-half wavelength, one can uniquely determine the direction of arrival over 180° of space of a single signal at a given Doppler shift. Crombie (*8*) showed that this simple two-antenna system was adequate to azimuthally resolve sea-echo signals from Florida, looking eastward across the south-to-north Gulf Stream current flow.

Concepts Behind the Present System

Because seawater is nearly a perfect conductor at high frequency (3 to 30 megahertz), the "ground-wave" propagation mode is employed (*9*). In this mode, vertically polarized electric fields are transmitted and received. The propagating fields at these frequencies follow the curvature of the earth and continue well into the shadow region beyond the horizon, even in the absence of atmospheric and ionospheric refractive index anomalies. Mathematical solutions for the ground wave—corrected to include the effects of sea-surface roughness (*9*)—are available. They show that (i) near the radiating source, the field decays with the expected inverse range dependence of free space, and (ii) far into the shadow region, the fields near the surface decay exponentially with range. This exponential range dependence ultimately dictates the maximum distance at which currents can be observed for a particular transmitted power. For the hardware described in the next section, the maximum range for the system—allowing for a 10-decibel signal-to-noise ratio (S/N) at the receiver (*10*)—is about 70 km; this has been verified in our recent experiments, which are discussed below.

Although the system does not employ ionospheric or atmospheric refraction to propagate beyond the horizon, it is incorrect to call it a "line-of-sight" radar (as is a microwave radar). In fact, trying to increase the useful range of the radar by elevating the antennas (in order to increase the distance to the horizon) is counterproductive, because there is a discontinuity in the propagation path in free space between the antennas and the highly conducting seawater. We have established this fact theoretically and also experimentally, by trying to put the antennas on roofs of buildings (but back several hundred meters from the water) to increase the range. We have found that the optimal locations for the antennas are at sea level on the beach, as close to the water as possible; in fact, it

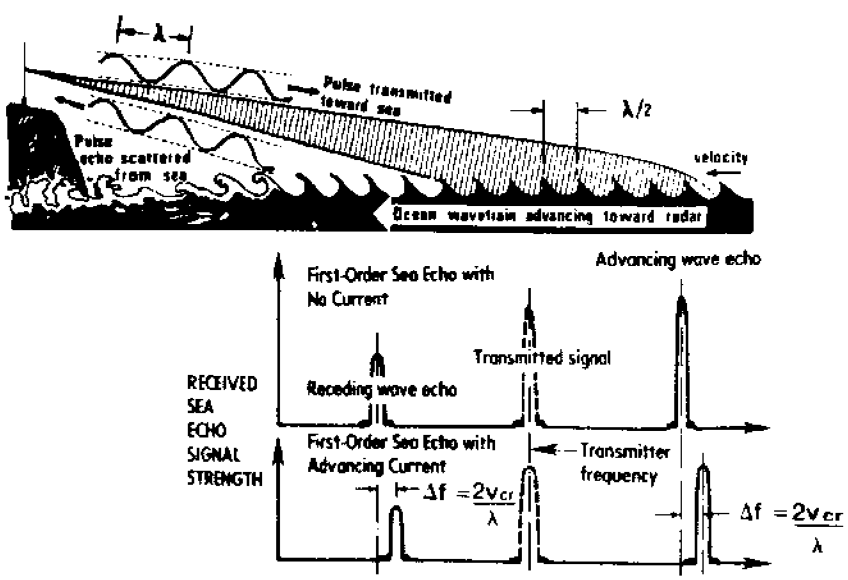


Fig. 1. Sketch showing the principles of first-order HF Bragg scatter from the sea, and resulting signal echo spectra without and with an underlying current.

is best if the grounding system beneath the antennas makes electrical contact with the seawater.

A separate antenna is used for transmitting. It produces a slightly directional pattern, peaked out toward the sea, with a half-power beam width of ±90°; its radiation in the backward direction is ~ 10 db lower than that in the forward direction, which minimizes unwanted illumination over land. As with nearly all radars, time gating of the received signal echo referenced to the transmitted pulse time determines the range to the sea echo. Our system transmits a 20-microsecond unmodulated pulse and digitizes the received echo signal every 20 microseconds after transmission. The signal sample from each range (time) gate thus represents the echo from an annulus of the sea surface 3 km in width, concentric with the radar location. A total of 25 consecutive range-gated signals are thus retained for every transmitted pulse, providing a total distance of about 75 km from the radar. The transmitted pulse repetition interval is 1 millisecond.

Since echo-signal Doppler shifts are to be related to current velocities, the time series for each range gate is spectrally processed. This is done digitally at the radar site with a fast Fourier transform (FFT) algorithm. Appropriate digital filtering of the signals is performed before the FFT to prevent spectral aliasing and to maximize S/N. Since the sea surface is a random variable, the sea echo is also a random variable. In fact, each spectral power point output from the FFT is an independent random variable, following a chi-square distribution with two degrees of freedom (*11*).

In the first series of experiments, three colinear independent receiving antennas were employed. The received signal was sampled on each antenna separately and sequentially for each transmission every millisecond, with the other two antennas switched open to minimize mutual interactions. Therefore the FFT outputs from the three antennas (for a given range gate) can be thought of as being measured simultaneously; the only theoretical difference between the signals at the antennas is due to the phase path differences undergone by an echo, at a particular Doppler frequency from a particular direction, arriving at the different positions of the three elements. Three antenna elements, each separated for our first experiments by one-quarter wavelength (3 m at 25 Mhz), aligned parallel to a straight coastline, can unambiguously resolve two sea-echo signals at a particular Doppler frequency from 180° of space. For two signals with complex amplitudes $\dot{A}_1$ and $\dot{A}_2$ from angles α_1 and α_2 (with respect to the perpendicular to the coastline), the three complex received voltages $\dot{V}_A$, $\dot{V}_B$, and $\dot{V}_C$ can be solved in closed form for the desired angles and amplitudes, with the following results (asterisks denote complex conjugates)

$$\alpha_{1,2} = \sin^{-1}\left[\frac{-\tan^{-1}\left(\frac{\mathrm{Im}(x_{1,2})}{\mathrm{Re}(x_{1,2})}\right)}{\pi/2}\right] \quad (2)$$

and

$$\dot{A}_{1,2} = \frac{\dot{V}_A x_{2,1} - \dot{V}_B}{(x_{2,1} - x_{1,2})} \quad (3)$$

where

$$x_{1,2} = \frac{(|\dot{V}_C|^2 - |\dot{V}_A|^2) \pm i(4|\dot{V}_C\dot{V}_B^* - \dot{V}_B\dot{V}_A^*|^2 - (|\dot{V}_C|^2 - |\dot{V}_A|^2)^2)^{1/2}}{2(\dot{V}_C^*\dot{V}_B - \dot{V}_B^*\dot{V}_A)}$$

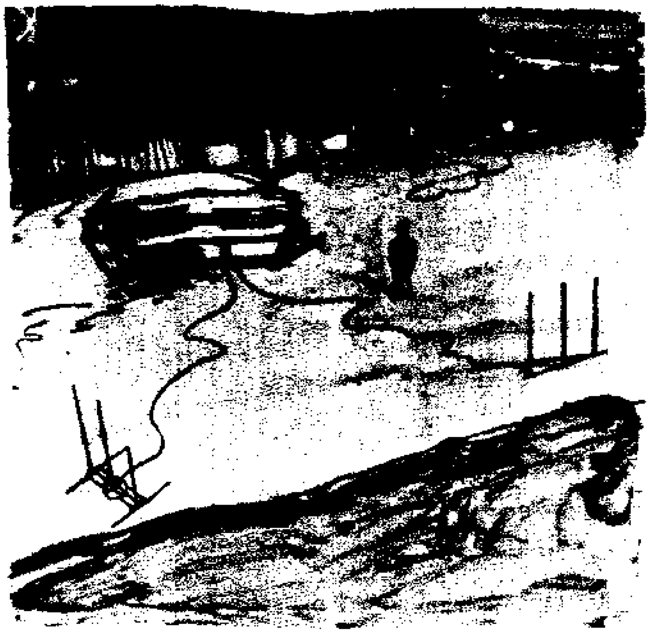
In reality, since the sea-echo signal amplitudes $\dot{A}_1$ and $\dot{A}_2$ are random variables to which random noise is added, the angles of arrival determined from Eqs. 2 to 4 contain a random error that decreases with increasing S/N. Extensive simulations and special experiments have shown that for 10-db S/N, such angular errors are less than 1° for $|\alpha| < 70°$. We have recently changed to a four-antenna configuration (arranged in a square) to resolve two signals from 360°; this permits us to operate the radar on a peninsula or an island with ocean water subtending more than 180° around the site.

Two sites are required to obtain two radial current-vector components along lines pointing in different directions in order to construct a total current vector at a particular point on the sea. For a straight coastline, the question arises as to how far apart the sites should be. Since a total current vector can be constructed only within the common overlapping areas seen by both sites, it is desirable to maximize this area (by moving the sites closer together). On the other hand, as the sites become close (superposed in the limit), they see most points on the sea in the common area along nearly the same radial direction, which makes construction of the total vector inaccurate. Consequently, we defined the optimization criterion for site separation as the product of the common coverage area times the average of the sine of the angle between the lines to the two sites. This product has a broad maximum, indicating that for a coverage distance from a single site of about 70 km, a site spacing anywhere between 25 and 55 km is adequate.

Various trade-offs were considered in selecting the frequency range 25 to 26 Mhz for our first series of tests (the radar wavelength of 12 m is, to first order, scattered from ocean waves with a 6-m wavelength). At these frequencies atmospheric and external man-made electrical noise are often low, being equal to internal electrical receiver noise, whereas at lower frequencies atmospheric noise seen by the radar increases sharply. In addition, antenna sizes also increase with decreasing frequency, requiring larger structures and more ground area. On the other hand, ground-wave propagation loss decreases with decreasing frequency, offsetting the noise dependence. There are additional reasons for operating at higher frequencies, however. For one thing, above 25 Mhz ionospherically propagated echoes are rarely encountered, whereas at lower frequencies such distant echoes can be folded in with the desired short-range sea return. Two other important reasons for higher frequencies are oceanographic in nature. First, the Bragg-scattering 6-m ocean waves are relatively short and are likely to be present more of the time than longer waves, which require stronger winds to develop them. A wind with a velocity greater than 3 m/sec, blowing longer than 1 hour, will develop 6-m waves to their (equilibrium) root-mean-square height of ~ 10 cm. Inasmuch as the waves are used only as a "tracer" for the underlying currents, it is desirable that they be present as often as possible. Second, the shorter the ocean waves under observation, the more they are influenced by currents very near the surface. A rule of thumb (*6, 7*) is that the depth of the layer whose current will affect a surface wave of length L is $L/2\pi$ (about 1 m for L = 6 m). Hence, if one wants to observe currents in the uppermost ocean layers by measuring their effect on the phase speeds of gravity waves, he should use as high a radar frequency as possible. These factors led us to select 25 to 30 Mhz for our initial operations.

Hardware Description

The present two-unit radar system was designed as a prototype of an operational version, with considerably more flexibility than will ultimately be needed, in order to facilitate changes as experience is gained in the field. Yet this system was built to be transported by vehicle (see Fig. 2), easily erected on a beach, and capable of being operated from a portable power supply (a 2.2-kilowatt gaso-



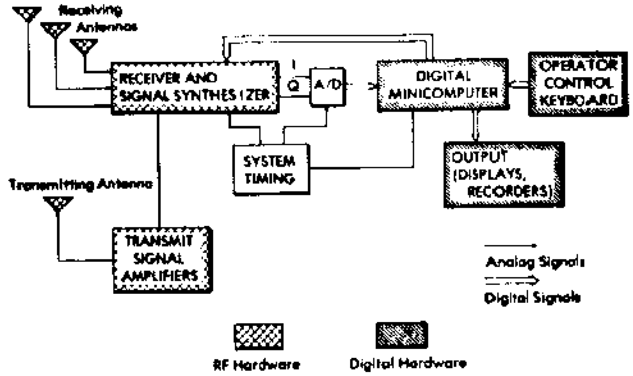


Fig. 2 (left). Sketch of the system as operated on the beach. Transmitting antennas are on the left and receiving antenna on the right. Fig. 3 (right). Block diagram of radar system.

line generator). The entire radar is controlled by a minicomputer, which also does the signal and data processing in the field. The end result is a map—drawn on a pen plotter—of the surface-current vector field.

The system radiates ~ 2.5-kw-peak pulse power, as a stream of 20-μsec pulses every millisecond; thus the average radiated power is only 50 watts. The radar is presently capable of transmitting any operator-selected frequency between 25 and 35 Mhz (in 200-khz increments), but so far we have operated primarily between 25 and 26 Mhz. The transmitting antenna is a log-periodic vertical monopole array of three (or four) elements designed especially for this application at Lawrence Livermore Laboratories (*12*). Both versions were designed to have an input impedance of ~ 50 ohms (real) from 25 to 27 Mhz; the three-element version has a half-power beam width of ± 90°, while the four-element version has ± 43°.

The individual receiving elements are readily available fiberglass-encased citizens-band whips cut to a height of 1.575 m and each fed against a quarter-wavelength, four-element, radial ground screen. The three (and currently four) receiving elements are aligned on the beach with a tape measure and compass. These elements are each connected through one-half wavelength of coaxial cable to a switching network and preamplifier box, which cycles sequentially through each of the antennas at a rate of 1 msec per antenna. From this switch, the signals then pass through a single preamplifier and coaxial line several tens of meters in length to the receiver hardware in the van. From the antenna switch onward, the signals from each antenna pass through the same hardware, eliminating mismatch problems through separate channels. The entire antenna system can be unfurled by two men in about 1/2 hour.

The heart of the radio-frequency system is the receiver (Fig. 3), designed by Barry Research, Inc., especially for this radar. In addition to its obvious function, the receiver also synthesizes the desired carrier frequency and the pulse stream to be transmitted. This stream is amplified in hardware designed and built in-house. Every 20 μsec, the receiver gain is changed under computer control, called a sensitivity time control (STC), in order to compensate for the decrease of echo strength with range. The echo is coherently mixed down to zero-intermediate-frequency in-phase and quadrature (I and Q) signals. These I and Q signals are then digitized with a ten-bit analog-to-digital (A/D) converter every 20 μsec.

Fig. 4. Photograph of complete radar radio-frequency and digital hardware.

and all subsequent signal processing is done digitally. This includes filtering (called preaveraging, over 1/2 or 1/4 second) to reduce the signal bandwidth to 2 or 4 hertz. The filtered signals for each range gate and each receiving antenna are then collected for 128 or 256 seconds as the input to a 512-point complex FFT; thus, for the 128-second option, for example, the displayed spectrum has a Doppler resolution of 1/128 hertz over a window from − 2 to + 2 hertz. (These parameters can be selected by the operator.) The 1/128-hertz Doppler resolution translates into a radial current velocity resolution of ~ 5 cm/sec.

The heart of the digital system for radar control and data processing is a Digital Equipment Corporation PDP 11/34 minicomputer. The operator communicates with the system through a portable keyboard terminal. Moving-head magnetic disk and nine-track magnetic tape units are available for loading system software into the computer and also for recording and archiving processed radar data. Graphic displays and pen plotters are available to display raw spectra and current-vector plots. Further description of the system hardware is found in (*10*); a photograph of the complete digital and radio-frequency hardware (excluding antennas) for one site is shown in Fig. 4.

Experimental Results and Digital Data Analysis

Initial field operations began with the new radar system in southern Florida during late 1976; there was an additional final week of operations in Florida from 20 to 26 March 1977, during which fairly extensive independent measurements of surface currents were made for comparisons. The Florida area was selected for initial operations and system calibrations because of the fairly regular but strong south-to-north Gulf Stream flow east of Miami. The two sites were located at South Miami Beach (20° 46′00″N,80°07′58″W) and Fort Lauderdale (26°05′01″N,80°06′38″W), approximately 36 km apart. The latitudes and longitudes of the two sites are entered into the computer, along with the azimuthal bearings of the two receiving antenna arrays. The software then calculates the x, y positions of a rectangular grid (3 by 3 km) of points to the east of the baseline joining the two sites—at which current vectors will be plotted from the radar data—after conversion from the radar-oriented polar coordinates (range and azimuthal bearing from each site). Most of the measurements were made on 25.4 or 25.6 Mhz, with a 128-second coherent integration time (providing a Doppler resolution of 1/128 hertz).

The output of a single FFT is a complex random variable, having Rayleigh amplitude and uniform phase probability densities. The desired first-order portion of the sea echo is random because of the statistical nature of the scattering sea surface. The remaining portion of the FFT output can be thought of as additive random noise with respect to its effect on the desired first-order signal. In reality, there are at least four types of noise, originating from different sources: (i) external atmospheric or man-made noise, (ii) internal receiver noise, (iii) second-order radar sea echo (*13*), and (iv) processor noise due to limited system dynamic range, system nonlinearities, and quantization noise. Finally, the actual current field beneath the waves, instead of being uniform, is more likely to be somewhat turbulent within the spatial resolution scales seen by the radar. Hence, the total signal plus noise is random, and from this we intend to extract (i) an estimate of the azimuth angle of arrival of the signal at each Doppler frequency output from the FFT, (ii) an estimate of the radial current velocity at this range and azimuth, and (iii) the sea-echo signal amplitude.

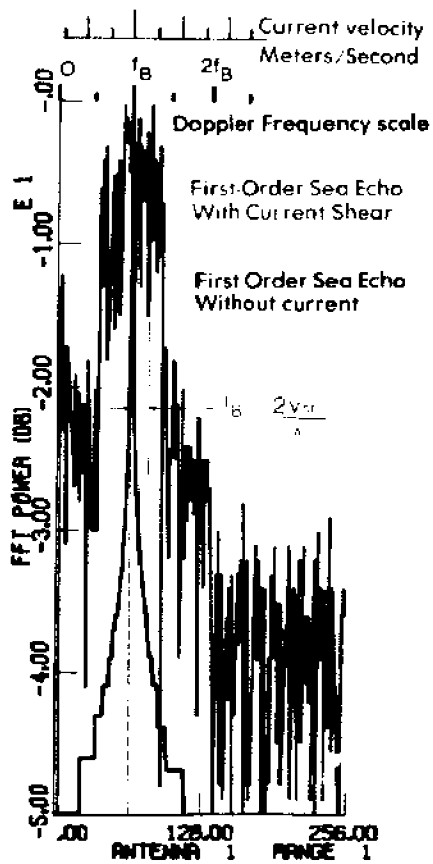
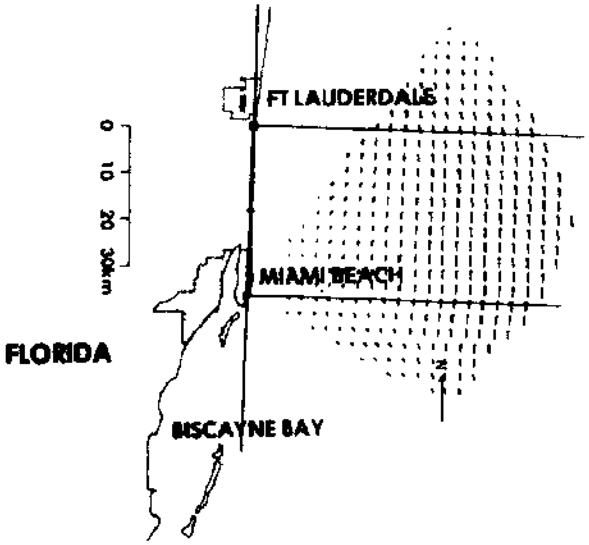


Fig. 5. Plot of FFT spectral power output. The black spectrum is the idealized test sea-echo spectrum in the absence of a current. The gray spectrum is the measured sea echo at 37.5 km from Fort Lauderdale, as modified by Gulf Stream current shear.

Since extraction of the angle of arrival, using the equations given above, requires the use of coherent simultaneous signals from each of three (or four) receiving antennas for a given range cell, we cannot average the individual outputs of the FFT's in order to reduce the effects of random signal fluctuation and noise. Instead, we go through the following process. Figure 5 is an example of the right half of the amplitude-squared output of the FFT processor for the 37.5-km range gate for sea echo measured at Fort Lauderdale. A threshold level is established for the usable portion of the signal (for example, 20 db down from the mean peak level), and the remainder of the FFT output is discarded. The solid curve shows the expected position of the echo in the absence of any current over the semicircular range cell; it occurs at a Doppler shift f_d (Eq. 1). All echo points at Doppler shifts different from f_d are therefore due to currents, and a radial current velocity scale centered on f_d can be given in terms of these Doppler shifts, as shown in Fig. 5. The angle of arrival of the signal at each of these Doppler shifts (or radial current velocities) is then obtained from the complex signals V_A, V_B, and V_C at each of the three antennas, using Eqs. 2 to 4.

At this point, for a given 128-second run and for each range gate, we have an array of azimuth angles and signal echo amplitudes as a function of radial current velocity. We then interchange the roles of the dependent and independent variables, considering radial velocity as a function of azimuth angle. After accumulating and storing radial velocity data over several consecutive 128-second runs (typically ten), we then average the radial velocities that fall within preset angular "bins."

This averaging is actually done in a manner that gives preference to higher-quality points. First of all, each sample radial velocity point in a particular angular bin is weighted by the ratio of the signal (amplitude squared) to the average noise power level for that same point; higher signal amplitude values give more accurate angle estimates. Second, other quality factors are used to weight the radial velocity samples. For example, in the absence of noise, the amplitudes of $x_{1,2}$ given in Eq. 4 will always be unity. Hence samples whose values of $|x_{1,2}|$ de-



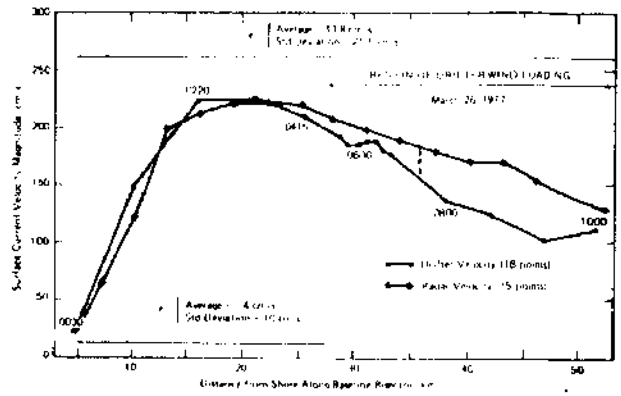


Fig. 6 (left). Computer-generated map of the Gulf Stream current on 20 October 1976 as deduced by radar. Fig. 7 (right). Comparison of radar-deduced surface velocity magnitude with drifter measurements.

part significantly from unity are weighted lower. Finally, the signal-to-noise ratios for all of the samples in a particular angular bin are averaged; this is used in a final thresholding process to decide whether the (weighted) averaged radial velocity for that bin will ultimately be used. If it is not used (because the signals are too low) or if there were no values falling in the bin, then a value for the radial velocity at that angle is calculated by interpolation from the adjacent range-azimuth cells.

In the process of producing a map, the data from both sites are combined (in our case, either by data telemetry between the two sites or by physically transporting the data tapes from one site to the other). Then the arrays of radial current velocities from each radar site together with range and azimuth (in polar coordinates) are entered for each rectangular grid point; also, direction cosines at the grid point are calculated for the radial lines to the sites. This allows the total current vector to be plotted at that grid point. The angular sectors very near the shore are sometimes excluded because the nearly parallel radial velocities seen from each site at these grid points give rise to large vector errors; integration techniques to improve the quality of the maps near shore are being investigated. Figure 6 is an example of a map made in Florida by using these data processing steps. The well-known horizontal shear of the Gulf Stream (outward from the shore) is clearly visible in these maps.

The point to be emphasized is that all of the averaging, weighting, and thresholding procedures described above are done digitally (not arbitrarily or subjectively), according to rules that are being optimized. The mathematical steps involved, beginning with the angle extraction, are nonlinear in nature. Hence it is not possible to obtain mathematical error estimates in closed form. The optimization of the processing algorithms must therefore be based on two methods of quality assessment. First, simulations are employed in which one begins with known current patterns, randomizes the first-order sea-echo spectrum, adds random noise, converts to a time series, and then processes this simulated echo signal to see how well the original current patterns are recovered. We have been using such simulations for nearly 3 years to arrive at our present algorithms. Second, independent measurements of surface currents are obtained during radar operations, using drifters and timed-released floats. Comparisons of these measurements with radar data are the subject of the next section.

Comparison with Drifters

As an ultimate calibration standard, one would like to employ independent measurements of near-surface currents as "ground truth." However, since differences of tens of centimeters per second have been documented in drifter current measurements, there is considerable doubt as to whether disagreements of this order between drifter- and radar-deduced currents are due to radar errors or drifter errors. Furthermore, the two techniques are so dissimilar in nature that there are many reasons why they should respond differently to conditions near the surface. Nonetheless, since drifters are the only established quantitative method of estimating surface currents, we made a series of radar measurements on 23 to 26 March 1977 in Florida in conjunction with ship tracks of drifters in order to establish some initial credibility for this new remote-sensing technique. The Nova University vessel *Youngster III*—supported by a Hi-Fix Navigation system—tracked a drifter at several positions in the radar coverage area over 8- to 12-hour periods on 23 and 25 March. This drifter was drogued with rigid vertical aluminum baffle plates extending 46 cm below the surface float. Each track consisted of a 5- to 8-minute drift whose start and end points were marked navigationally; from this a mean (Lagrangian) drift velocity was calculated. In addition, the National Oceanic and Atmospheric Adminstration vessel *Virginia Key*—supported by a miniranger navigation system—tracked a cork float on 23 and 24 March at other locations in the coverage area. Again, each track lasted about 5 minutes.

The velocities deduced from both radar and drifter measurements, and the differences between them, were relatively similar in all cases. Significantly, the drifter velocities show considerable differences from day to day. For comparison, we show here our longest set of drifter measurements, made eastward from shore (at the midpoint between the two radar sites) to a range of 50 km; these drifter measurements, made with the *Youngster III* and the drogued buoy, required 12 hours to complete. These measurements are shown in Fig. 7 along with radar-deduced current velocities. The total current-vector magnitudes are plotted for each technique.

The agreement is very reasonable, within the range of expected drifter variances.

Both techniques recorded the current shear with distance from shore quite accurately, and observed the current maximum on this particular day at approximately 20 km from shore. Most of the disagreement beyond 27 km was due to the fact that a sudden onset of high winds and breaking waves caused the drifter to tip over, so that it was not measuring surface-current drift properly. Measuring the average error, ε (between straight-line segments joining the two sets of points) and its standard deviation over the path out to 27 km, we obtain 10 cm/s for the standard deviation. If we include the entire path, this standard deviation is 21.5 cm/s.

The 10 cm/s difference may well be the best obtainable agreement between these two techniques because they are intrinsically observing different quantities. The drifter measurement is Lagrangian in nature, averaged over only a short line (400-500 m); the radar measurement is Eulerian, averaged over an area of about 3 by 3 km.

Applications and Future Directions

The HF radar remote-sensing system appears to provide considerably expanded observational capability for coastal physical oceanographic research. Since it is transportable and offers output current maps on site in near real time, the system has a great potential for operational coastal current monitoring and for quick response to offshore accidents. Inasmuch as surface currents are highly variable, elusive, and expensive to measure by existing in situ techniques, this instrument offers an attractive alternative. To duplicate the large areal volume of data vectors obtained with only a 1/2-hour radar operation would require many ships or aircraft tracking drifters simultaneously—an experiment that would cost hundreds of thousands of dollars. Our discussion with commercial manufacturers lead us to believe that streamlined operational versions of our prototype radar could be available for about $50,000 per complete radar pair.

The need to understand and better define the structure of currentlike water movement near the surface becomes more evident as we attempt to further interpret and refine the accuracy of this system. Both theoretical analyses and carefully planned experiments should be undertaken to quantify the effects of current turbulence within the radar cell, wave-wave interactions, and current shear with depth on the radar measurements. Furthermore, the actual linear horizontal drift of particles at the surface (for example, oil) and its relation to mean near-surface current velocity must be determined, especially under conditions of high winds and breaking waves. The similarities and differences between Eulerian areal and Lagrangian linear measurements need to be better understood. The prospect of having continuous surface-current data should provide the impetus to correlate currents with their short-term driving forces (such as winds, waves, and tides). Such a correlation is potentially a means of using the surface-current data to measure, indirectly, those driving forces.

Summary

A high-frequency radar remote-sensing system for measuring and mapping near-surface ocean currents in coastal waters has been analyzed and described. A transportable prototype version of the system was designed, constructed, and tested. With two units operating tens of kilometers apart, the currents were mapped in near real time at a grid of points 3 by 3 km covering areas exceeding 2000 km², out to a distance of about 70 km from the shore. Preliminary estimates of the precision of current velocity measurements show it to be about 10 cm/sec.

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S C I E N T I F I C   R E S E A R C H

Session Chairman: Nick Fofonoff
Woods Hole Oceanographic Institution

MOORING MOTION INFLUENCES ON CURRENT MEASUREMENTS

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ABSTRACT

An important observational problem related to improving coupled ocean-atmosphere models is the determination of the vertical distribution of horizontal currents generated in the upper mixed layer of the ocean by the passage of a storm. Mixed layer shears might be as large as 0.04 sec^{-1}. Because rectification of near-surface current measurements by mooring line motions reduces the accuracy of near-surface circulation studies, to what extent do moored current measurements represent the near-surface horizontal velocity field? Results from several intercomparison tests indicate that mooring-related rectification of AMF vector-averaging current meter (VACM) measurements made near the surface beneath a surface-following float moored in deep-water was small, approximately a few cm sec^{-1}, or 10-15 percent of the near-surface current generated by a storm.

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INTRODUCTION

Reviews of intercomparison tests of moored current measurements and of observations of upper ocean current shears have been discussed elsewhere (Halpern, 1977; 1978). This paper will focus on the influence produced by mooring line motions on the Savonius vector-averaging current meter (VACM). Attention is focused on the VACM because numerous previous studies (e.g., Beardsley et al., 1977; Halpern and Pillsbury, 1976; Saunders, 1976; SCOR Working Group 21, 1975; Gonella and Lamy, 1974) have shown it to record near-surface currents more accurately than other kinds of rotor/vane instruments. We restrict our discussion to deep-water regions.

INTERCOMPARISON TESTS IN DEEP-WATER

For many years before the 1972 SCOR (Scientific Committee on Oceanic Research) Working Group 21 Third Intercomparison Test, current measurements were made beneath surface buoys with the realization that the data contained spurious currents produced by vertical motions of the instrument, high-frequency surface wave motions and cable vibrations (e.g., Webster, 1967). Results from the 1972 SCOR Test (SCOR Working Group 21, 1975; Gould and Sambuco, 1975; Gould et al; 1974) indicated that current measurements made at intermediate depths beneath surface buoys moored in deep water were undoubtedly contaminated by mooring motion. Soon afterwards, it was widely conjectured that erroneous current measurements would be obtained at all depths beneath a surface-following buoy. Evidence contrary to this view has since been provided by Zenk et al. (1978), Saunders (1976), Halpern et al. (1974) and Pollard (1974).

Previous intercomparison tests were made under conditions of relatively low wind speeds, small sea heights and large current speeds, and thus were not suitable for studying the in situ characteristics of the Savonius rotor/vane VACM during conditions typical of storm-generated mixed layer deepening. During the Mixed Layer Experiment (MILE) which occurred in August and September 1977, in the northeast Pacific at O.W.S. PAPA (50°N, 145°W), several intercomparisons of VACM data were made when 36-hour wind speeds and significant wave heights were greater than 15 m sec^{-1} and 3 m, respectively (Halpern and Davis, in preparation). During the 19.5-day experimental period, the mean surface current speed was about 5 cm sec^{-1}. Comparison of VACM data recorded at 8 m beneath a surface-following toroidal buoy and at 9 m beneath a stable spar buoy indicated that speed measurements made near the surface beneath a surface-following buoy will contain a large amount of mooring motion ("noise"), as expected, and that the characteristics of the VACM reduced the amount of mooring noise contained in the Cartesian component data. During a 24-hour interval of the storm, the 8 m (TOROID) and 9 m (SPAR) scalar speeds computed from the rotor counts measured at 1.875-min intervals were 77.5 ± 3.9 cm sec^{-1} and 36.4 ± 5.1 cm sec^{-1}, respectively, but the rms difference between individually measured east (or north) component speeds was about 5 cm sec^{-1} (Figure 1). Because of the vibrations of the mooring line and the vertical motion of the VACM beneath the surface-following buoy, large scalar speeds were recorded. During the 5.25-day intercomparison test when wind speeds were 3 m sec^{-1} to 21 m sec^{-1}, the vector-mean speeds were less than 1 cm sec^{-1} different. The fast response of the VACM vane and the high-frequency Cartesian speed sampling scheme allow for a more representative measurement of velocity despite the larger rotor-scalar speed caused in part by the motion of the surface-following buoy. Kinetic energy density spectra (Figure 2) of the 8 m (TOROID) and 9 m (SPAR) VACM records measured during the 5.25-day test encompassing the passage of the intense low-pressure system contained a 1:1 correspondence between energy levels for frequencies below 4 cph. At frequencies above 4 cph, the 8 m (TOROID) spectrum flattened. The change in slopes of both spectra at frequencies between 1.5 and 3.5 cph might be an indication of the occurrence of internal wave motions near the Brunt-Väisälä frequency.

CONCLUSION

The small number of intercomparison tests conducted with VACMs placed near the surface beneath surface-following buoys moored in deep water, indicated that spurious currents produced by mooring line motions were greatly reduced by the fast-response sensors and the internal recording mechanism of the instrument. The effect of high-frequency surface motions on VACM data was small during the large winds and wave heights encountered during MILE (Davis and Weller, 1977). Reduction of cable strumming (Softley *et al*., 1977) will probably also minimize the amount of rotor-pumping produced by vibrations of the mooring cable.

ACKNOWLEDGMENTS

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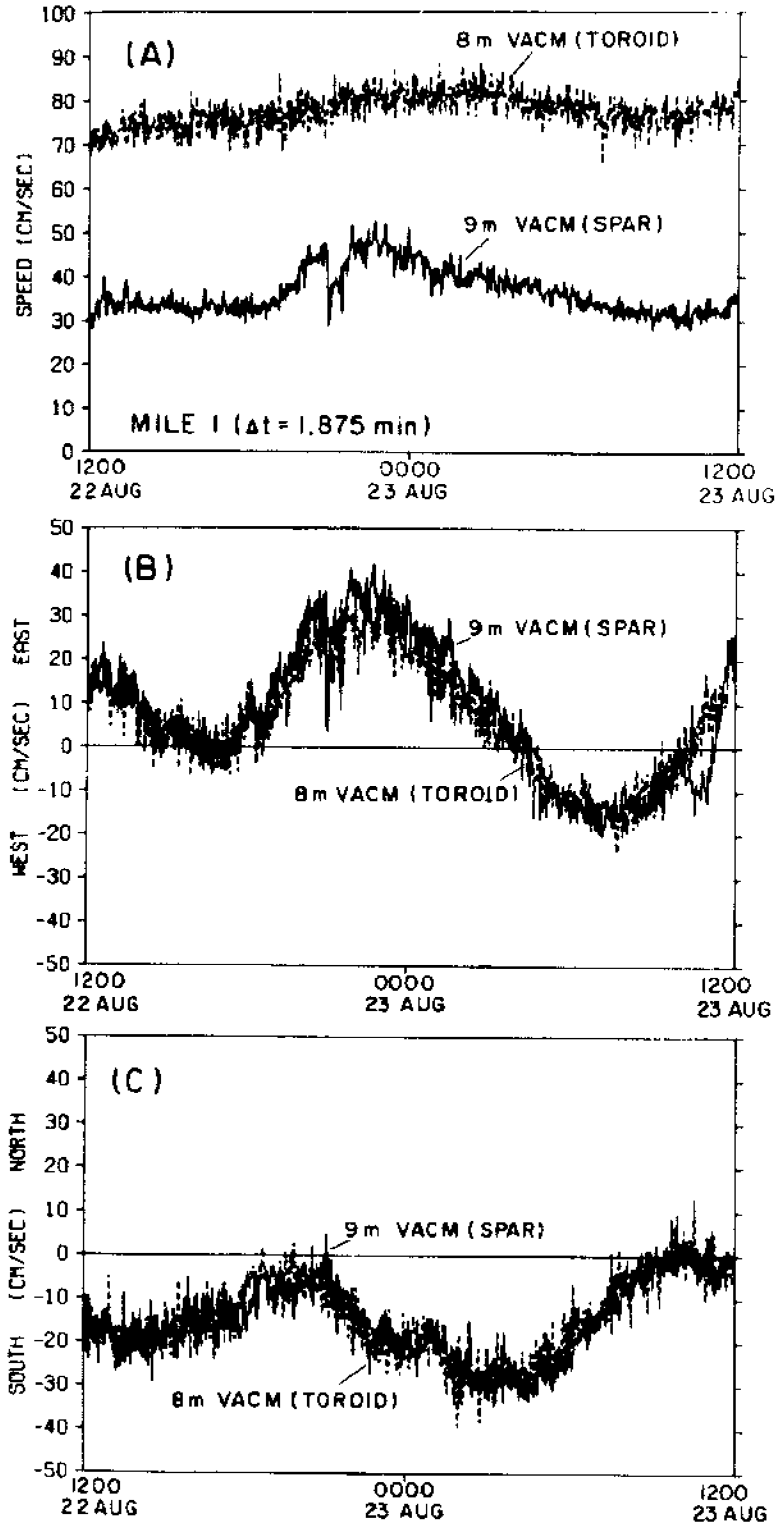
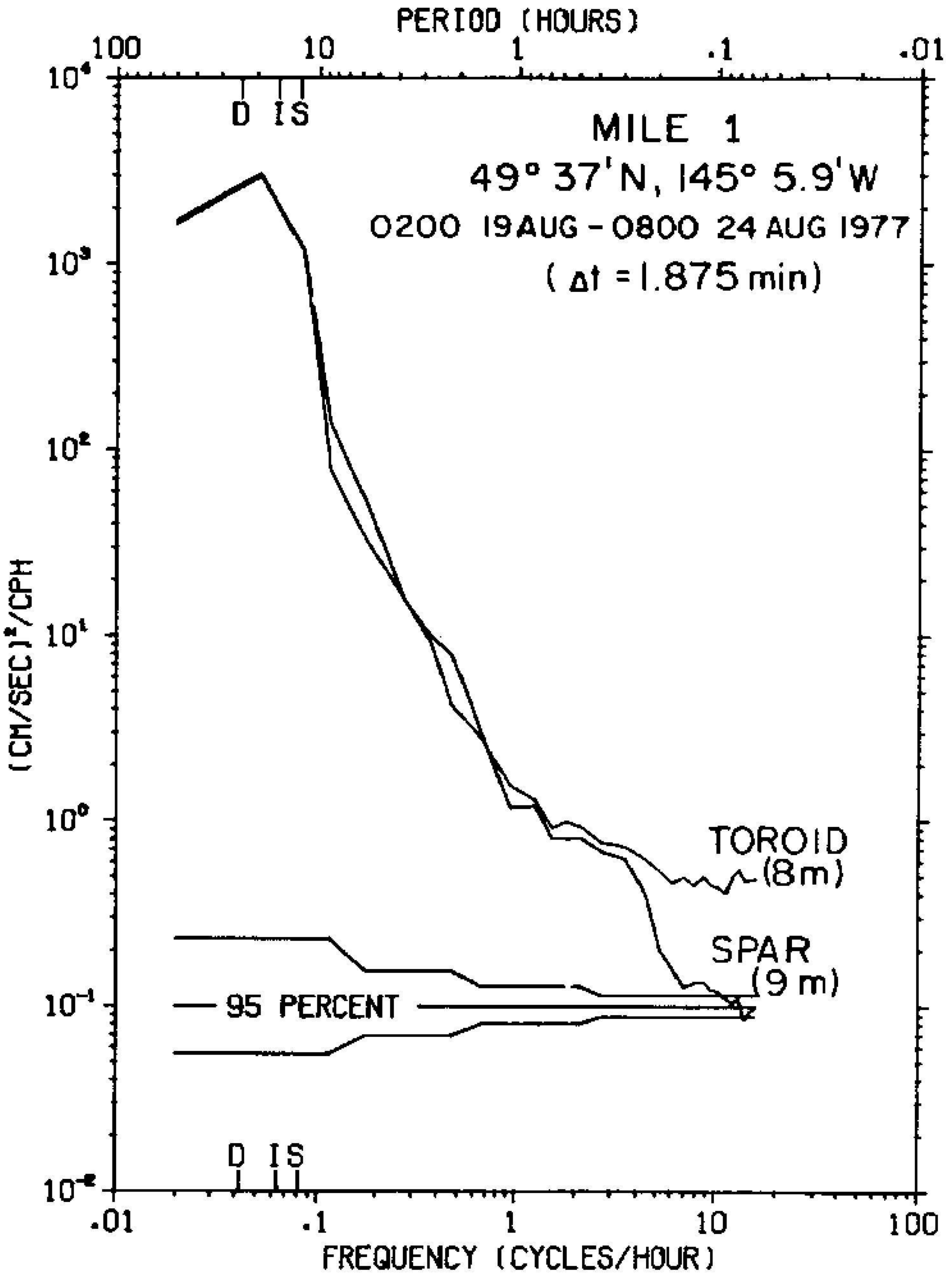


re 1. Time-series of (A) speed computed from number of rotor counts recorded during 1.875-min sampling interval, and (B) east-west and (C) north-south component recorded at 1.875-min intervals.



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PHYSICAL OCEANOGRAPHIC RESEARCH USING THE ATTENDED PROFILING CURRENT METER (APCM) AND THE CYCLESONDE

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ABSTRACT

About half the physical oceanographic observations at the University of Miami are current profile measurements. These measurements are gathered by two distinct methods: the Attended Profiling Current Meter (APCM), which has been primarily developed and used by Dr. Walter Düing in his studies of intense ocean currents such as the Gulf Stream, the Equatorial Current and the Somali Current where near-surface current meter moorings are impractical or high vertical resolution velocity data are required; the second method involves the use of an automatic unattended current profiler--the Cyclesonde. The Cyclesonde, developed by John Van Leer, has been used to study current profiles on continental shelves and in the upper 300 meters where long time series of CTD/velocity profiles are desired or where profile array data with a single ship are available. Time series profiles are particularly useful in studying inertial waves, mixing processes, bottom and surface boundary layers or complex mean flow patterns associated with fronts. About 20,000 velocity profiles have been collected by APCM and Cyclesonde techniques.

The principal source of error in the APCM is navigational uncertainty in the ship's position, which is required to convert the velocity profile relative to the ship into absolute velocity profiles. Other errors include time lag, angle offset, rotor shading and surface wave pump up. The roller coupling used in both methods greatly reduces the surface wave noise introduced in the speed sensor at depths below the zone of direct wave orbital influence. Typical APCM errors are 3-5 cm and Cyclesonde errors are 1-3 cm/sec, compared to fixed level current meters or other profiling techniques.

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INTRODUCTION

Two types of devices for obtaining vertical profiles of horizontal ocean currents in the upper ocean (generally 500 m depth or less) are now used at the University of Miami. The first of these is the Attended Profiling Current Meter, or APCM (Düing and Johnson, 1972), which is intended for use from a ship in regions of intense currents, when near-surface current meter moorings are impractical or velocity data with high vertical resolution are required. This instrument has been used successfully in the Gulf Stream, in the North Equatorial Current and in the Somali Current.

The second device is the Cyclesonde (Van Leer, 1976). This is a buoyancy-driven CTD/velocity profiler which makes repeated automatic profiles on a taut wire mooring in the upper 300 m of the ocean. It has been particularly useful for studying oceanographic phenomena such as coastal upwelling, bottom boundary layers, inertial waves and tides. Such data have been gathered in experiments off the coasts of Oregon and Peru and on the West Florida continental shelves. Cyclesondes have also been used in deep water to study the surface layers during the GATE Experiment.

Because of the different measurement techniques used with these instruments, each device has its own characteristics that influence the quality of data obtained. A brief description of each instrument will first be given, followed by some examples of the types of data which can be obtained. Finally, a discussion of data quality for both instruments is given.

DESCRIPTION OF THE APCM AND ITS DATA

The APCM consists of three major parts. A roller block couples the front of the instrument to a hydrowire. The roller decouples the APCM from the ship-forced vertical heaving motion of the wire, which would contaminate velocity data if the profiler were fixed to the end of the wire. The second part of the APCM is the hull, which consists of a PVC pipe filled with buoyancy balls to make the overall system almost neutrally buoyant. The hull also acts as a direction vane by trailing down-current from the wire. Its 3-meter length serves to damp out rapid fluctuations in direction. The final component is a current (speed and direction), temperature and depth recorder made by Aanderaa which is inserted in the bottom of the hull. The magnetic compass within the Aanderaa will indicate the orientation of the hull once per sample period, while speed is integrated between samples.

The complete APCM is ballasted slightly heavier than sea water so that it sinks down the hydrowire. If the end of the hydrowire is weighted with 300-500 pounds of lead, and if the ship steams steadily on the wire to reduce its angle relative to the vertical, a rather uniform descent rate of 10 to 15 cm/sec can be maintained. Using a sampling period of 30 seconds, this gives a 3 to 5 meter vertical resolution for the resulting profile data.

An APCM can be seen in Figure 1 being lowered over the side of a moored ship in the Gulf Stream during Project SYNOPS (Düing and Johnson, 1972). A recent example of a time series of equatorial current surveys made by a single ship is shown in Figure 2. The ship sequentially occupied a series of stations spanning the equator. These data illustrate the high vertical resolution of current velocity attainable with the APCM and the value of mobility in surveys of low frequency oceanic phenomena.

DESCRIPTION OF THE CYCLESONDE AND ITS DATA

The Cyclesonde was designed to make long time series of vertical profiles on moorings at fixed locations (Van Leer, 1976). It may be thought of as replacing an anchored ship making repeated CTD and APCM casts. Cyclesondes (Figure 3) have usually been used on moorings (Figure 4), with both internal recording and radio telemetry. They are often deployed in groups of four or five to form a synoptic array over some region. Profiles are made on a preset schedule (typically every one to four hours), and can operate from weeks to months depending on the water depth profiled and the frequency of profiling. The Cyclesonde logs up to 15 channels of data with 12-bit resolution at present periods from 2 to 60 seconds. The frequency of sampling makes the analysis of inertial, tidal or mean motion possible without the usual vertical aliasing found in fixed-level current meter arrays (Van Leer, 1978).

An example of Cyclesonde temperature and velocity data recorded in June 1975 is shown in Figure 5. These contoured data are based on twice hourly profiles over a 4-1/2 day period. They illustrate the complex vertical structure of the tidal motion as well as the development of the bottom boundary layer with time.

APCM DATA QUALITY

Since the APCM is used from aboard an anchored or drifting ship, only relative velocity profiles are obtained. These relative profiles are then made absolute by correcting for the ship's drift or motion on the mooring. Thus, navigational uncertainty can be an important source of error when measuring currents with this technique. Anchored radar reference buoys are often used as navigational references. A method using shore-based radar transponders is being developed to precisely locate the ship's position. This method should be accurate to about 100 km offshore and will appreciably improve the accuracy of absolute profiles.

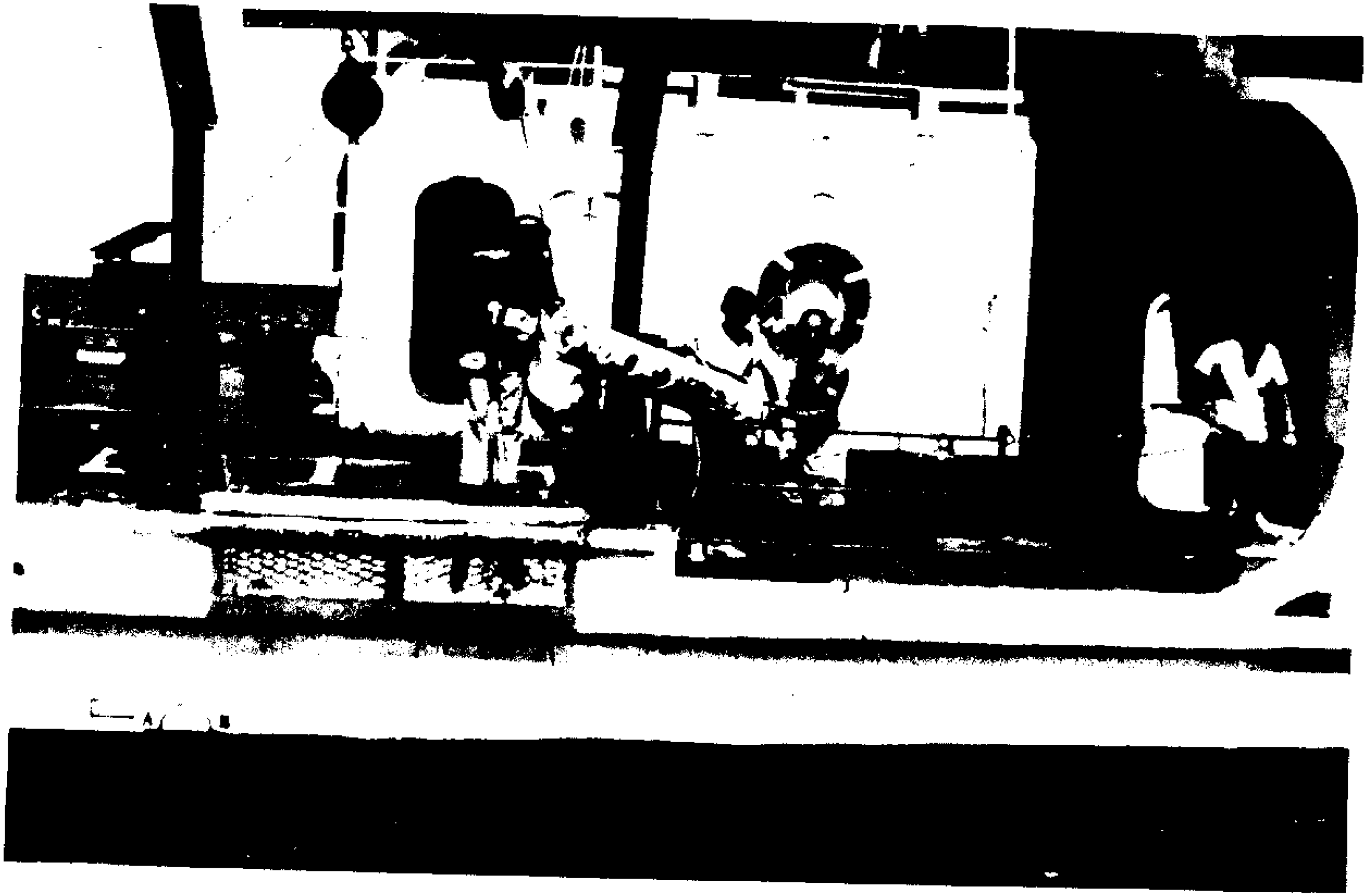

Figure 1. Attended Profiling Current Meter (APCM) being lowered over the side of an anchored ship during project SYNOPS.

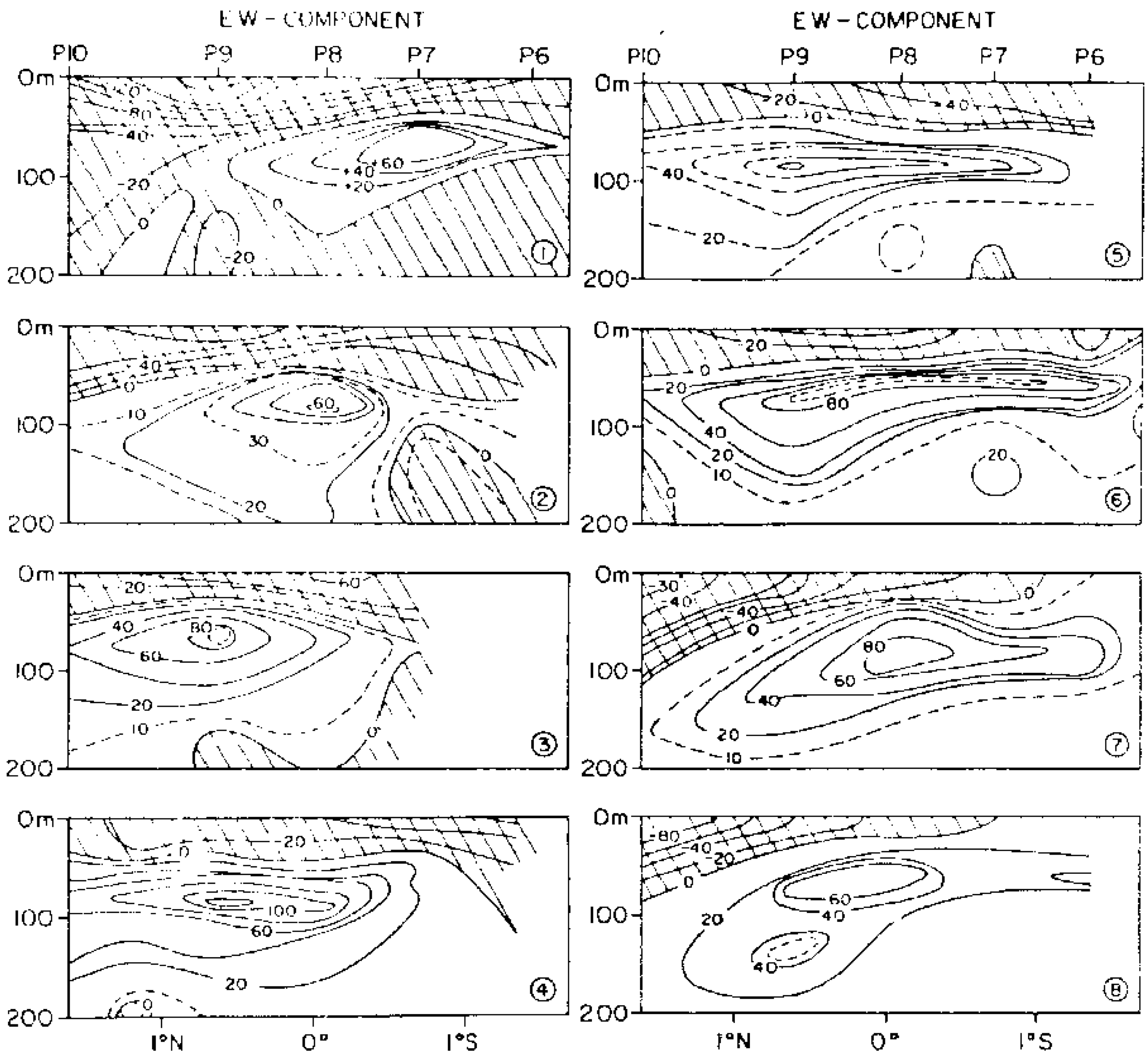

Figure 2. Time series of cross-equatorial sections at $28^{O}W$ at roughly 2.5 day intervals by Duing et al., 1975.

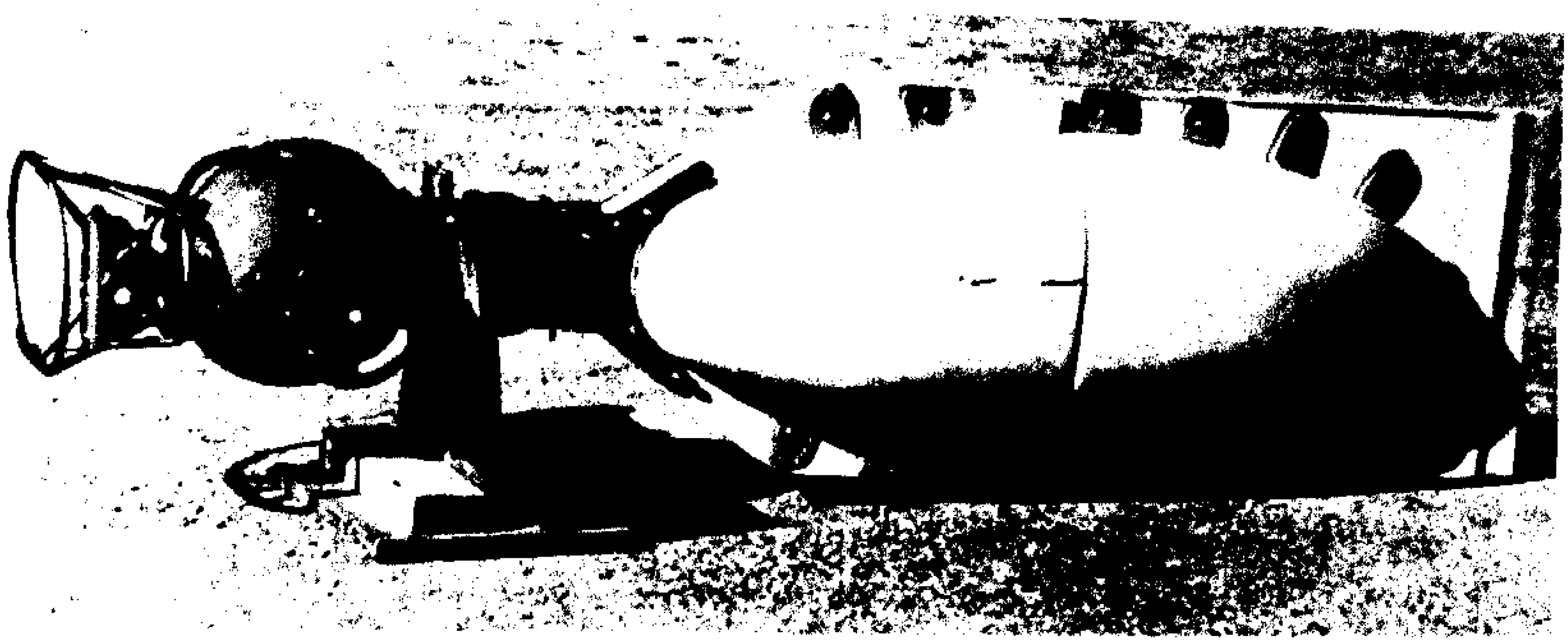

Figure 3. Side view of the MK-II Cyclesonde showing the instrument housing, snatch block, and propulsion module.

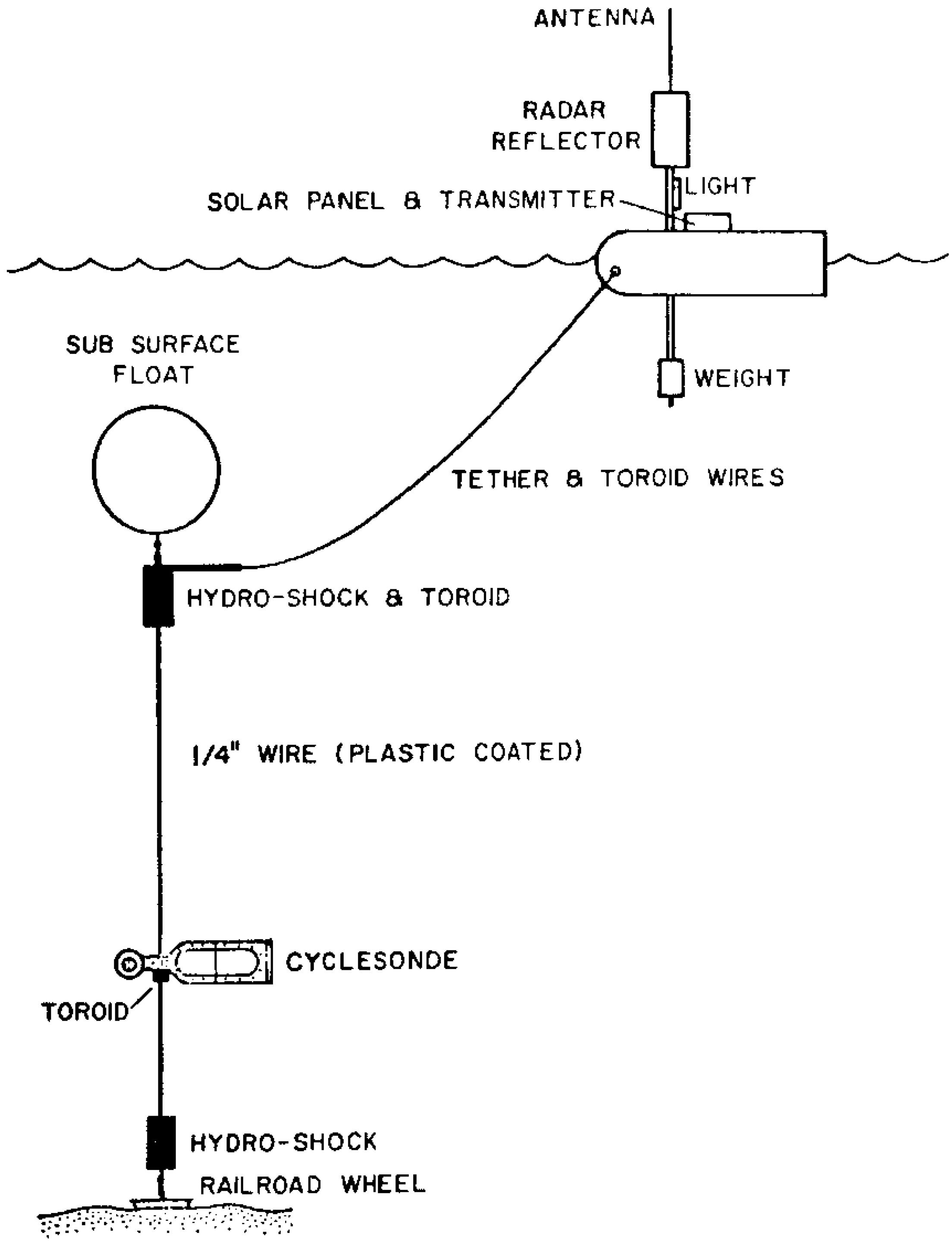

Figure 4. Taut wire subsurface mooring used to deploy the Cyclesondes on continental shelves (0-300 meters). The Cyclesonde may profile from 1 meter above the bottom to within 15 meters below the sea surface.

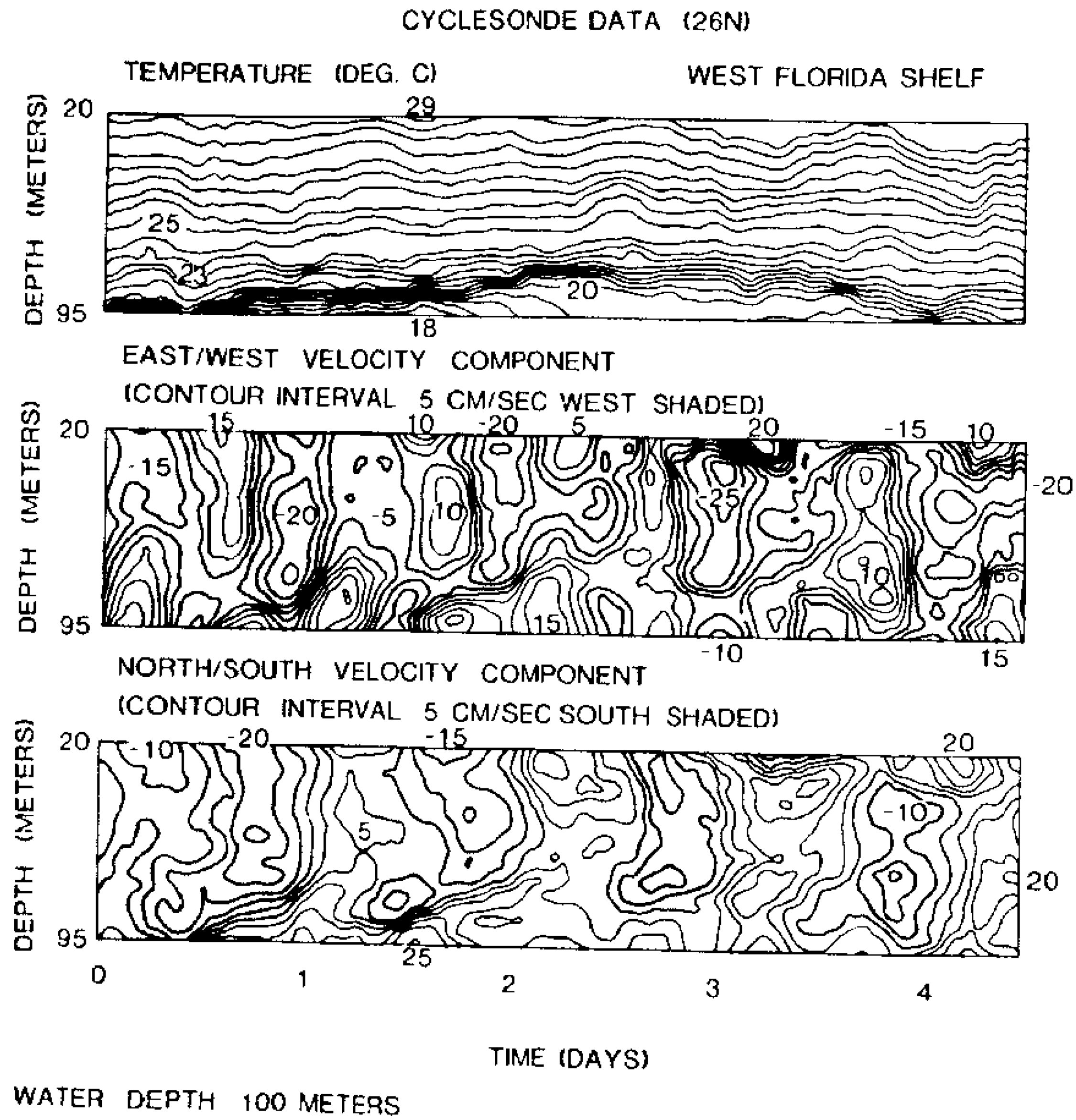

Figure 5. Depth-time contours of temperature, u-component and v-component velocity from record 27/2 (July 1975).

Something more can be said about the relative precision (or internal consistency) of APCM profiles. Figure 6 shows two pairs of APCM profiles. The first pair was obtained during the GATE experiment (1974 from R/V Iselin, ship drifting), while the second pair was obtained during the INDEX experiment (1976, from R/V Atlantis II, ship steaming to maintain a constant wire angle). For each pair, the time separation between profiles is about one hour. The r.m.s. difference between a profile pair (for either pair) is about ±5 cm/sec. Ignoring the possible influence of high-frequency environmental signals (internal waves, for example), this can be taken as a reasonable estimate of the precision attainable in APCM measurements under the controlled conditions which prevailed during these observations. These controlled conditions are as follows:

1) wire angle maintained at <5° if possible;
2) instrument descent rate <15 cm/sec;
3) relatively constant ship drift over the observation period;
4) ambient relative currents >10 cm/sec.

CYCLESONDE DATA QUALITY

The Cyclesonde commonly records current (speed and direction), temperature, pressure and conductivity. Nominal accuracies for these quantities are given in Table 1.

TABLE 1

Full Scale	Least Count Resolution	Calibration Accuracy
Speed $\frac{(15\ \text{sec})}{\text{Sample}}$ 275 cm/sec	± .067 cm/sec	± 1/2 cm/sec
Direction 360°	± .178°	± 1/2°
Temperature 20°C	± .005°C	± .01°C
Pressure 200 dbar	± .05 dbar	± .10 dbar
Conductivity 30 $\frac{\text{mmho}}{\text{cm}}$	.0073 $\frac{\text{mmho}}{\text{cm}}$	.01 $\frac{\text{mmho}}{\text{cm}}$

Recently, an effort to compare Cyclesondes with fixed-level current meters has been made. Also the internal consistency of Cyclesonde data has been evaluated by comparing the up and down traces of currents obtained from a given instrument in a given experiment. Figures 7 to 10 show the results of such a comparison from two separate instruments. The data were obtained during a 1975 experiment on the West Florida continental shelf in about 100 m of water. Table 2 summarizes the characteristics of these two data sets and instrument moorings.

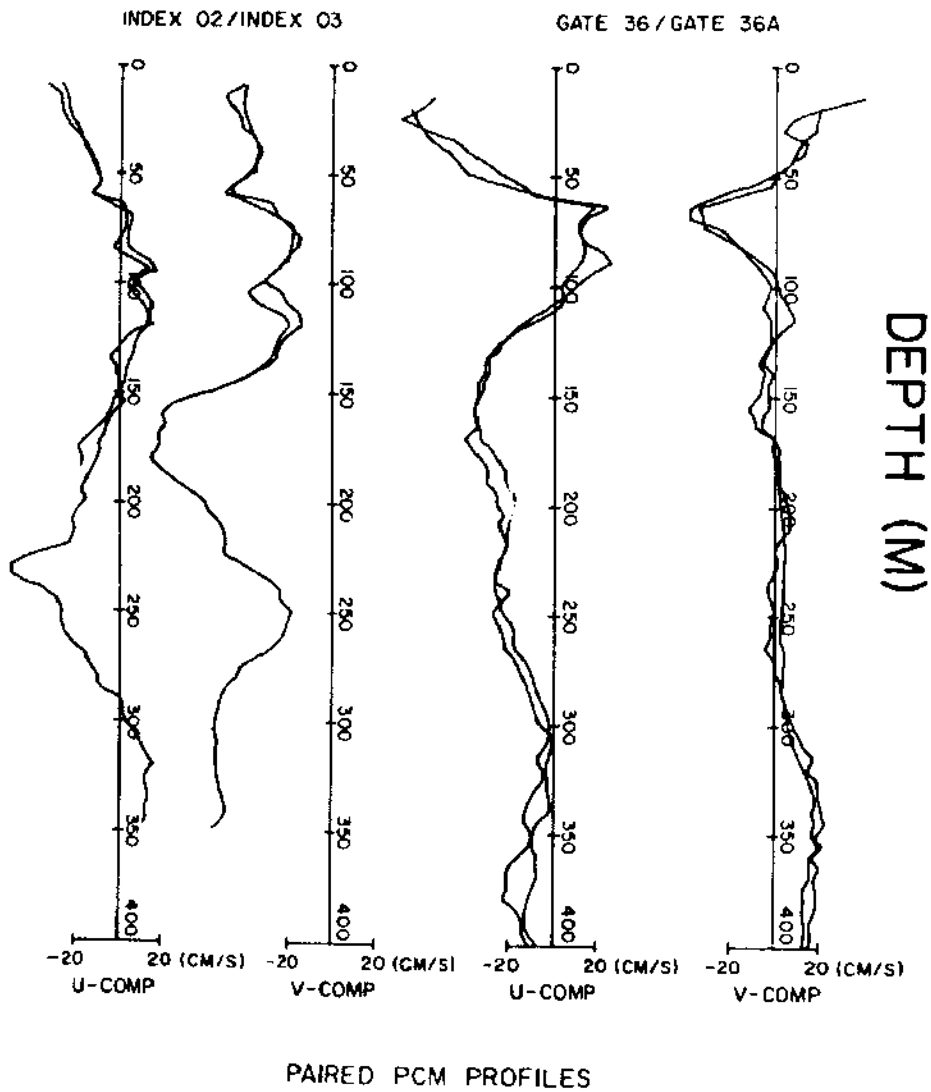

Figure 6. Pairs of APCM velocity profiles taken at the same location. The time separation between profiles in each pair is about one hour.

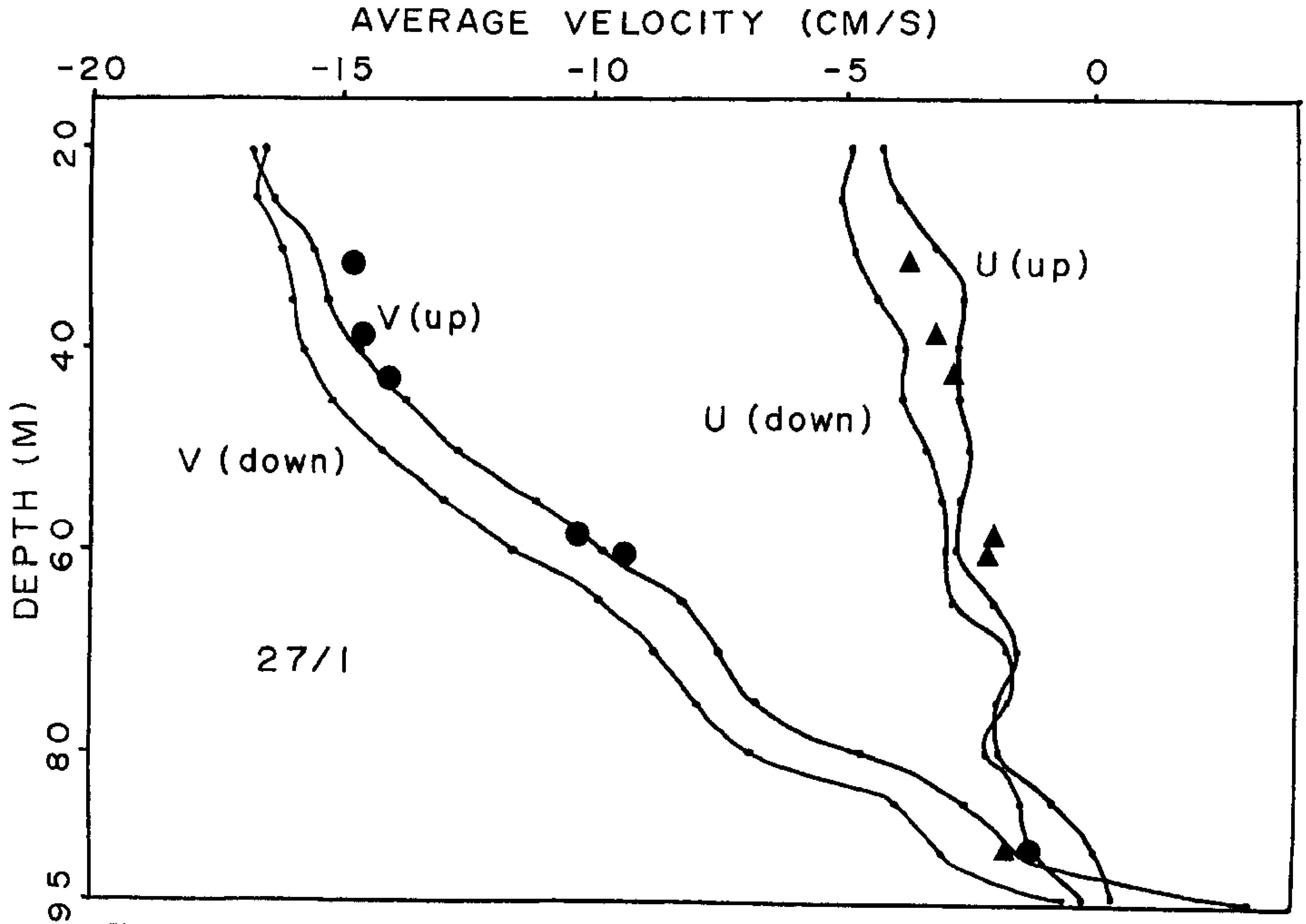

Figure 7. Velocity-component profiles with up and down values separately averaged. Aanderaa current meter means for the same time period as 27/1 are shown with ▲ for u and ● for v.

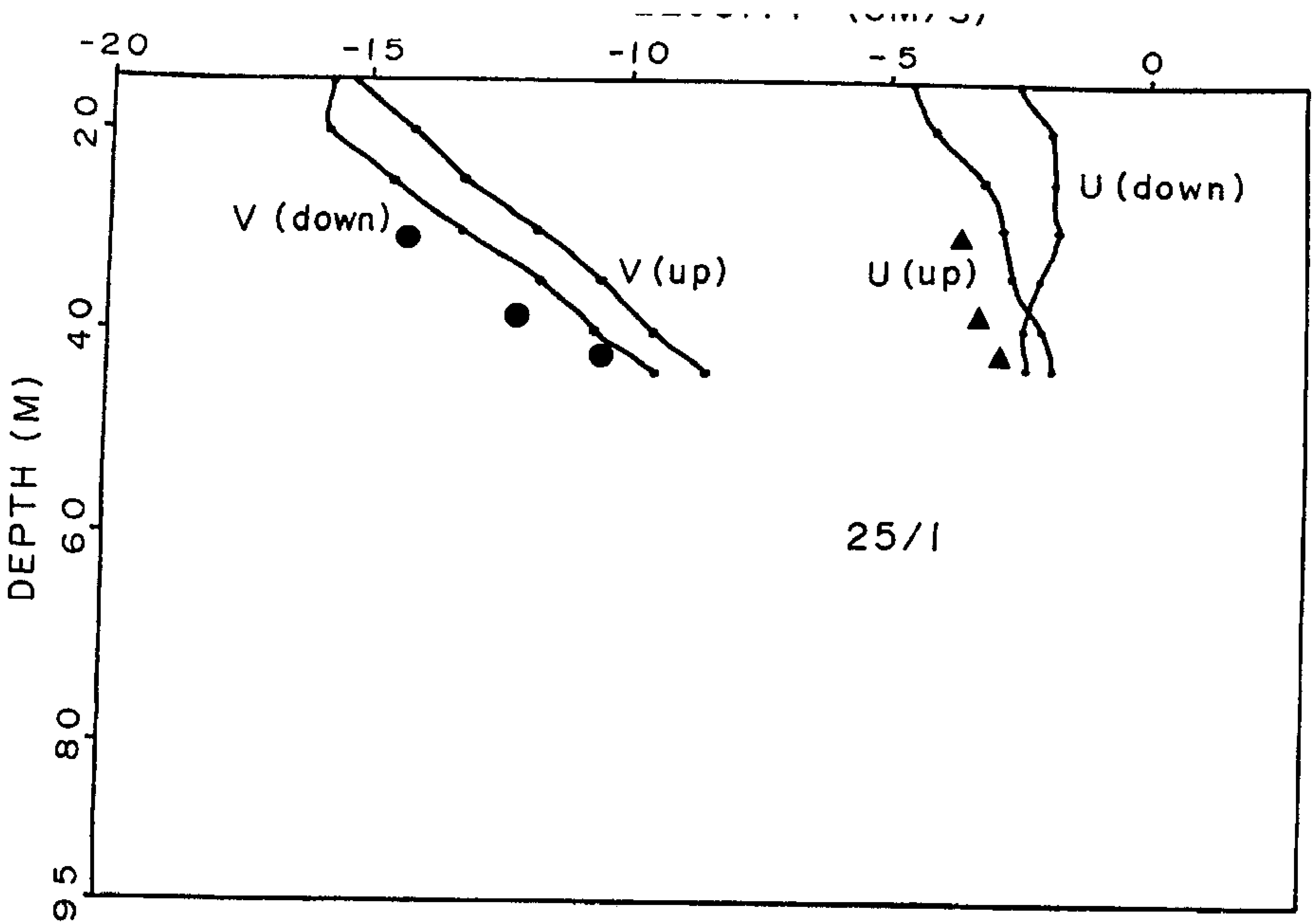

Figure 8. Velocity-component profiles with up and down values separately averaged. Aanderaa current meter means for the same time period as 25/1 are shown with Δ for u and o for v.

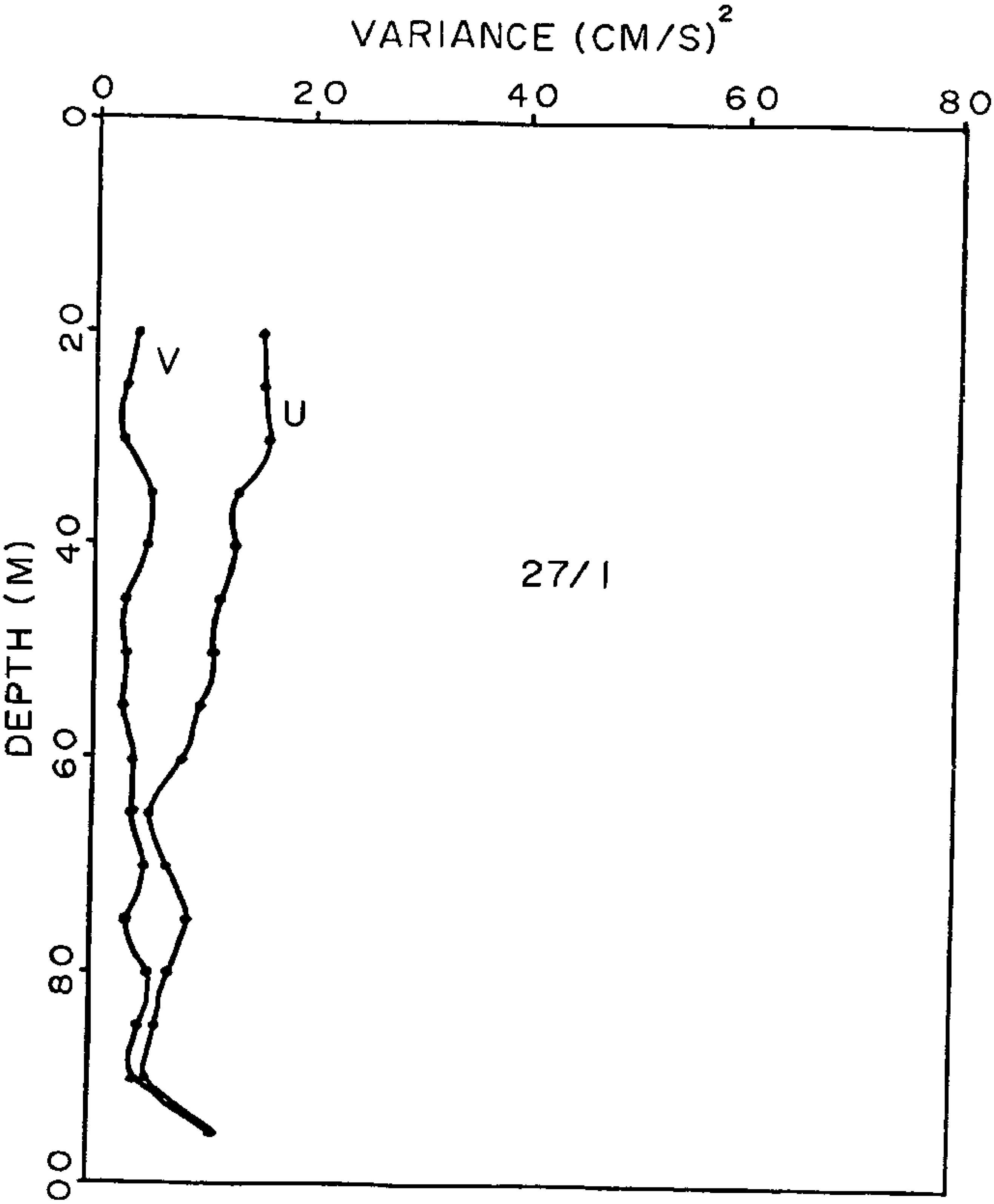

Figure 9. Half the average variance between adjacent up and down profiles for 27/1.

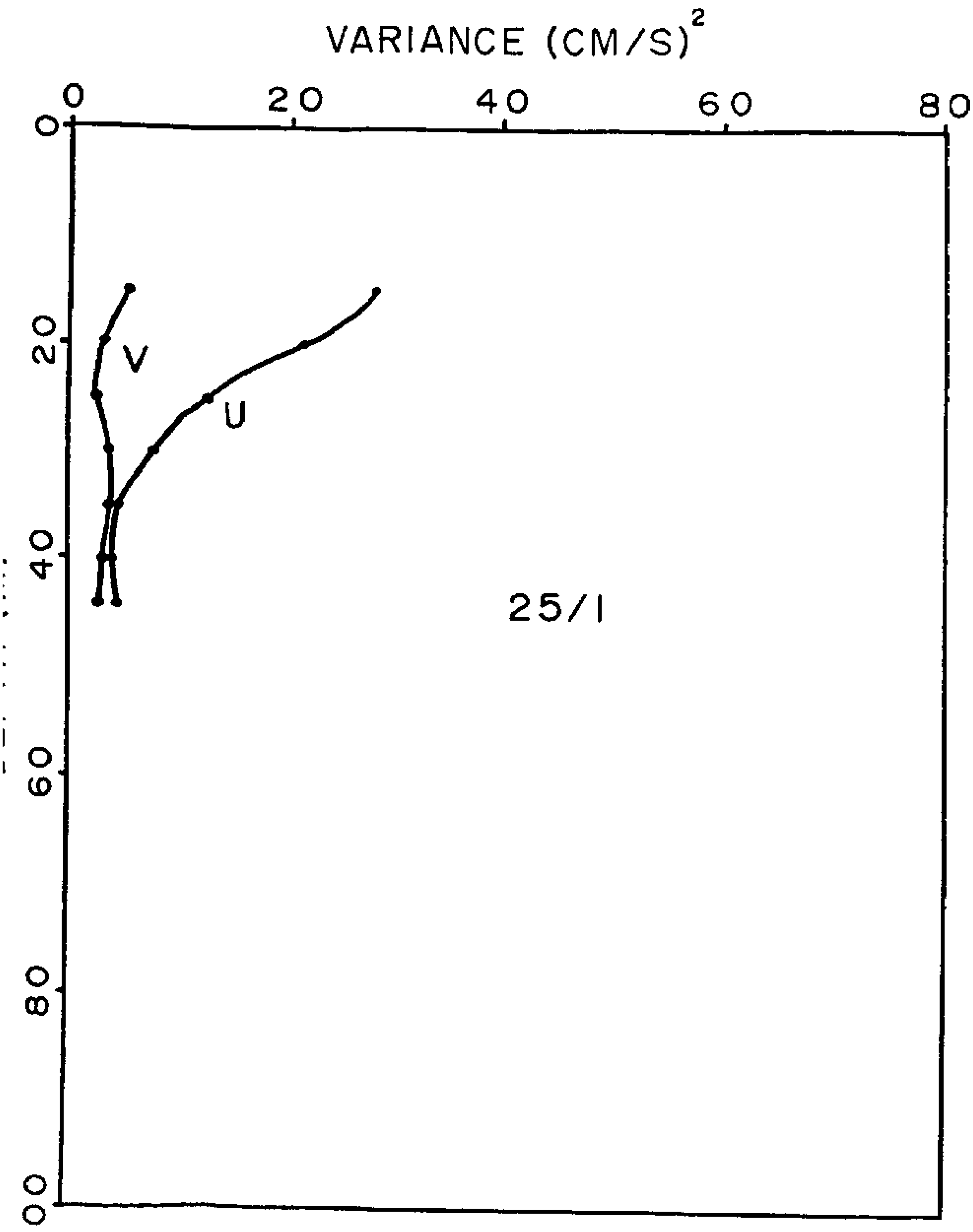

Figure 10. Half the average variance between adjacent up and down profiles for 25/1.

TABLE 2

Inst. No.	Fig. No.	No. of Profile Pairs	Approx. Depth Range (m)	Type of Float	Surface Wind Conditions
25/1	8 & 10	56	15-45	Surface	<10 kts
27/1	7 & 9	119	20-95	Subsurface	<10 kts

Systematic and nonsystematic errors were resolved using the following approximate (but, as it turned out, highly useful) technique. For each data set:

1) current data were interpolated to uniform depths (every 5 m);

2) these data were split into groups of all up and all down traces;

3) time-average currents were separately computed for the up and down groups (Figures 7 and 8) and then subtracted from the corresponding original data for each group;

4) a variance of the difference signal between the up and down groups obtained in 3) was calculated. One-half of this value was taken as an estimate of the uncorrelated "noise" level in the data (plotted in Figures 9 and 10).

Note that the time differences between data points in a pair are ~5 minutes near the surface, increasing to about 30 minutes at the bottom.

SYSTEMATIC ERRORS (Figures 7 and 8)

Clearly, systematic differences can exist between the averaged up and down traces. The algorithm used to compute horizontal speeds in Figures 7 and 8 used the averaged speed during the 30 seconds between the previous sample and the present sample and the direction observed during the present sample. Thus, the computed speed values will lag the true value by half the sample interval. In regions of strong vertical shear, this will produce a hysteresis effect in speed. In 27/1, for example, with the Cyclesonde vertical speed of 10 cm/sec, the horizontal speed values are spatially lagged by 150 cm and the vertical shear is

$$\frac{15 \text{ cm/sec}}{5500 \text{ cm}} = 2.7 \times 10^{-3} \text{sec}^{-1}$$

in the bottom-most 55 meters. This gives an average lag of about .4 cm/sec on both up and down going profiles. This would nearly bring the V_{up} and V_{dn} profiles in Figure 7 into coincidence. Clearly, this computational error was responsible for about half (.8) of the difference between up and down going profiles. We have corrected the algorithm for future computations, but the short time available did not permit recomputation and redrafting of all these figures. Where the average of up and down profiles is used, the errors should nearly cancel out.

Plotted on the same figures are simultaneous average currents observed by fixed-level Aanderaa current meters moored within one kilometer on subsurface moorings. (The triangular symbols are average "u" and circles are average "v" components.) These results show that comparable data within ±1 or 2 cm/sec can be obtained by either technique. Note there is some indication that the nearsurface Aanderaa may be over-registering due to wave action in record 25/1. The remaining offsets between up and down profiles are probably due in part to certain characteristics of the sensors on the MKII version of the Cyclesonde (Van Leer, 1976). The two current rotors in these devices are each enclosed in a four-strut cage (see Figure 3). As a result (Perkins and Van Leer, 1976) the rotor speed calibration has a ±10% variation with a functional form $\cos(4\sigma_A + \alpha_A)$ where σ_A is the true attack angle (angle of the flow relative to the falling or rising instrument cage). Thus, the speed calibration is relatively sensitive to our estimate of σ_A in certain ranges. The quantity σ_A has been determined by an iterative scheme with the assumption that the instrument is level. If a small (not unknown) pitch angle of the instrument is present, this can cause a systematic offset in up and down current traces. The instrument modifications described below will substantially reduce this problem.

NONSYSTEMATIC ERRORS (Figures 9 and 10)

In these figures, the variances of the difference signals for these two data sets are shown. Note in particular that the variance of 25/1 (surface mooring) tends to increase toward the surface somewhat more rapidly than does the variance of 27/1 (subsurface mooring at about 20 m depth). Comparison of other data sets from surface and subsurface moorings under conditions of higher winds shows that this effect will become more pronounced with increasing wind. These elevated "noise" levels near the surface are probably caused by a combination of mooring motion and "rotor pumping," although the Cyclesonde, because it is held to the wire by a relatively friction-free roller, is strongly decoupled from vertical motions of the mooring line. The instrument modifications listed below will also reduce this problem.

INSTRUMENT MODIFICATIONS

As a result of the analysis described above, the following modifications to the Cyclesonde are now planned or are being carried out:

1) alteration of the rotor cage design to (a) reduce the number of struts, or (b) make the struts smaller. This will make speed computations less sensitive to variations in attack angle and thus reduce the "pitch angle" errors discussed above;

2) installation of pitch and roll sensors, also to reduce attack angle uncertainties;

3) testing of vector-averaging current sensors as a means of reducing near-surface velocity contamination;

4) redesign of Cyclesonde moorings (particularly in deep water) to reduce horizontal motions of the mooring line near the surface.

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MEASUREMENT OF TURBULENCE IN OCEAN BOUNDARY LAYERS

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ABSTRACT

This paper is concerned with the acquisition of information on turbulent mixing in the boundary layers of the ocean, that is, near the sea surface, near the sea bed, in coastal regions and in estuaries. In such problems, natural fluctuations with periods ranging from a few tenths of a second to a few weeks are of greatest concern, with specific emphasis on continuous time series over periods of at least 30 minutes. For useful measurements in this area, accuracies of 0.1 cm/sec often are required. Presently, my group is using mechanical, acoustic and electromagnetic meters. Only the mechanical units meet the desired specifications, and they have too high a threshold velocity (1.0 cm/sec), are too large when deployed in groups of three, and are too often contaminated by filaform seaweed to be considered satisfactory. However, it is not just the suitability of the flow sensors themselves but also the nature of the devices on which they are mounted and the care with which they are deployed that determines the accuracy of current measurements in general and turbulence data in particular. Precise flow meters located in the wake of a frame part or deployed in the disturbed pressure field caused by a support arm produce results that are just as inaccurate as judiciously spaced sensors with less desirable response characteristics. Furthermore, unresolved frame motion can render velocity fluctuation measurements useless.

When deployed from a properly designed support device and with a good understanding of their assets and shortcomings, instruments such as our pulse output mechanical current meters often can be used to obtain results of the scientifically required accuracy. When used in this fashion, however, it is essential that the investigator have a thorough understanding of the instruments based on a comprehensive testing program. Also he must have a good theoretical understanding of their operation and of the flows to be examined in order to permit exploitation of the test results and to avoid misinterpreting their implications in regard to field deployment.

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INTRODUCTION

The turbulent diffusion of heat, mass and momentum is of fundamental concern in a wide variety of oceanographic problems and is of special importance in problems involving ocean boundary layers. Yet knowledge of the turbulent processes in the ocean is deficient to a degree that makes reasonable models of exchange processes impossible. Historically, such models have been based on simple eddy diffusion hypotheses, and the constant or variable turbulent diffusion coefficients have been treated more as adjustable parameters than as physically predictable variables. However, this approach is clearly not satisfactory from a scientific viewpoint, and spurred by recent advances in other areas of geophysical fluid mechanics, the need to understand the specific processes responsible for heat, mass and momentum transfer in both the boundary layers of the ocean and its interior is now widely recognized. To accomplish this important task, measurements of ocean turbulence fields and the small-scale motions that give rise to them are required.

Because of the complexity of the overall problem and because of the author's primary interest in sediment transport mechanics, our early investigations were oriented toward the nature of the turbulent flow in the immediate vicinity of solid boundaries. Furthermore, working with turbulent flow in the neighborhood of the sea bed or an ice cover provides a major logistical advantage in a field that otherwise has few; that is, in this region, the flow meters can be mounted on fixed frames or on relatively sturdy masts.

In addition to the specific studies of unsteady, nonuniform, stratified and rotating bottom boundary layers under natural conditions with which we have been concerned in the past, we now are involved with investigations of turbulent mixing in the surface regions of highly stratified estuaries. In the latter studies, the advantage of being able to support a mast or frame on a solid boundary is lost, but the ability to determine position accurately at a high sampling rate is retained. Furthermore, by making measurements from a moderate size vessel during relatively calm periods, the disturbing effects of surface waves can be reduced to an acceptable level. In the various bottom boundary layer investigations, emphasis has been on measurement of all six Reynolds stress components on a minimum of four levels, as well as on accurate determination of the mean velocity field. In contrast, the estuarine turbulence studies are degraded by the loss of a stable platform from which to deploy the flow sensors. Therefore, they involve the occasional measurement of Reynolds stress components and turbulent heat and salt fluxes, but focus on the comprehensive determination of velocity, temperature and salinity fields produced by moderate to small-scale, deterministic ocean motions. In the former case, the field investigations are motivated by the difficulty of reproducing particular ocean conditions at reasonable scale in the laboratory; whereas, the surface layer studies in highly stratified estuaries are motivated by the need to understand what small-scale, deterministic motions are responsible for the turbulence production and the need to obtain crude turbulent kinetic energy estimates as constraints on turbulence models.

In this paper, some of the difficulties associated with obtaining turbulence data from ocean boundary layers are outlined, along with a few experimental techniques that we have found useful in coastal and estuarine regions. The ocean turbulence measurement problem can be divided into three parts. The first involves identifying the best method for approaching a given problem, the second relates to the choice of sensors and the third involves the design of frames on which the sensors are to be deployed. The phrase "method of approach" is used here to denote the scientific scheme that is to be used in the measurement program. Unfortunately, ideal flow meters and sensor support devices do not now and probably never will exist, so all three of these parts of the problem must be considered together and in light of the characteristics of the given flow. Some general comments in regard to each of these parts of the problem are presented in the next section. The final part of the paper is devoted to the particular flow sensors and instrument frames that we use.

GENERAL CONSIDERATIONS

Methods of Approach. Before deciding what sensors and frames to use in a particular ocean turbulence investigation, it is necessary to determine exactly what flow variables are best to measure. Then the time and space scales that must be resolved need to be identified and the accuracy with which the measurements must be made needs to be determined. Two substantially different approaches can be taken concerning the first consideration. In cases for which available knowledge about the physics of turbulence production from laboratory and theoretical studies is good and in which the basic geometry of the region of interest is relatively simple, it usually is more accurate to elucidate the small-scale deterministic motions responsible for producing the turbulence and to calculate the resulting Reynolds stresses or turbulent kinetic energies, than to measure the latter directly.

Under most, if not all, circumstances, much greater precision can be obtained in the controlled environment of a laboratory than in the field, and the former clearly is the place in which to carry out basic research on the physics of turbulent flow. As long as a field situation of interest is characterized properly by a set of laboratory data, and these data agree with available theory, then there is little reason to doubt the applicability of the results to the field situation. Under these conditions, the major experimental task is to ensure that the basic flows are indeed the same locally and to determine the relevant characteristics of the natural one. No harm may be done by attempting to confirm the prediction with actual turbulence measurements, but nothing is gained if the experimental study is not accurate enough to permit a definitive statement. This is the case all too often. Furthermore, it usually is much more difficult to obtain accurate turbulence data in the field and the entire design of an experimental program, not to speak of its cost, may depend on whether this is necessary or not. One way to study ocean turbulence, therefore, is to measure the mean velocity field accurately, and then to calculate the Reynolds stresses.

However, in complicated flow situations, the available knowledge is not sufficient, or at least not obviously sufficient for this purpose, and not all field situations can be reproduced easily in the laboratory. For example, it is difficult to make a horizontally uniform turbulent Ekman layer in the laboratory, let alone one that is time-dependent, stratified and disturbed by a wind-wave field. Also, there are occasions when available flow sensors can be situated more closely to a natural boundary relative to the scale of the flow, than to the wall in a laboratory case. In these instances, the loss of precision accrued by making measurements in the field may be more than compensated by the advantages gained from working there. However, this route will likely raise the cost and difficulty of the experimental program.

To determine a Reynolds shear stress of one dyne/cm^2 to $\pm 20\%$ by the eddy correlation method, the flow sensors must be able to measure velocity components to an accuracy of better than 0.1 cm/sec at all frequencies contributing significantly to the cospectrum. This means that both zero drift and instrument instability must be less than this value, and that the sensors must be calibrated to this accuracy. Data acquired by my research group over the past decade in a wide variety of environments suggest that averaging times significantly shorter than 30 minutes are insufficient to resolve important low frequency components in natural boundary layers; whereas, comparable errors (10 to 15%) are incurred if the flow sensors do not respond to frequencies that are much higher than $U/\Delta z$. Here U is the local mean velocity and Δz is the distance of the sensor from the sea bed. In natural turbulent boundary layers, this requires a high frequency response of nearly 10 Hz, even when the turbulence measurements are made a few tens of centimeters or more from the boundary. Of course, the wave number resolution of the flow sensing instrument also must be small relative to the distance from the sea bed.

To obtain useful mean velocity data in natural boundary layers, the necessary accuracy usually can be reduced by a factor of three or so and the instrument need not be able to respond at high frequency as long as it averages velocity components linearly. Likewise, the wavenumber resolution limit is no longer relevant. However, it still is necessary to average over 30 minutes or so because substantially greater accuracy is required in resolving the near boundary shear. In ocean cases, time averages longer than 30 minutes are impractical because of the inherent unsteadiness of such flows induced by tides. This results in a limit to the accuracy with which turbulent stresses can be measured by the eddy correlation technique in such problems, and thus a limit on the accuracy needed in sensors designed only for that purpose.

Generally, it is precision at relatively high frequencies that is important for turbulence studies. For many boundary layer investigations, the concern is with sensors or sensor arrays that are small in vertical scale. In addition, in unsteady and nonuniform flow fields such as occur in most natural situations of interest, stress profiles are neither constant nor simply varying; thus, a field of sensors rather than just one or two must be used. This can be done by most of us only if the sensors are relatively inexpensive. Here it should be noted that high accuracy measurements from a single point are of value only if they are representative of a region or can be generalized with an available theory to that accuracy.

To emphasize the need for a dense set of turbulence sensors in experiments on natural boundary layers, some typical stress profiles from the upstream side of a gently sloping, nearly sinusoidal sand wave 2.1 m in height and 90 m in wavelength are shown in Figure 1. As is typical in nonuniform flows (Smith and McLean, 1977a, 1977b), the shear stress first increases with distance from the boundary, then reaches a maximum and decreases. This structure clearly precludes using a "constant stress layer" assumption in analyzing turbulence data from flows that might be even slightly nonuniform. Figure 2 shows a series of low pass filtered shear stress profiles made over successive 20-minute periods in a partially mixed estuary. The stress field is quite complicated and obviously does not follow that predicted by one-dimensional, homogeneous density turbulence theory. Similarly, a single shear stress measurement made at an arbitrary distance from the sea bed is of little scientific value in such flows. Of course, it is to elucidate the reasons for these complications that we are investigating the mechanics of natural unsteady and nonuniform boundary layers.

For basic geophysical research, available sensors are not likely to be ideal. This situation arises from a need to proceed with measurement programs as soon as any method of obtaining the desired information, at acceptable accuracy, has been found. Under these circumstances, the investigator must understand thoroughly both the characteristics of his sensors and those of the environment he is examining. Often such knowledge, plus that concerning specific interactions between sensor and environment, is gained in an iterative manner. This is the case whether an off-the-shelf device is used as is, modified, or whether a new instrument is designed.

In the field of geophysical fluid mechanics in general and in the field of ocean turbulence studies in particular, a substantial effort is required to test and evaluate flow meters and flow meter support systems before results can be considered reliable. Furthermore, it is the obligation of every experimental scientist to carry out a calibration and testing program that is sufficient to guarantee results accurate to the degree required by the scientific problem.

To unoerstand the flow field being investigated, it is essential to have a good comprehension of related experimental and theoretical

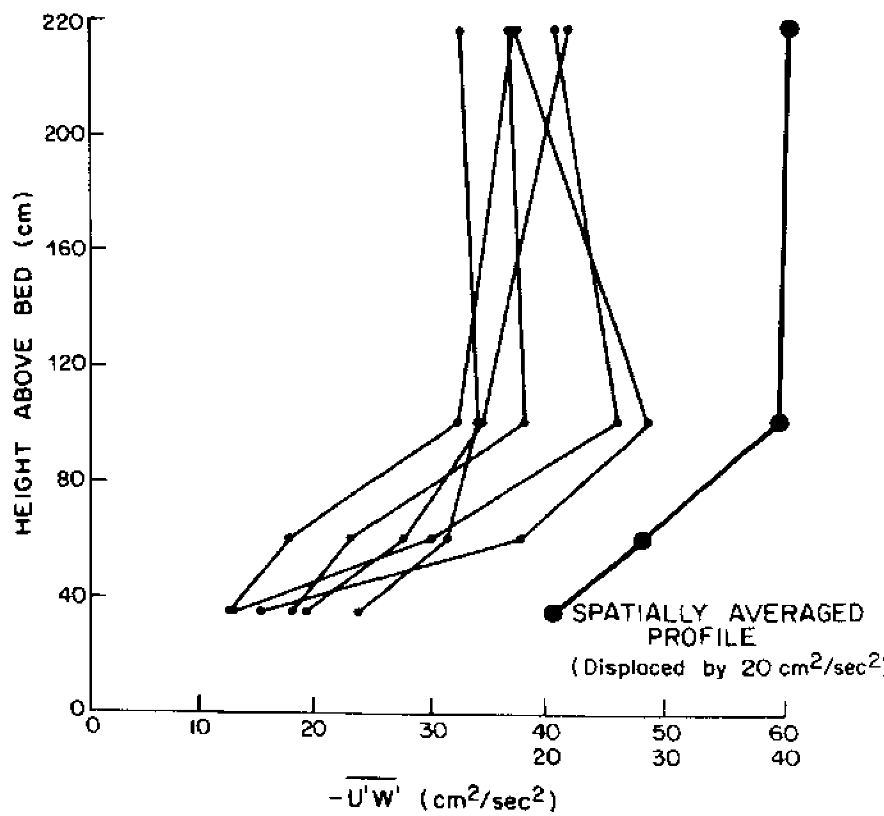


Figure 1. Shear stress profiles for the upstream side of a gently sloping, nearly sinusoidal sand wave 2.1 m in height and 96 m long.

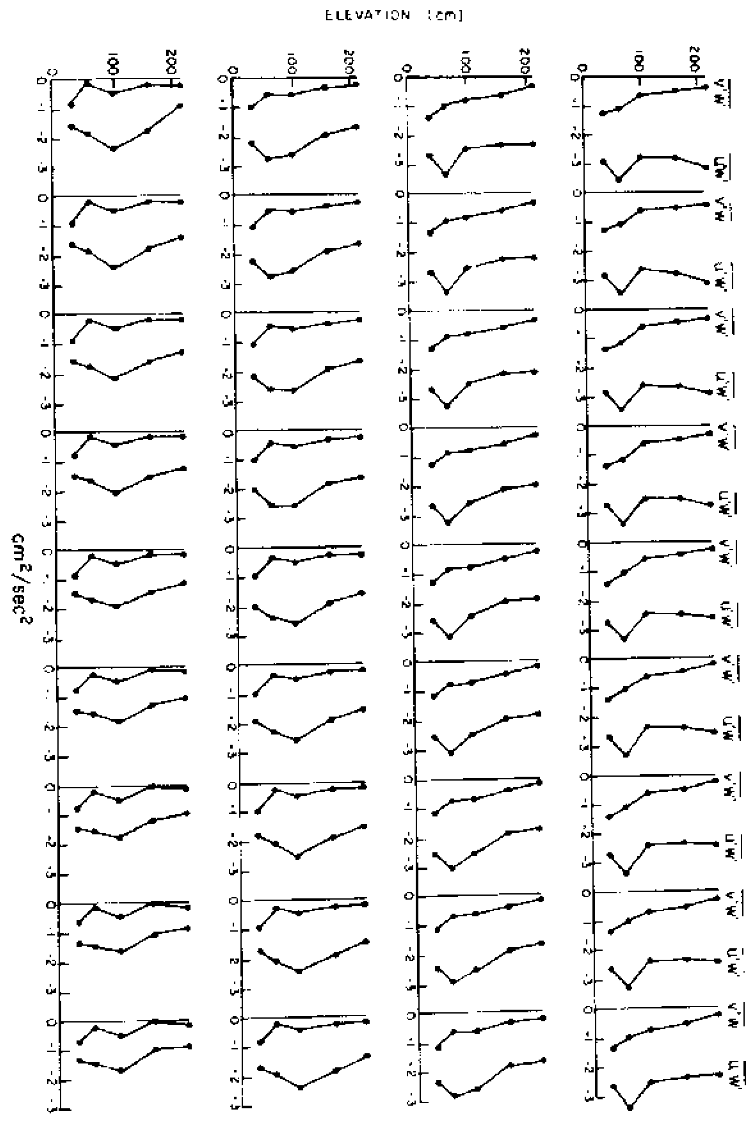


Figure 2. Successive low pass filtered shear stress profiles taken every 33 sec for 20 minute periods of a 40 minute record showing the low frequency structure of the near bottom stress field.

results and to be able to use the tools of theoretical fluid mechanics to determine the applicability of these results to the case at hand. Even with the iterative approach method above, it is necessary to be able to maximize the amount of information gained at each step and to use it effectively in anticipating the results of the next experiment.

Current Meters. A number of potentially useful flow measurement techniques for bottom boundary layer studies exist, and sensors based on many of these principles are available either commercially or privately. Most have advantages and disadvantages that make them useful for certain types of experiments and not for others. Just as there is no best current meter for all flow measurement in the interior of the ocean, no single flow sensor is best for all boundary layer investigations. For this reason, we now have available for use with our impellor-type current meters two types of electromagnetic flow meters, one travel-time acoustic current meter, three types of hot film sensors and three other kinds of mechanical current meters. The relevant characteristics are threshold velocity, zero drift, stability, frequency response and susceptibility to contamination.

Electromagnetic current meters are convenient to use and they produced some of the earliest bottom turbulence measurements (Bowden and Fairbairn, 1956; Bowden, Fairbairn and Hughes, 1959; Bowden, 1962). However, high zero drift rates and relatively low frequency response for a given level of precision still severely limit their utility in many ocean turbulence studies. Also, we have found it necessary to make three-component measurements in order to guarantee accurate results, and these sensors are difficult to mount in pairs without having serious flow interaction problems. Recently, Marsh-McBirney developed a three-component electromagnetic current meter in a spherical housing, but the prototype is too large to deploy in bottom boundary layer investigations; also the zero drift rate is too high and the precision at 2 Hz is too low for use in turbulence studies. Some of these problems probably can be overcome with proper design, and further work on high precision, low zero drift, three axis electromagnetic flow meters definitely should be encouraged.

Our travel-time acoustic current meter works very well at low flow rates but suffers from a complicated calibration with angle of attack. As the electronics package is situated much too close to the transducers, the instrument is clumsy and very sensitive to flow direction. Also it is somewhat larger than one would like for bottom boundary layer investigations.

Thermal flow sensors are easily contaminated but are capable of high frequency and small-scale response. These often are best used in conjunction with an array of lower frequency turbulence measuring devices. Also, heated probes are most usefully deployed on a bottom mounted frame attached to a rigidly moored vessel, as they need considerable tending and as they must be oriented into the mean current. Devices for cleaning the probes, of course, must be used with them. Such sensors are an integral part of any careful turbulence investigation whether it be in the ocean, in estuaries or in rivers, but for the present at least, they must be considered auxiliary turbulence measuring devices and not the primary ones.

Strain-gauge or drag-type mechanical current meters are sensitive to flow acceleration as well as flow velocity, and thus are inconvenient to use in turbulence and wave studies. Also, they are susceptible to high drift rates unless carefully designed. Their main advantage is that a three-axis sensor of relatively small dimensions can be constructed. Savonius rotor current meters do not have the frequency response necessary for near-bottom and estuarine turbulence investigations, and are neither small enough nor accurate enough to be used near the sea bed as a primary mean velocity sensor.

Instrument Frames. Even when making measurements in relatively shallow water from bottom-mounted frames, both the type of flow sensor to be used and the type of frame on which it is to be mounted must be considered carefully. When the sensors are subject to large zero drift rates, there is little point in using a precision flow sensor in the immediate neighborhood of an obstruction or designing an expensive uncluttered frame that is difficult to deploy. It is also necessary to remember that cables and instrument support brackets as well as the basic instrument frame, can disturb the flow at the measurement site. Even an open tripod can cause streamlines to slope upward and outward a few degrees. The factors of primary concern here are: wake production, pressure field distortion, frame stability, frame vibration and frame orientation. The first two of these can be accounted for to some extent and must be in an investigation of high precision, but such corrections use idealized geometries and approximate expressions for velocity fields, resulting in systematic residual errors.

Instrument frames usually are much too large to calibrate satisfactorily. Flume tests with scale models are not effective for this purpose as they do not usually employ a realistic shear profile, rarely include cables and sensors, and are not often examined for the disturbance produced at specific instrument sites. Nevertheless, they are useful for estimating distortions in general flow pattern caused by bulk frame geometry.

Wakes from large obstacles are disastrous in any turbulence study and are difficult to handle from the flow measurement correction point-of-view under all circumstances. Nevertheless, wake theories are reasonably accurate in their predictions of steady velocity fields, and useful corrections can be made if turbulence data are not of direct concern and if the mean flow is fixed in direction and magnitude. Unfortunately, in many problems of geophysical interest, the latter conditions are not fulfilled. When the frame orientation cannot be adjusted as the flow direction changes, wake corrections are inevitable. In the long run, if the flow is from an unfavorable bearing relative to the frame, one usually ends up throwing out the data or treating it separately and recognizing that it is substantially degraded. The fact that this must be done in cases where internally recording bottom-mounted systems are deployed, argues against their use in most situations for which a wire-lowered ship-tended system could be substituted.

When designing frames and masts to support flow sensors for precision mean flow and turbulence studies, it is very important to consider the hydrodynamic effect that they produce when located in the type of flow to be examined. Flow blockage should be minimized in general and in the vicinity of the sensors in particular. Frame parts that might cause wakes to be produced in the neighborhood of the sensor should be avoided when possible and always kept to a minimum diameter. Redundant sensors, although expensive and clumsy, should be added to circumvent the wake problem when high-quality flow data from all directions are required.

Finally, if the flow in the immediate vicinity of the boundary is to be examined for sediment transport, geochemical or benthic ecological purposes, then the lower part of the frame must be designed to prevent the support structure from scouring into the sediment and moving, rotating or tipping as it does so. In addition, flow sensors must be judiciously placed to prevent scour beneath them and a system to determine the exact elevation of the bed at the measurement site is desirable if not mandatory. In investigations of this type, local bed topography also should be measured with sufficient accuracy to guarantee that the boundary is planar or to permit elucidation of the resulting nonuniform flow effects. In most boundary layer investigations, it is desirable to determine the density field in the immediate vicinity of the sea bed in order to guarantee that flow stratification corrections are unnecessary or that they can be made properly.

INSTRUMENTATION USED FOR NEAR-BOUNDARY TURBULENCE AND ESTUARINE MIXING STUDIES AT THE UNIVERSITY OF WASHINGTON

Pulse Output Mechanical Current Meters. Soon after I began working on near bottom flow problems at the Woods Hole Oceanographic Institution in 1963, it became clear that none of the commercially available current meters was satisfactory for making turbulence measurements. The one with the most potential was a small impellor type unit made by a French company (Neyrpic, Inc.). Both the rotor housing and the readout system of this flow meter were poorly designed, but the rotors had a number of desirable hydrodynamic properties. Their major deficiency was a lack of symmetry, making it impossible to use them in experiments in which the flow could reverse direction. Subsequently a symmetrical rotor with similar characteristics, but with smoother leading and trailing edges, was fabricated. With the addition of a slightly modified bearing system and a completely redesigned rotor housing, a basic flow sensor usable in bottom boundary layer and turbulence studies was produced. This did not differ in any critical way from the modern version shown in Figure 3.

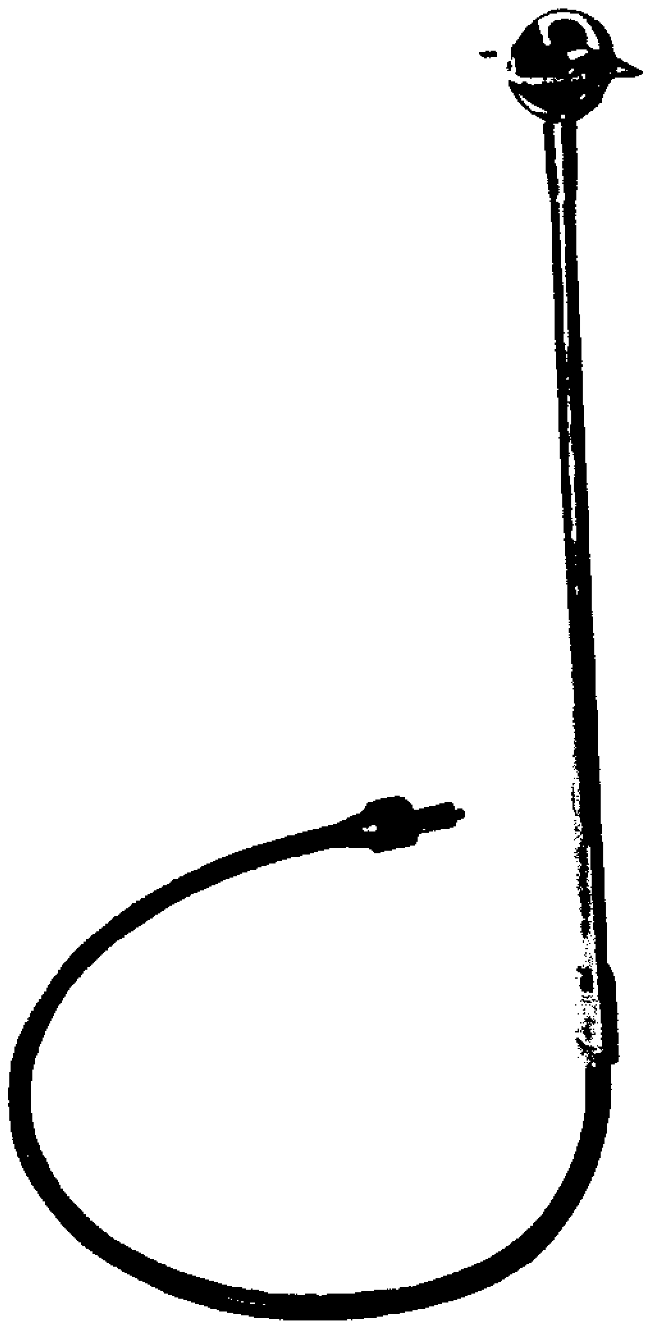


Figure 3. Pulse output mechanical current meter.

The original Neyrpic flow meter had a pulse output. After every half revolution, the thickness of a gap between the back of the rotor and a pair of electrodes changed in a stepwise manner, causing a pulse-like variation in resistance between each electrode and the case ground. The Neyrpic readout system was susceptible to drift, and after trying several more elaborate designs for the output circuitry, the entire sensing system was replaced with an optical one. A few years later, two phototransistors, wired in parallel such that they produced pulses of opposite polarity, were mounted in the stem of the current meter. These were illuminated alternately as the rotor turned; this was accomplished via a beam from a light source between them, reflected back to the phototransistors from a strip of mylar tape mounted on the tip of the rotor blade. Although this system worked quite well for currents of moderate and high speed, low pulse rates from low velocity flows combined with cross-over distortion produced by the phototransistor pair to make signal processing difficult and occasionally inaccurate. Also, it was difficult to align the mirrors on the tips of the blades so that all four pulses were equally spaced in time, at a constant flow speed; thus, only one pulse per revolution usually could be extracted with the desired accuracy. In 1972 the optical readout system was replaced with one that used a Hall effect sensor and tiny magnets mounted near the ends of the rotor blades. The Hall effect system reduced this problem, but even with this passive magnetic field sensor, poorly aligned units can miss pulses when magnets are used in the tips of more than two blades.

From a fluid mechanical point-of-view, the current meters were tested and retested until reasonable angle of attack properties were obtained. At the onset, ducted meters were tried and it was found that these produced a maximum output at an angle of attack between 30° and 45° relative to the axis of the current meter. A subsequent investigation indicated that this was a property of flow through a duct at an angle of attack to a stream, and the original ducted current meter idea was discarded. However, without a duct, the rotors were not reliable at high angles of attack, so a band or very short duct had to be added. This was made shorter than the axial length of the impellor to minimize its effect at low to moderate angles of attack, and it was found to yield a satisfactory response over the entire range. Also it satisfied the constraint that the output vary monotonically with angle of attack in a given quadrant. Were the output of the current meter not approximately cosine and were this variation with angle of attack not monotonic in a given quadrant, then it would be impossible to determine flow direction uniquely from three orthogonally mounted sensors using the iterative technique described in the next paragraph.

A head-on calibration for these pulse output current meters is shown in Figure 4, whereas typical calibrations with angle of attack for the most recent model are shown in Figures 5 and 6. These are given in terms of functions of angle of attack that multiply the cosine of this variable. Over the range for which we usually use the pulse mechanical

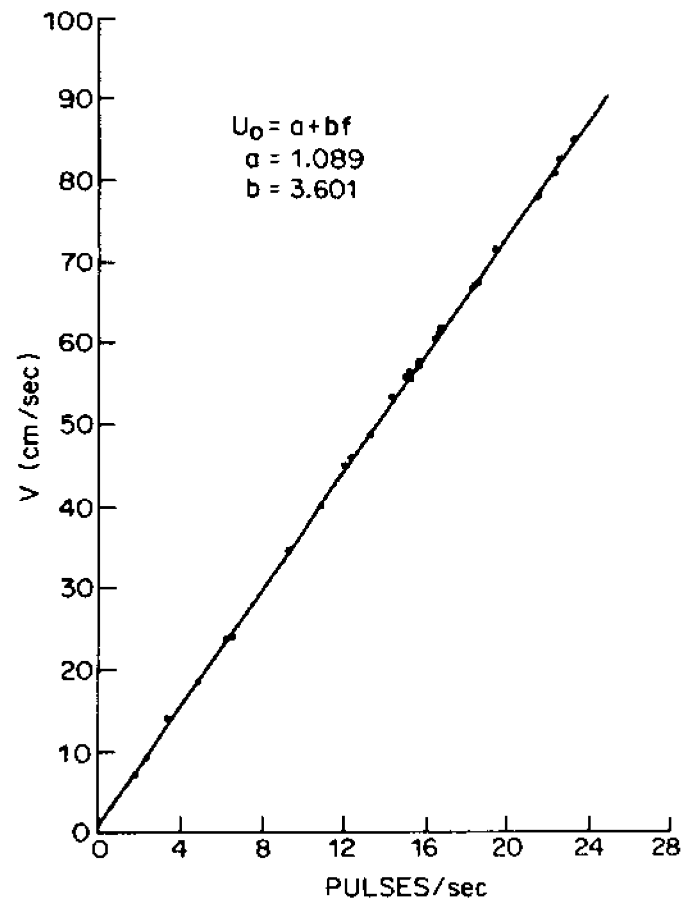


Figure 4. Calibration of several pulse output mechanical current meters at zero angle of attack showing the degree of linearity and the differences that can be expected between various units or various rotor settings in a single unit.

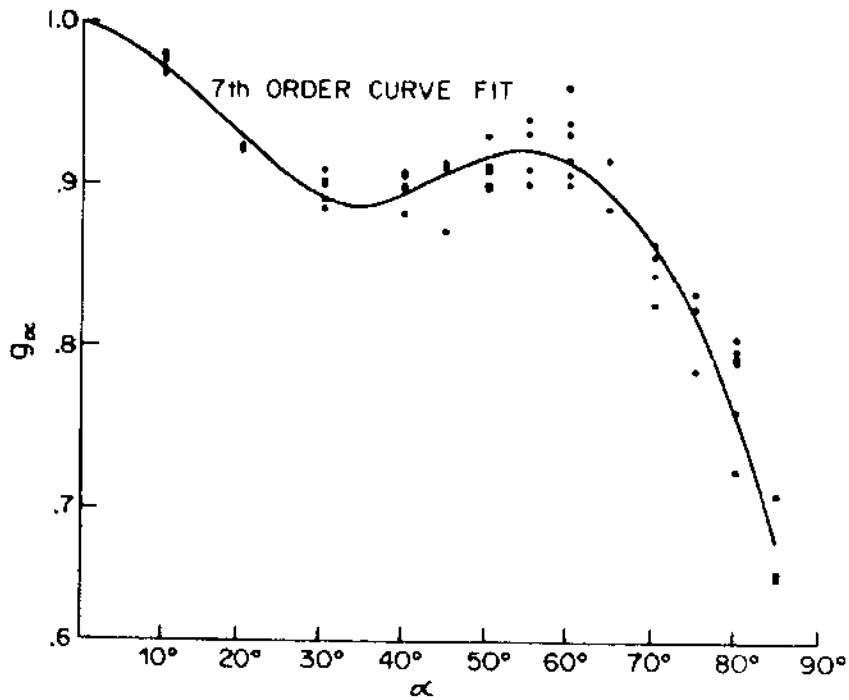


Figure 5. Angle of attack correction, for all pulse current meters considered together, when they are rotated around the axes of their support rods.

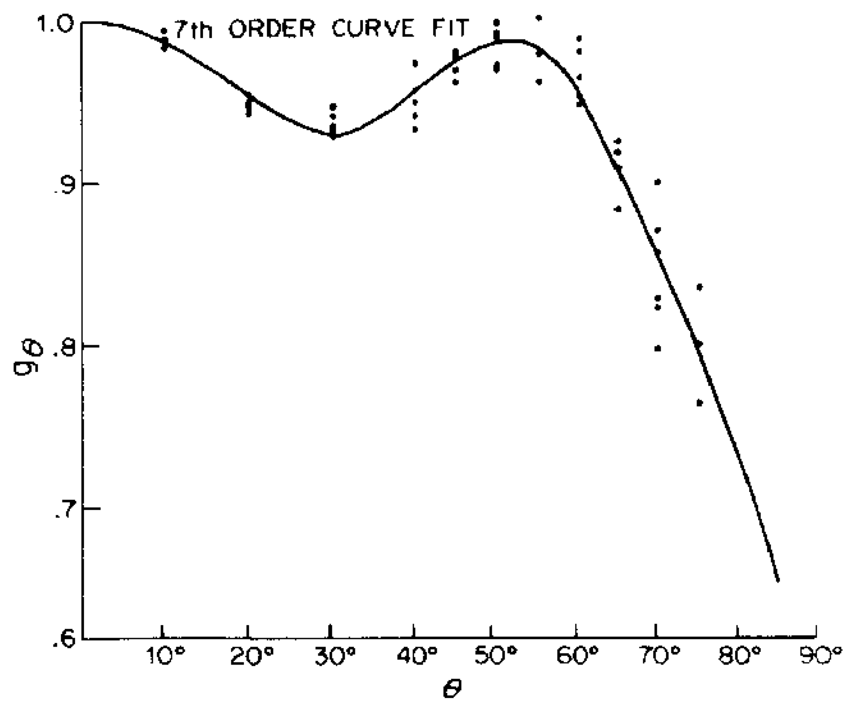


Figure 6. Angle of attack correction, for all pulse current meters considered together, when they are rotated in the upstream direction in the plane of their support rods.

current meters, this angle of attack correction varies only slightly with flow speed. At zero angle of attack, the calibration equation is:

$$u_\phi = a + bf, \tag{1}$$

where u_ϕ is the flow speed, a and b are empirically determined constants and f is the output frequency. If the current meter is rotated through a yaw angle α, from head on, around the axis of its stem, then the calibration equation becomes:

$$u = (a + bf)\ g_\alpha(\alpha), \tag{2}$$

where u is the measured velocity component and $g_\alpha(\alpha)$ is an angle of attack correction factor of order unity. Similarly if the current meter is rotated through a pitch angle θ, from head on, in the plane of the stem, then the calibration equation becomes:

$$u = (a + bf)\ g_\theta(\theta), \tag{3}$$

where u is the measured velocity component and $g_\theta(\theta)$ is the angle of attack correction.

Due to the pressure forces that arise on the stem when it is at an angle of attack to the flow $g_\theta(\lambda) \neq g_\alpha(\lambda)$ where λ is any angle. Thus the general calibration equation for a single current meter is:

$$u = (a + bf)\ g(\alpha, \theta). \tag{4}$$

Denoting the total angle of attack as β, we see that:

$$\tan^2\beta = \tan^2\theta + \tan^2\alpha. \tag{5}$$

If $g(\theta, \alpha)$ is defined as a function of $\tan\theta$ and $\tan\alpha$, $g(\theta, \alpha)$ is determined by linearly interpolating, with arc angle ϵ, between $g_\alpha(\beta)$ and $g_\theta(\beta)$ and this yields:

$$g(\theta, \alpha) = g_\theta(\beta) + \frac{2\epsilon}{\pi}\,[g_\alpha(\beta) - g_\theta(\beta)], \tag{6a}$$

$$\beta = \tan^{-1}\,(\tan^2\theta + \tan^2\alpha)^{1/2}, \tag{6b}$$

$$\epsilon = \tan^{-1}\frac{\tan\alpha}{\tan\theta}\,. \tag{6c}$$

The most accurate data processing procedure is to assume that the current meters respond in a cosine manner, then to calculate the flow direction relative to the triplet orientation. From this, angle of attack corrections for each meter are determined, and then a new flow direction is calculated. With a few iterations, convergence to better than $\pm 1.0\%$ of the actual flow is attained. Use of on-board, NOVA 1200 computer eliminates the need for a perfect cosine response in the current meters, in our case, and even in internally recording systems, microprocessers can be used to make the required corrections. Faster computational methods for making the angle of attack corrections are available for specific triplet geometries, but this iterative one always can be used and can be carried to whatever accuracy is attainable or desirable.

The accuracy of a specially calibrated single current meter is better than 0.1 cm/sec or ±0.5% of the actual reading, whichever is larger. Even as a group, the head-on calibration is linear and yields a precision of ±0.3 cm/sec or ±1.2% of the actual reading, whichever is larger. For flow speeds above 7 cm/sec, the angle of attack correction is good to ±0.3 cm/sec or ±2% of the actual value, whichever is larger. If desirable, this could be improved somewhat, but we have not done so because it has not been necessary in the cases that we have examined. The single current meter accuracy is a fair but slightly pessimistic representation of the precision, and certainly the precision is not better than ±0.05 cm/sec. In spite of their somewhat archaic design, these pulse output mechanical current meters can be used to provide measurements of high accuracy and these data are not degraded substantially until frequencies in excess of 5 Hz are encountered. Frequencies up to about 10 Hz can be resolved, but the transfer function for the region between 5 and 10 Hz is not known very well, and because of the wave number cutoff of the flow sensors, this band is not usually of interest.

In addition to the vertical scale of each velocity sensing unit and its frequency response, the wave number resolution of the turbulence measuring array must be taken into account. The distance constant for the 4.0 cm diameter impellor used in the pulse-output mechanical current meters is approximately 7.2 cm. Thus, with two magnets per rotor, eddies with downstream wave lengths of less than 7.2 cm cannot be resolved. Similarly, the cross-stream extent of the triplet in its ordinary boundary layer configuration is about 20 cm so only turbulent eddies with cross-stream scales significantly larger than this are resolved accurately. Nevertheless, this configuration still provides a reasonably good evaluation of the velocity fluctuation field associated with the most energetic turbulent eddies and provides a moderately matched frequency and wave number response, in addition to a precise determination of vertical shear. The lack of sensitivity to horizontal displacement of the component sensors when mounted in a triplet results from the substantial anisotropy of near boundary turbulence and from the decrease in spectral density with increasing wave number.

High accuracy can be attained only if the threshold velocity for the current meter is not crossed. In the mass produced units, the mechanical threshold is somewhat below 1.0 cm/sec. With the optical readout system, the crossover distortion problem alluded to above required an electronic threshold of nearly 2.0 cm/sec, but this problem was eliminated when the Hall effect readout method was introduced. To avoid threshold problems, the current meters typically are oriented such that each senses a substantial component of the mean flow. After the angle of attack corrections have been made, the velocity and Reynolds stress components are rotated back into the most desirable geographically oriented coordinate system. In turbulent flow investigations over non-uniform boundaries, we usually rotate the components of the Reynolds stress tensor into a mean streamline coordinate system, but as the frame orientation is measured and the angles of rotation are recorded no information is lost.

In our Arctic experiments to measure the boundary layer under sea ice, the masts were configured so that they could be rotated in the horizontal plane. The same scheme is used on bottom-mounted frames, except in this case the frame is designed to rotate itself into the mean flow direction when it is lifted off the sea bed. Only when deployed on the continental shelf in an internally recording mode does the problem of threshold crossing arise in flows of moderate mean speed. Then it is necessary to accept that certain data will have to be discarded or at least recognized as inferior.

The pulse output mechanical current meters have the advantage of being relatively small but quite rugged and are only seriously disturbed by seaweed if it is of the filaform type. When a triplet is used, it can be configured such that all meters are in the same plane or nearly so; thus, the small size means that they can be stacked quite close together in the vertical and still permit acceptable resolution of the turbulent structure within the overall constraints produced by the finite size of the array and the finite wave number resolution of the impellor.

In summary, the specific advantages of an array of pulse output mechanical current meters are (1) their ability to resolve mean shear with high accuracy, (2) their good frequency and wave number response at this accuracy, (3) their near cosine response with angle of attack, (4) their capability of being used singly, in pairs or in triplets, and (5) their low cost per unit. Their greatest disadvantage is a susceptibility to fouling by filamentous green algae or grass. Moreover, their frequency and wave number response is too limited for many turbulent flow applications, while their size is too large for some types of bottom boundary layer and sediment transport measurements.

Support Brackets. In most cases the support frames for the pulse output mechanical current meters are constructed of 3/4" (19.05 mm) O.D. stainless steel tubing. This has the advantage of being both non-corrosive and nonmagnetic, thus avoiding both chemical and physical interference with any sensors mounted thereon. Support blocks constructed of polyvinyl chloride (PVC) attach to both the current meter triplets and the stainless steel tubing. In the most commonly used design, the support blocks have two parts. These slide together and can be fastened with machine screws. One part of this bracket fits around the stainless steel tubing and bolts to it with two screws; the second part of the bracket fits around two of the three current meters, clamping them in the desired position. The third current meter is attached to the other two using small diameter laboratory clamps. The advantage of this sytem is that an entire current meter triplet can be taken off the frame and replaced after removing the two machine screws and three Electro-Oceanics connectors. Individual flow meters are oriented to within a fraction of a degree in each triplet, so a template must be used and this set-up operation cannot be done accurately while the triplet is attached to the frame. With the two-part brackets, this alignment can be accomplished precisely in the laboratory, and triplets can be set up and stored well ahead of a cruise.

Deployment Systems. Earlier it was noted that the specific frames and masts from which flow sensors are deployed are as important as the sensors themselves. This being the case, a review of the primary systems from which the pulse output mechanical current meters currently are being deployed and a brief discussion of the salient characteristics of each frame are presented in this section. The specific scientific projects under which these instrument frames have been deployed in the past are listed in Table 1. Table 2 lists the frames now in use.

Specific results from the nonuniform flow investigation in the Columbia River are presented by Smith and McLean (1977), McLean (1976), and McLean and Smith (in preparation) and Smith, McLean, Chubb and Begley (in preparation). Specific results of the Arctic Ekman layer investigation are presented by Smith (1974), McPhee (1974) and McPhee and Smith (1976). Results obtained using the Arctic profiling fish in the spring of 1976 are presented by Morison and Smith (in press). Results pertaining to turbulent mixing in the Duwamish River are presented by Partch and Smith (1977) and Gardner and Smith (in press). Preliminary results of the Knight Inlet investigation are presented by Farmer and Smith (1978).

The support device that has yielded the highest quality turbulence data is the bottom boundary layer (BLF) frame shown in Figure 7. The basic frame design is that of an open tower comprised of 3/4" (19.05 mm) O.D. stainless steel tubing supported on four ski-like stainless steel feet. Fifteen centimeter-long spikes are bolted to the feet and penetrate the sediment beneath to keep the frame from sliding downstream. These feet also are weighted with lead to provide high stability when the frame is sitting on the bottom or suspended in the flow. To guarantee this stability, a scale model was constructed and tested in a tow tank before the prototype was built. One of the design goals was to produce a frame that would remain more or less vertical when hanging in a uniform flow so that some interior flow measurements could be made if necessary. Also, it was designed to have a damped response to all but the lowest frequency fluctuations in flow direction so that it would orient the sensors into the flow direction if held above the sea bed for a short period before being set down.

TABLE 1

Ocean Boundary Layer and Turbulence Measurements Carried Out in Recent Years at the University of Washington

1. Flow over large amplitude quasi two-dimensional sand waves

Location: Columbia River
Experiments: June 1968, 1969, 1971, 1972
Instrument frames: BLF, IFF
Measurements: Mean velocity (all years)
Reynolds stress (1972 only)
Bottom topography
Suspended sediment concentration

2. Arctic Ocean surface mixed layer investigations

Location: Beaufort Sea
Experiments: March-April 1970, 1971, 1972, 1974, 1976
Instrument frames: UIM, IFF or APS
Measurements: Mean velocity (all years)
Reynolds stress (all years)
Salinity and temperature profiles (1972, 1974, 1976)
Under ice topography (1970, 1971, 1972)

3. Near bottom flow on inner continental shelves

Location: Oregon continental shelf
Experiments: December 1975
Instrument frames: SUDS
Measurements: Mean velocity
Wave height and wave induced velocity
Turbulent kinetic energy

Abbreviations:

BLF	Boundary layer frame	APS	Arctic profiling fish
IFF	Interior flow frame	SUDS	Self-contained underwater data system
UIM	Under ice mast	SMM	Ship mounted mast
IPF	Interior profiling frame	ITF	Interior turbulence frame

TABLE 2

Estuarine Turbulence Investigations Currently in Progress
at the University of Washington

1. Mechanics of mixing in a salt wedge estuary

Location: Duwamish River (Seattle)
Experiments: August 1974, January 1975, October 1976, March 1977
Instrument frames: BLF, SMM, ITF, IPF
Measurements: Mean velocity
Reynolds stress
Turbulent salt flux
Turbulent heat flux
Turbulent kinetic energy
Salinity and temperature profiles

2. Mixing in the surface layers of fjords

Location: Knight Inlet (British Columbia)
Experiments: November 1976, August 1977
Instrument frames: IFF, APS, SMM
Measurements: Mean velocity
Internal wave velocity and salinity field
Turbulent kinetic energy
Interface topography
Salinity and temperature profiles

3. Mechanics of unsteady turbulent boundary layers

Location: Puget Sound
Experiments: June 1973, October 1973, September 1974, October 1974
Instrument frames: BLF, IFF, ITF
Measurements: Mean velocity
Reynolds stress
Turbulent kinetic energy
Small scale, high frequency flow structures
Bottom topography
Salinity and temperature

Abbreviations:

BLF	Boundary layer frame	APS	Arctic profiling fish
IFF	Interior flow frame	SUDS	Self-contained underwater data system
UIM	Under ice mast	SMM	Ship mounted mast
IPF	Interior profiling frame	ITF	Interior turbulence frame

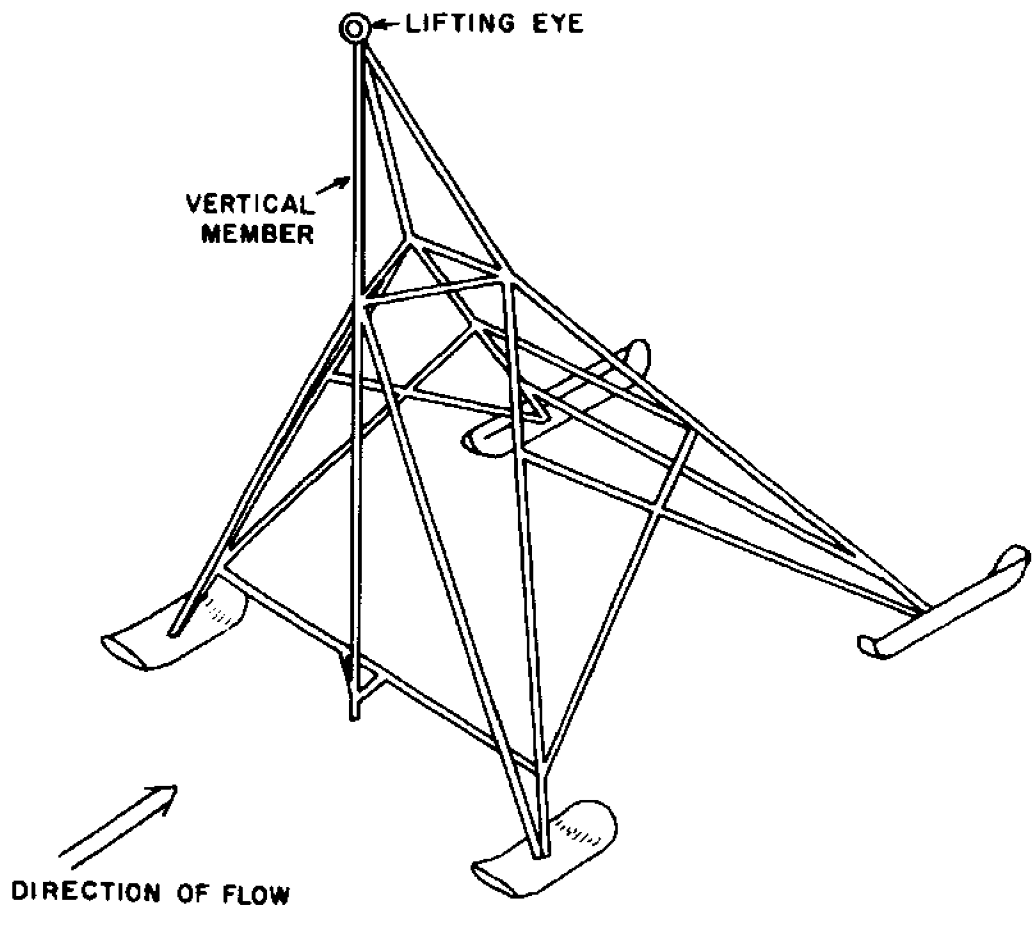


Figure 7. Bottom boundary layer frame.

The bearing of the frame and its attitude are recorded using a compass and two tilt meters, respectively. The mast to which current meters are attached is situated forward of the frame in order to reduce disturbances caused by wakes from the support arms and particularly from the pressure field induced in the flow by the presence of the frame and the other gear that it supports. The latter may include current meter junction boxes, cables, a compass, tilt meters, conductivity cells, pressure sensors and a precision echo sounder. A photograph of the instrument frame with a set of current meter triplets mounted on it is shown in Figure 8. The spheres on the two front feet are the lead weights used in balancing the frame.

The masts that we used in five Arctic mixed layer investigations were comprised of three meter long sections of 3/4" (19.05 mm) O.D. stainless steel tubing with flanges on each end so that the section could be bolted together. Several hundred pounds of lead were suspended at the base of the mast; the exact amount was determined by the drag on the mast which depended, in turn, on its length and the number of current meters attached to it. Flow-induced deflections of more than 3° were considered unacceptable. Figure 9 shows a photograph of the instrument frame as deployed under the ice in March 1972.

When concerned with currents and turbulence in the interior of the water column, wire-lowered rather than bottom-mounted instrument support systems must be used. No matter how well the motions of these frames are monitored, the turbulence measurements are substantially degraded compared with those obtained with bottom-mounted frames. When the research vessel is moored with three anchors in a shallow and calm estuary and when yawing of a well designed frame is measured with a compass accurate to 1° or better, Reynolds stress, turbulent salt flux and turbulent heat flux measurements can be made with tolerable accuracy. However, even with inertial reference gear, such measurements become questionable when wind waves are present or when the research vessel begins to yaw. If the ship is moored with a single anchor, about all that can be determined with any accuracy using a wire-lowered system (even when precision microwave navigation shows the vessel to be essentially stationary), are mean velocity and turbulent kinetic energy. In contrast, using a ship-mounted mast system such as the one described below, some Reynolds stress and turbulent heat and salt flux information can be obtained when the vessel is moored with one anchor, as long as a high frequency response precision navigation system shows that the vessel is relatively stationary over periods of time sufficient to yield usable time series (at least 5 minutes). When the ship is steaming with a ship-mounted mast, navigation inaccuracies and the broad spectrum of vessel motions make it difficult to determine anything but mean velocity and turbulent kinetic energy profiles. Nevertheless, the use of velocity profiling systems and ship-mounted masts provides a means of elucidating spatial structure that cannot be resolved in highly stratified estuarine systems by any other presently available oceanographic technique.

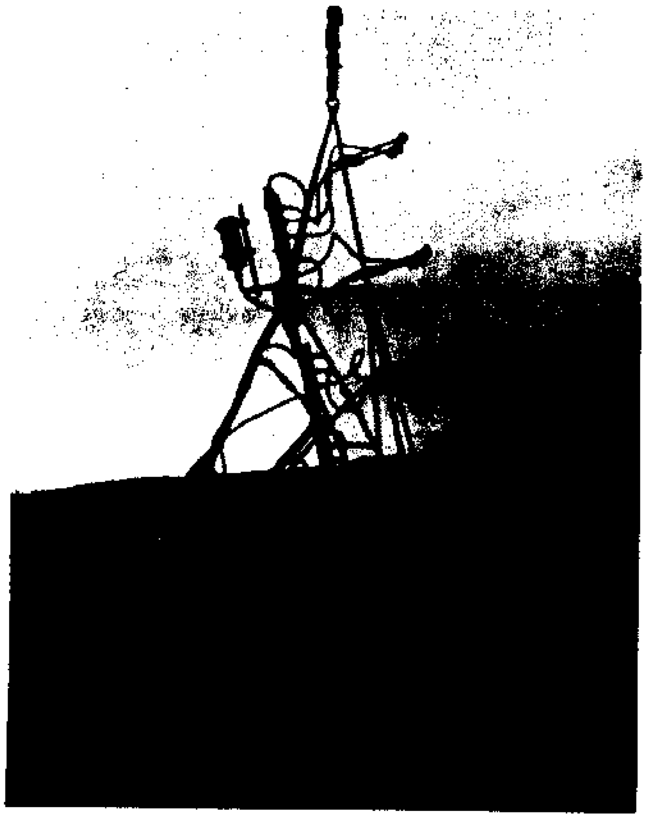


Figure 8. Photograph of bottom boundary layer frame with pulse output mechanical current meters attached to it in orthogonally oriented groups of three each.

Figure 9. Photograph of the under ice mast taken by divers during a 1972 mixed layer experiment in the Beaufort Sea.

The basic interior flow frame (IFF) that we use is sketched in Figure 10. Like most of our other frames, it is constructed primarily of 3/4" (19.05 mm) O.D. stainless steel tubing. From the front, the test section is an open 60 x 120 cm rectangle. Current meters mounted on the sides and top are oriented so that their centers can be located on the axis of frame rotation. As shown in Figure 11, two pairs of pulse-output mechanical current meters, not quite on the axis of rotation, are situated to yield downstream and vertical velocity components, whereas the electromagnetic current meter at the top, the pulse current meters and the acoustic current meter at the bottom provide measurements of any cross-stream flow component. Orientation of the frame is caused by the drag on the open network of tubing and through the drag on the pipe at the top. The latter is oriented perpendicular to the basic frame and has a large sphere on its downstream end. Orientation of the IFF is determined with tiltmeters and a compass.

A second type of wire-lowered frame called the interior turbulence frame (ITF) has been used to measure turbulent heat and salt fluxes. This device is based on an Arctic model Guildline CTD oriented to flush horizontally as shown in Figure 11. A large PVC fin attached to the downstream end orients it into the current. Brackets supporting masts of 3/4" (19.05 mm) O.D. stainless steel tubing in the vertical direction above and below the CTD provide support for current meter triplets of the type used on the boundary layer frame and Arctic masts. Also, this frame supports a special triplet configured to provide measurements of the three velocity components in the immediate vicinity of the Guildline temperature and conductivity sensors. This unit has the advantage of permitting turbulent heat and salt flux measurements, but it is not quite as stable as the standard interior flow frame.

The Arctic Profiling Fish (Figure 12) is basically a Guildline CTD with a triplet of pulse mechanical current meters configured symmetrically and mounted at its head, and an additional pressure case containing inertial reference equipment. This profiling system is described in detail by Morison and Smith (in press). The system is attached to the vessel by an armored electrical cable that leads to a large diameter block and then to a winch. The hydraulic winch has a 1.8 m diameter drum, so the lowering rate does not change much over the upper 100 to 200 m of the water column. Moreover, it is controlled automatically so that the Arctic Profiling System can run unattended for many days. Typically, the cycle time is about 5 minutes, yielding approximately 12 downcasts per hour. Due to the fish geometry, data from upcasts are degraded. Therefore, they are not always recorded. As is the case with data from all other frames, the measurements are logged on a NOVA 1200 computer.

The ship-mounted mast (SMM) is shown in Figures 13, 14 and 15 and a complete description of it is given by Gardner and Smith (1978). The mast is a 13 m long piece of 2 1/2" O.D. (63.5 mm) thick wall steel tubing strengthened and fared with a 3" x 1/4" (76.2 x 6.35 mm) steel

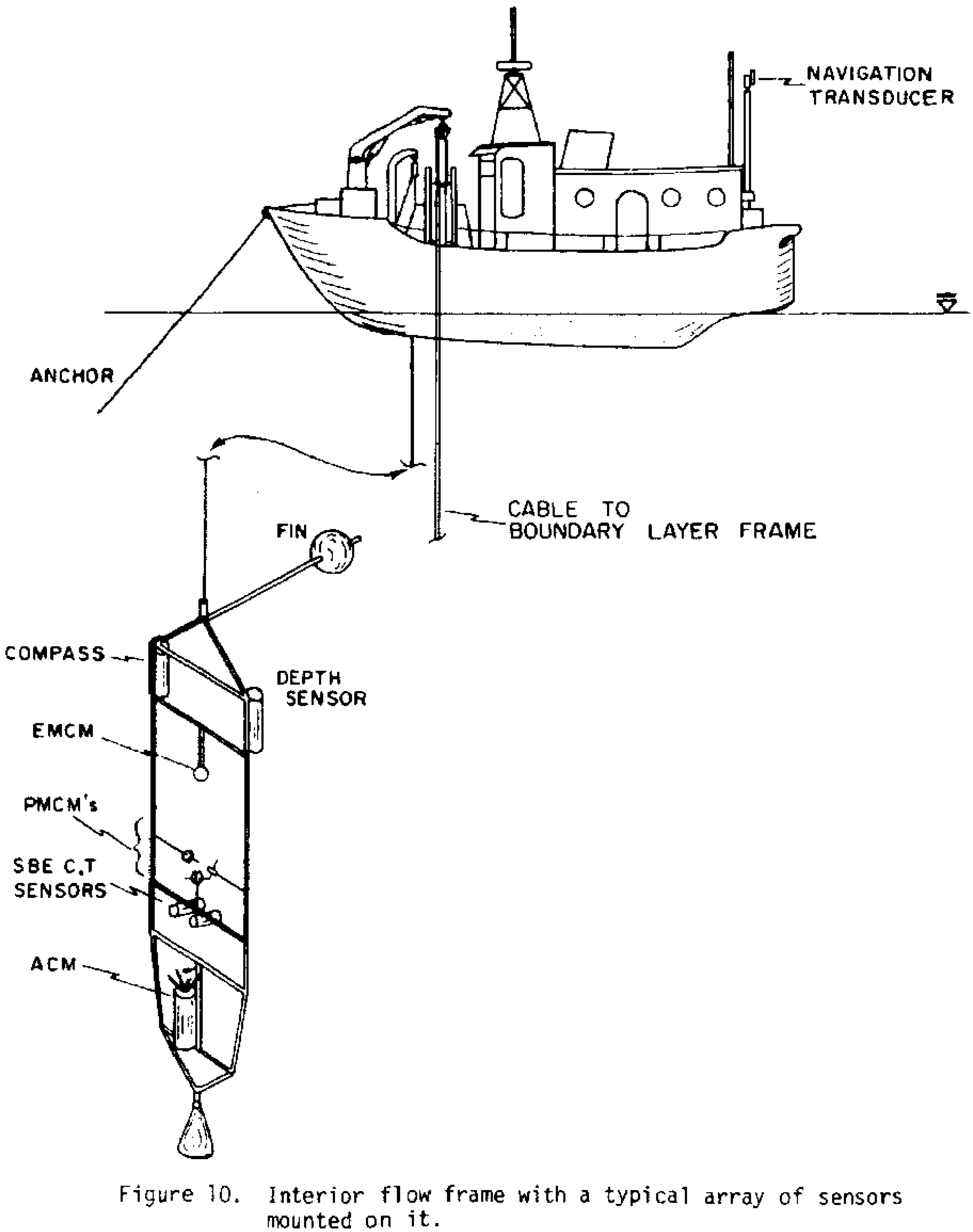


Figure 10. Interior flow frame with a typical array of sensors mounted on it.

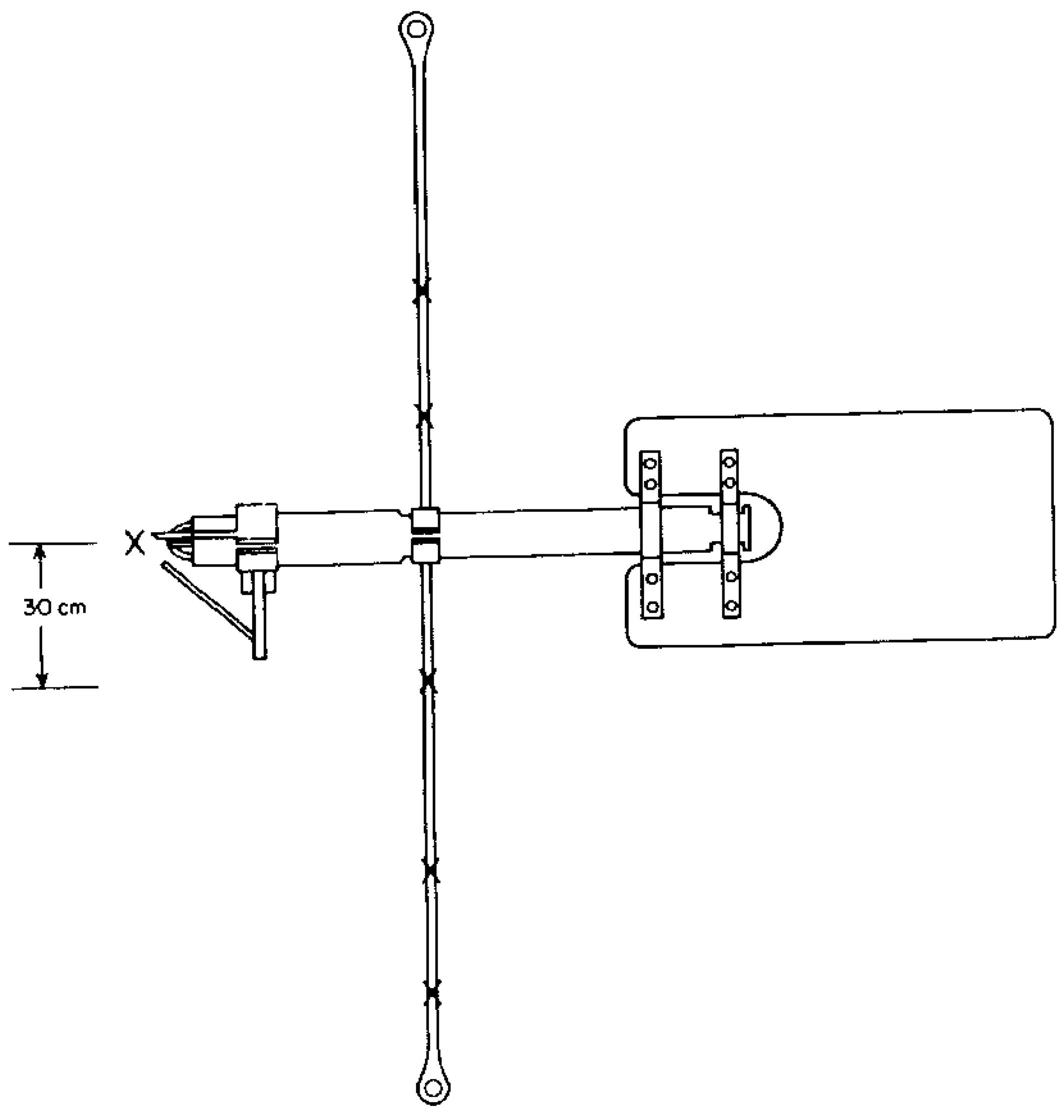


Figure 11. Interior turbulence measuring frame.

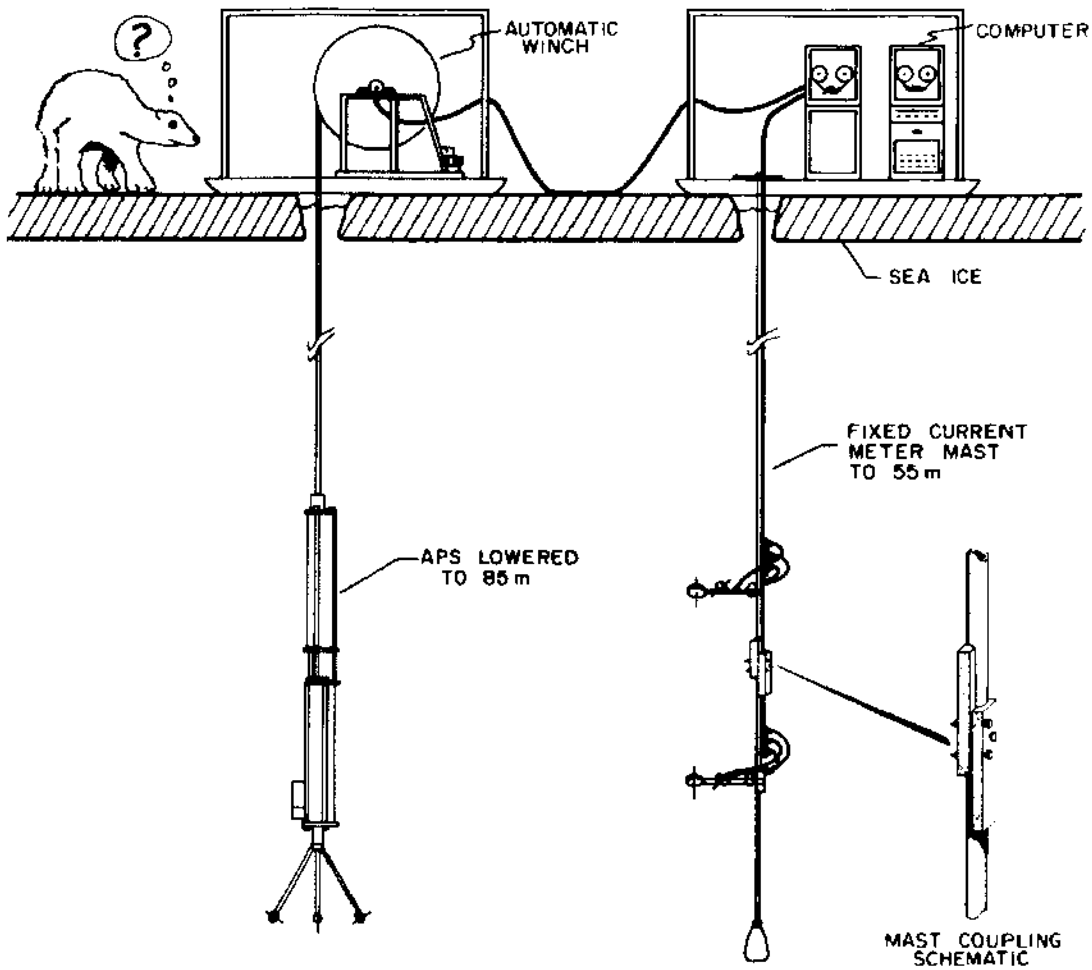


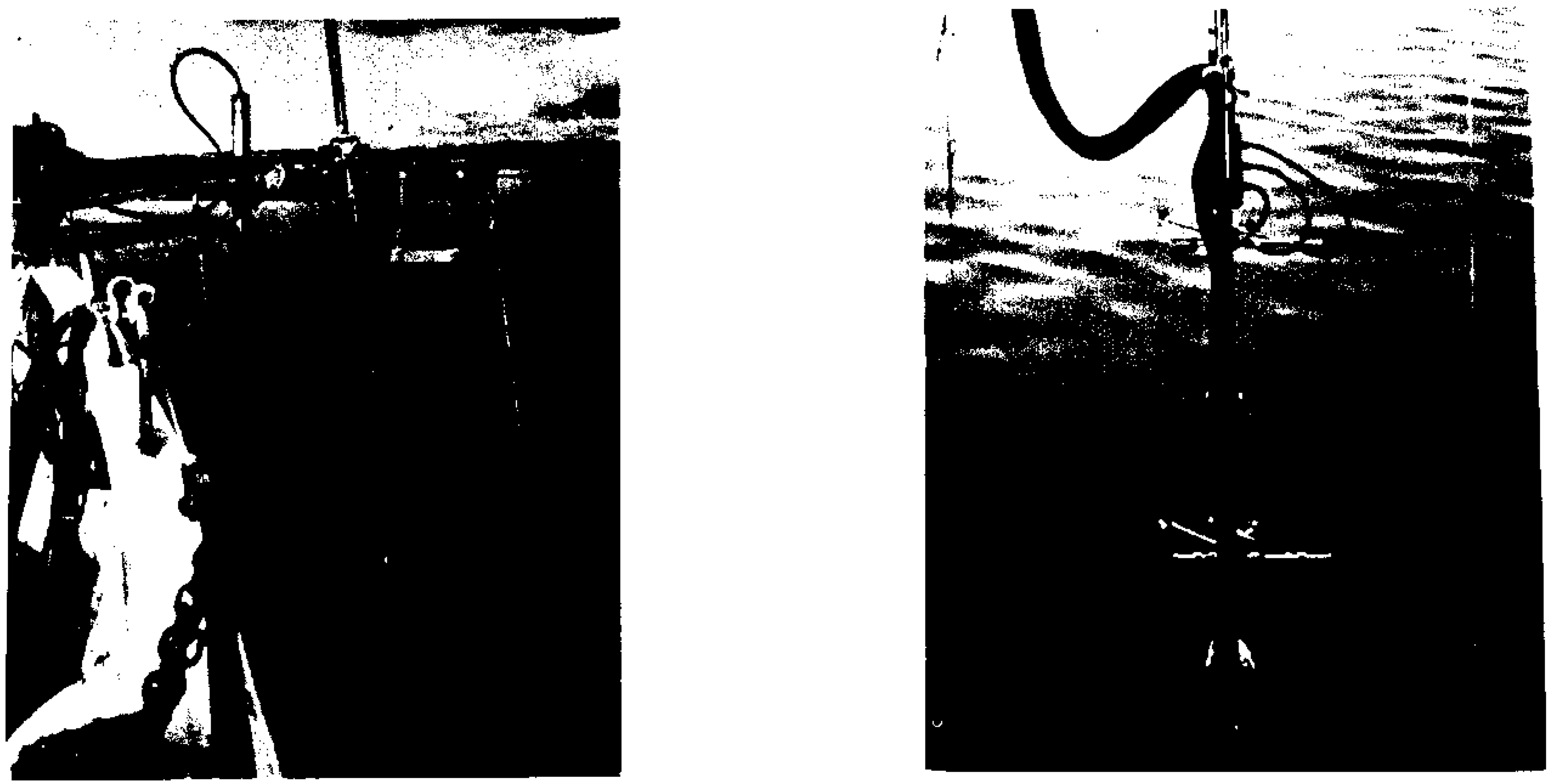
Figure 12. Sketch of Arctic profiling fish attached to its large diameter winch.

rib welded to the downstream side. This is attached to an I-beam by a special clamp that holds the mast torsionally rigid but permits it to pivot in the fore-aft direction (Figure 13a). Stays support the mast laterally. Junction boxes and instrument cables attach to the rib on the back of the mast, and the current meter triplets attach to special brackets on the side so that they are centered 20 cm in front of the mast (Figure 13b).

The bracket between the mast and the I-beam also permits the base of the mast to be rotated onto the research vessel after it has been raised approximately to the elevation of the pivoting bracket (Figure 14). To deploy it, the base of the mast is rotated out and then down until it is at a 30° angle with the vertical. Then the mast is lowered along its axis to the desired depth through the special pivoting bracket, and the stays are tightened. The latter operation is accomplished while the mast remains at the 30° angle. Once in the water at the desired extension (Figure 15), the special pivoting bracket that holds the mast to the I-beam is tightened. When underway, 230 kgms of lead at the base of the mast keep the base support wire under tension as long as the research vessel does not exceed about 4 knots.

The mast can be raised to service the current meters and lowered again in about 5 minutes. When in position, it enters the water 1.5 m aft of the point where the bow intersects the sea surface and is 2.3 m (or 1.7 ship hull widths) lateral to the hull at this point. Motion of the mast is monitored with the same inertial reference unit that is used with the Arctic profiling fish or with three accelerometers when both systems are being deployed at once.

The last support frame available in our inventory of equipment is the self-contained underwater data system (SUDS). The instruments deployed on all of the previously mentioned support devices are attached to a research vessel via an electronics cable. However, it occasionally is necessary to deploy a bottom current measuring system that is self-contained. Two types of frames have been used with SUDS. The first is a giant tripod shown in Figure 16 and the second a short, squat tower with a Y-shaped base. The former is required when sediment transport investigations are of concern, whereas the latter is sufficient when the general properties of the bottom boundary layer are of interest for physical oceanographic purposes. The large tripod is designed to minimize disturbance of the flow in the immediate vicinity of the sea bed and thereby to permit accurate measurements in this region. The data recording gear, SUDS proper, is housed in the sphere at the top of the tripod. An acoustic release and a cannister of rope attached to a submarine net float are situated above the tripod when it is deployed on the bottom. It is retrieved via the line from the cannister after the release has been fired and the net float has gone to the surface. This system is difficult to deploy and retrieve because of the large vertical extent of the tripod plus the additional gear that must be suspended above it.



a

b

Figure 13. Ship mounted mast in the down position. Note the stays mounted lateral to the mast and the support bracket that attaches it to the I-beam in part _a_ and the current meter triplets in part _b_.

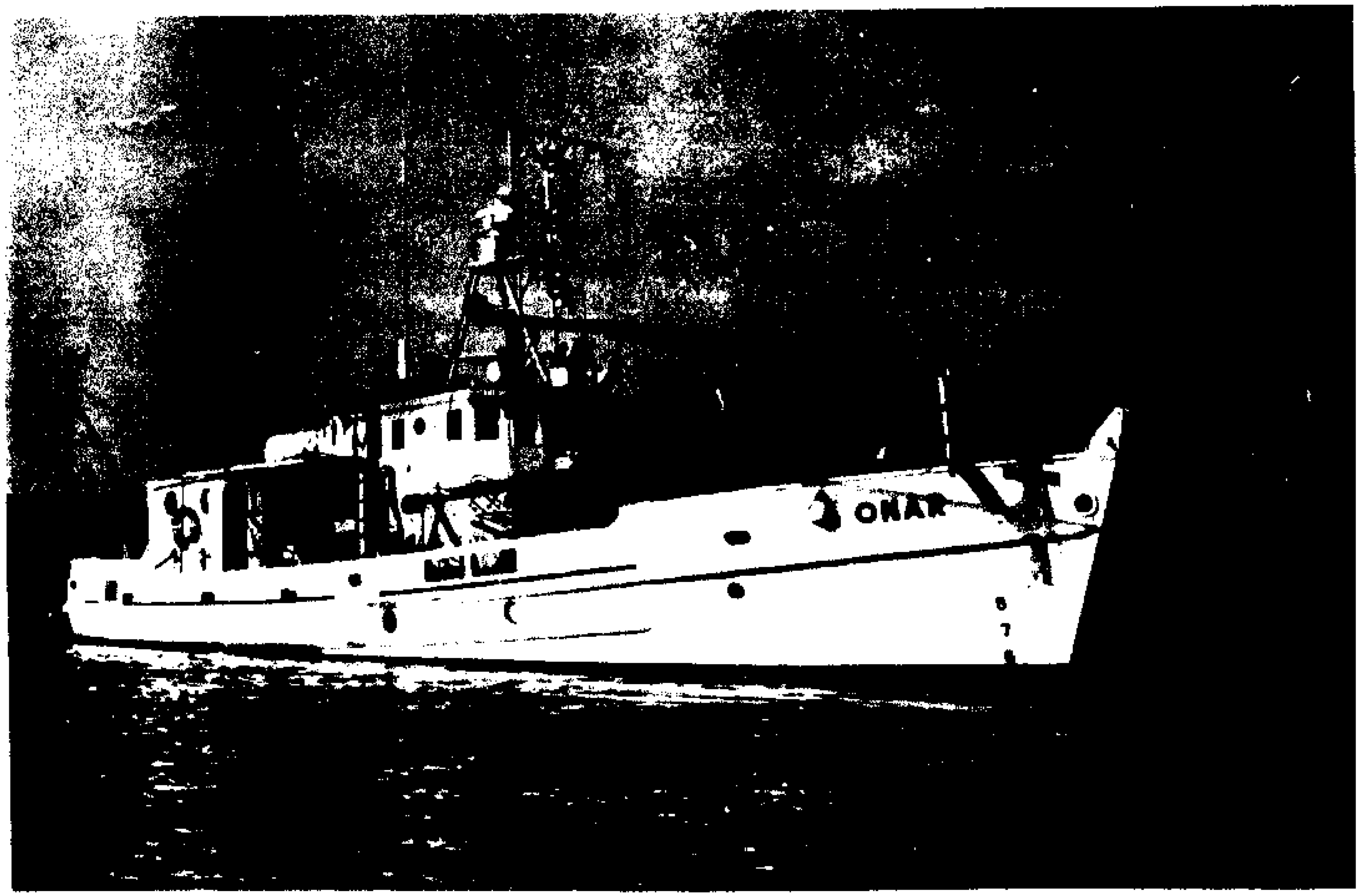


Figure 14. Ship mounted mast in the up position.

Figure 15. Ship mounted mast in use from an anchored vessel in Knight Inlet.

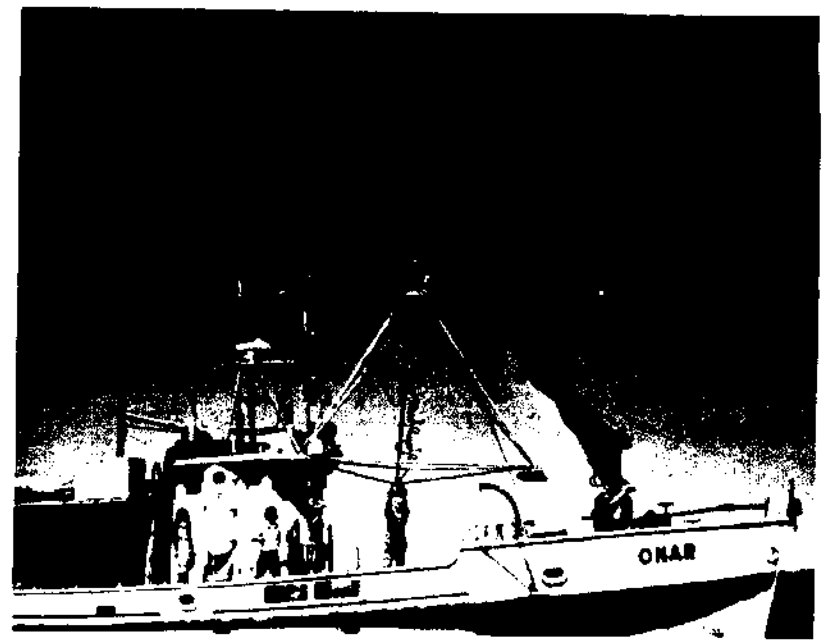


Figure 16. Photograph of the self-contained underwater data system mounted on its tripod.

ACKNOWLEDGMENTS

The current meter systems and the associated software described in this paper were developed under NSF Grants GA 14178 (8/1/69-3/31/75), OCE 75-15154 (4/1/75-3/31/77), OCE 77-09945 (5/1/77-4/30/78); ONR Grants N-00014-67-A-0103-0021 (11/1/70-12/31/73), N-00014-67-A-0103-0034 (9/15/73-9/14/74), N-00014-75-C-0186 (9/15/74-9/30/78); ERDA Grant EY-76-5-06-2225TA25 (Mods. 5-7) (10/1/75-12/31/77); with the specific assistance of Russell Paul, Harold Lee, Michael Welch, George Bean, James Morison, George Gardner, Eric Partch, Charles Long, Stephen McLean, Carol Price, Hella MacIntosh and John Beck.

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SHALLOW CURRENT MEASUREMENTS

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ABSTRACT

The dynamics of mixed layers and the variability of coastal current systems are two important problems that require the measurement of near-surface currents. Near the surface, the wave field generates currents of higher frequency than the current field of interest, leading to the requirements for a current meter which properly averages motion at frequencies higher than the sampling frequency. A mechanical meter, dubbed the vector-measuring current meter (VMCM), which measures two orthogonal components of the current, has been developed, tested and compared with other current meters. Results show the meter to perform well under conditions in which it is expected to be used. Two versions have been developed--one for use in shallow water, on a mooring which does not rotate with respect to the bottom; another for deep oceanic measurements, in which mooring rotation is accounted for in the averaging scheme.

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The current meter is configured in much the same way as other current meter systems (Figure 1). The aluminum pressure cage and propeller assembly reside inside a structural cage made of one-half inch titanium rod. Two sets of propellers are mounted perpendicular to each other. Symmetrical response to flow fore and aft is insured by including a fan on either side of each hub. Bearings are free flooded, and the shaft is encoded such that four clock pulses occur with each full rotation of a fan. The direction of rotation is detected and, along with clock pulses, steps an up-down counter in the electronic package so that the contents of this counter are proportional to the net flow in the direction of the shaft between the two fans.

The performance of each fan assembly in terms of linearity of the rotation rate is a function of current (Figure 2) and cosine response to direction of the current (Figure 3) is deemed exceptional.

Extensive laboratory testing in tow tanks has been performed and reported by Weller (1978). These experiments were designed to test the response of the current meter to a mean tow speed on which a high frequency oscillation of the instrument was superposed. The intent of these tests is to determine how well high frequency motions, due for instance to surface waves, are averaged. Generally, the test results are encouraging, the worst performance occurring when the maximum oscillatory velocity just equals the mean tow speed and the direction of oscillation is either parallel or perpendicular to the tow direction. Since such conditions are not expected to occur consistently or frequently in the ocean, these problems are not considered to significantly affect the instrument's performance.

Two sets of intercomparison tests were performed in the ocean. In the first, the VMCM was compared to the Marsh McBirney cylindrical probe electromagnetic (EM) current meter (Figure 4). Both instruments were moored 17 meters apart in 20 meters of water. The meters were mounted near the top of taut, subsurface moorings, 6 meters beneath the surface. Measurements from both systems compare well, although the onshore component measured with the EM meter has a mean component which was found to be caused by electronic drift. An intercomparison with a vector averaging current meter (VACM), was performed during the MILE experiment* (Figure 5) in the upper layer of the deep North Pacific. The two instruments were mounted two meters apart beneath a surface mooring. Here again, the comparison is excellent. The differences observed are of the same order as differences found between identical instruments separated by the same length as the two instruments in the test.

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*The VACM data were obtained by David Halpern, PMEL.

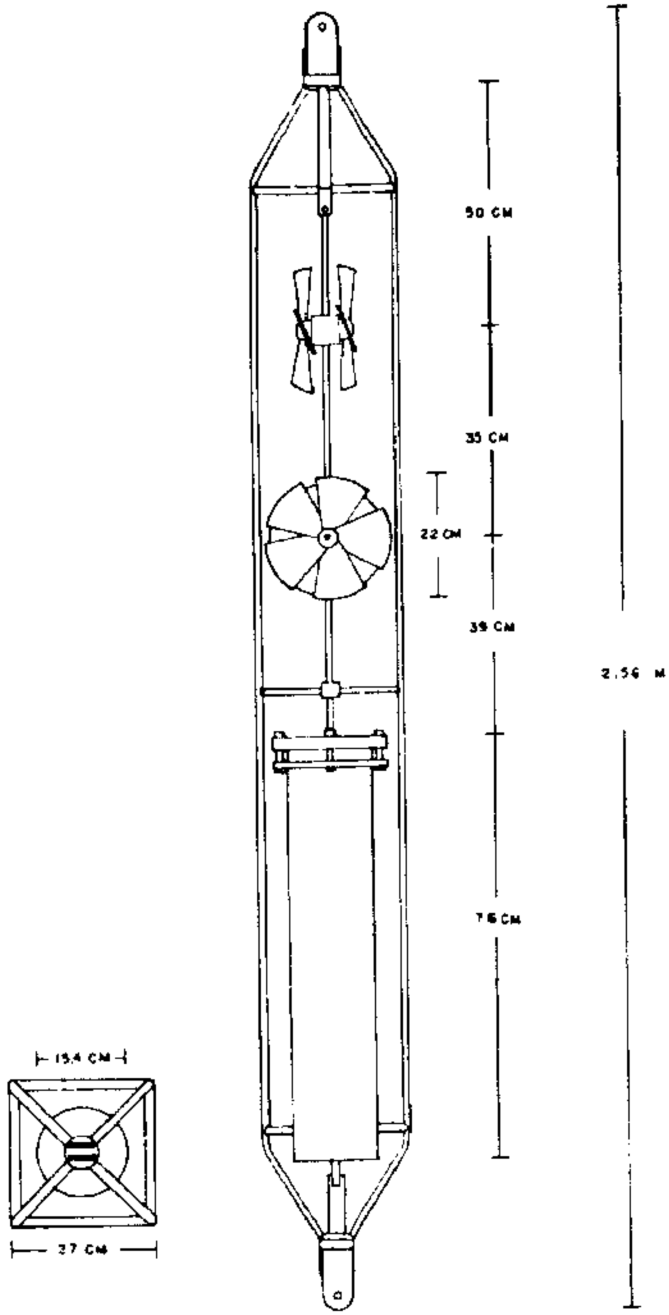

Figure 1. Vector Measuring Current Meter (VMCM).

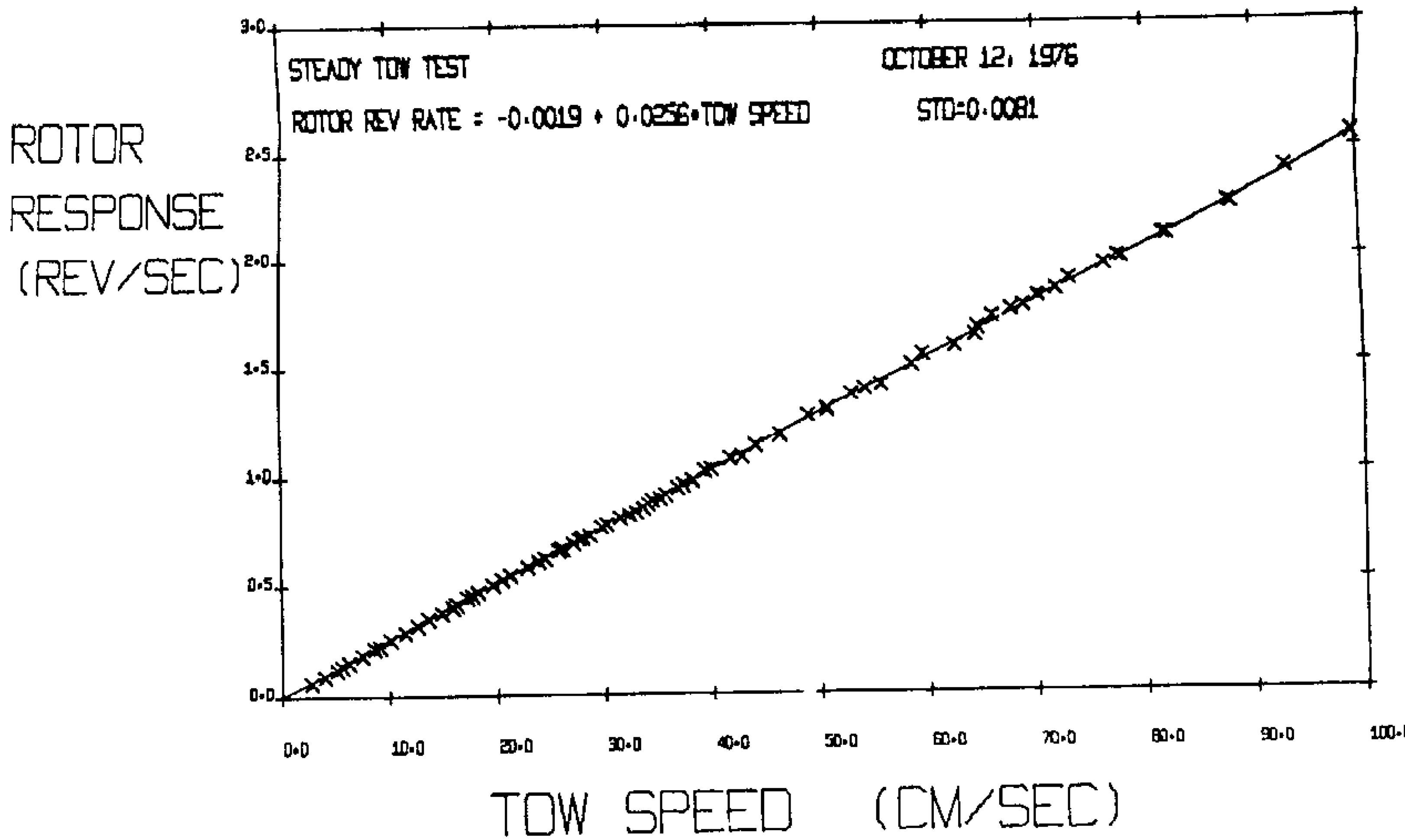

Figure 2. Rotor Calibration: Rotation rate as a function of low speed.

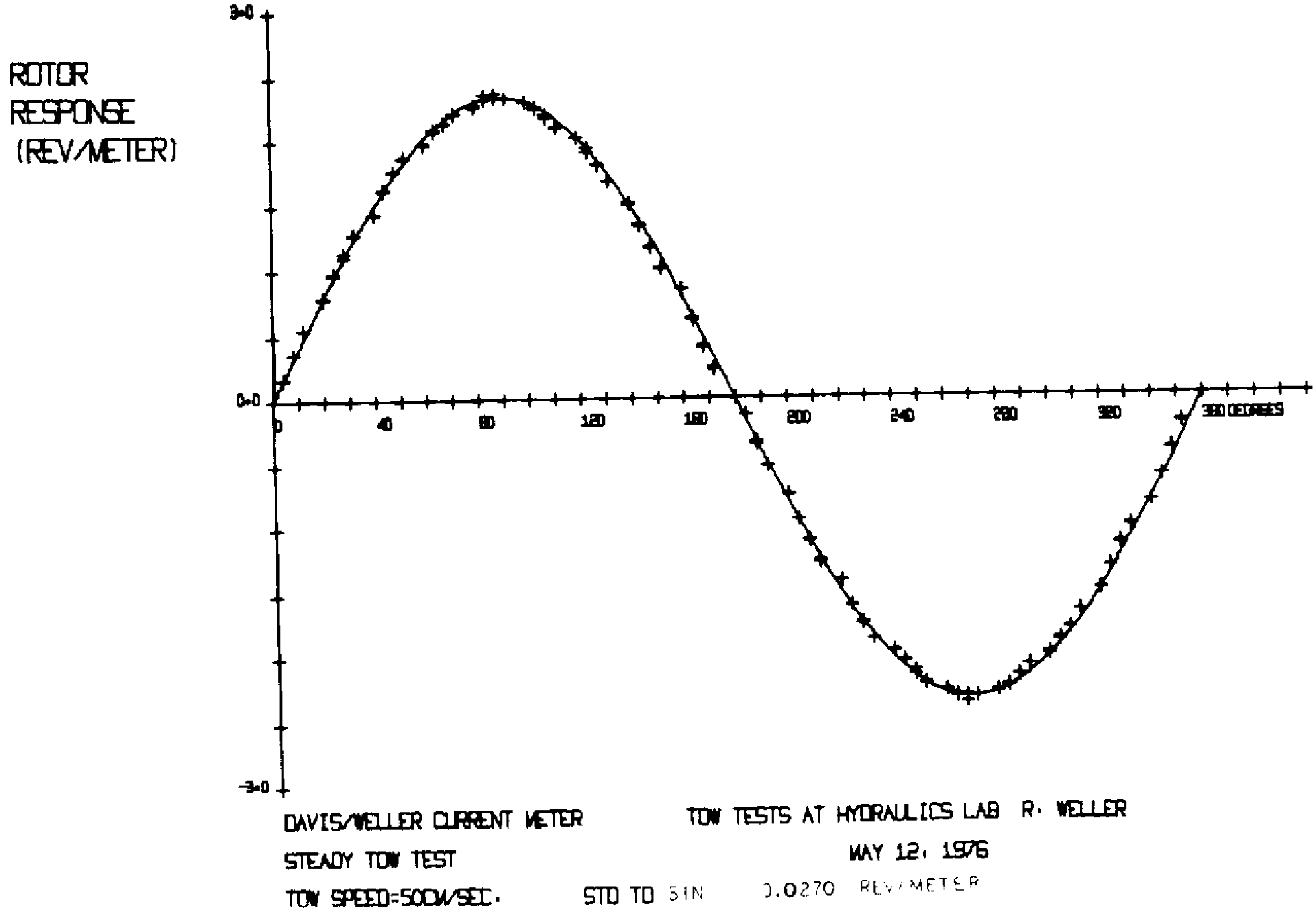

Figure 3. Rotor calibration: Angular response.

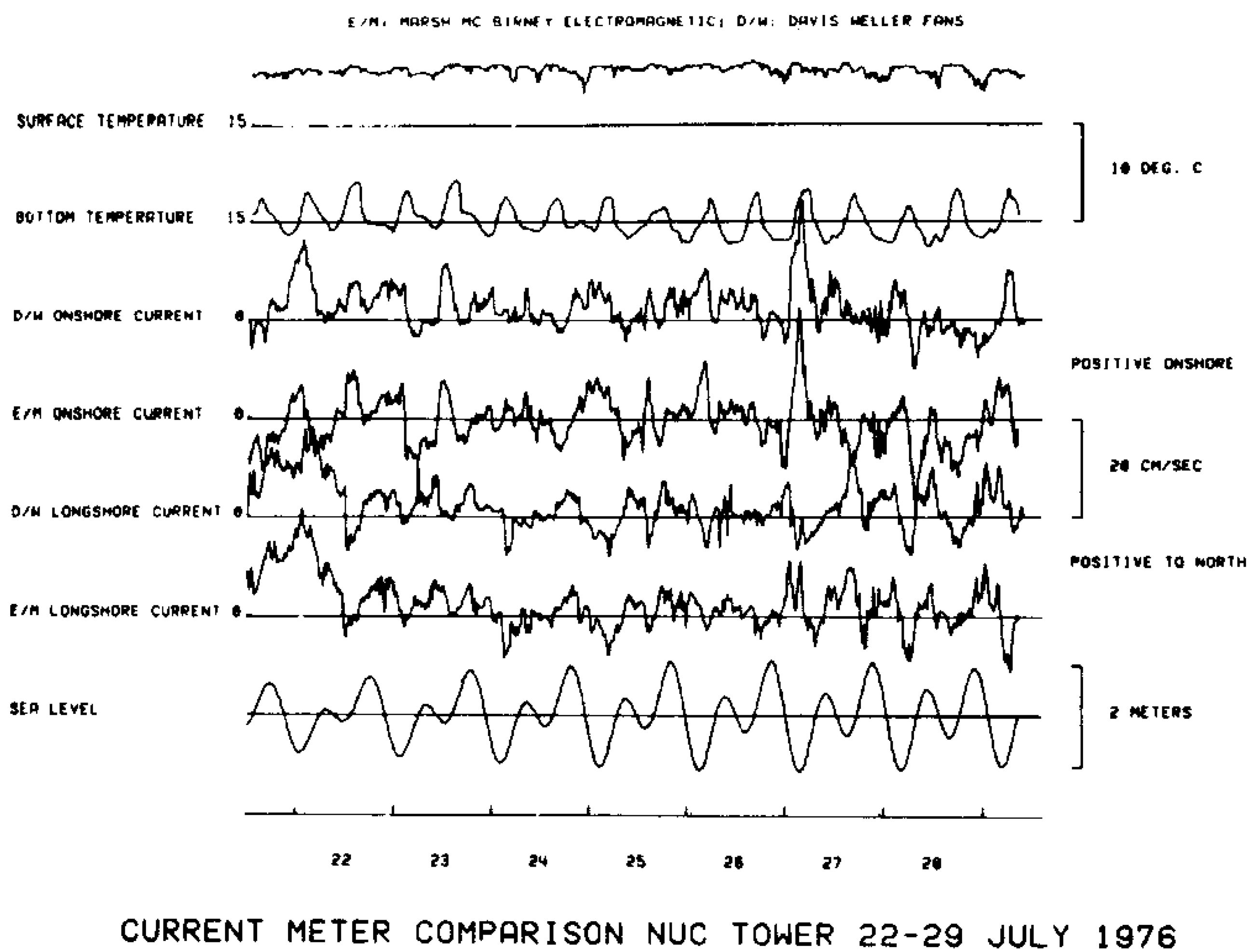

Figure 4. Intercomparison between VMCM and EM current meters.

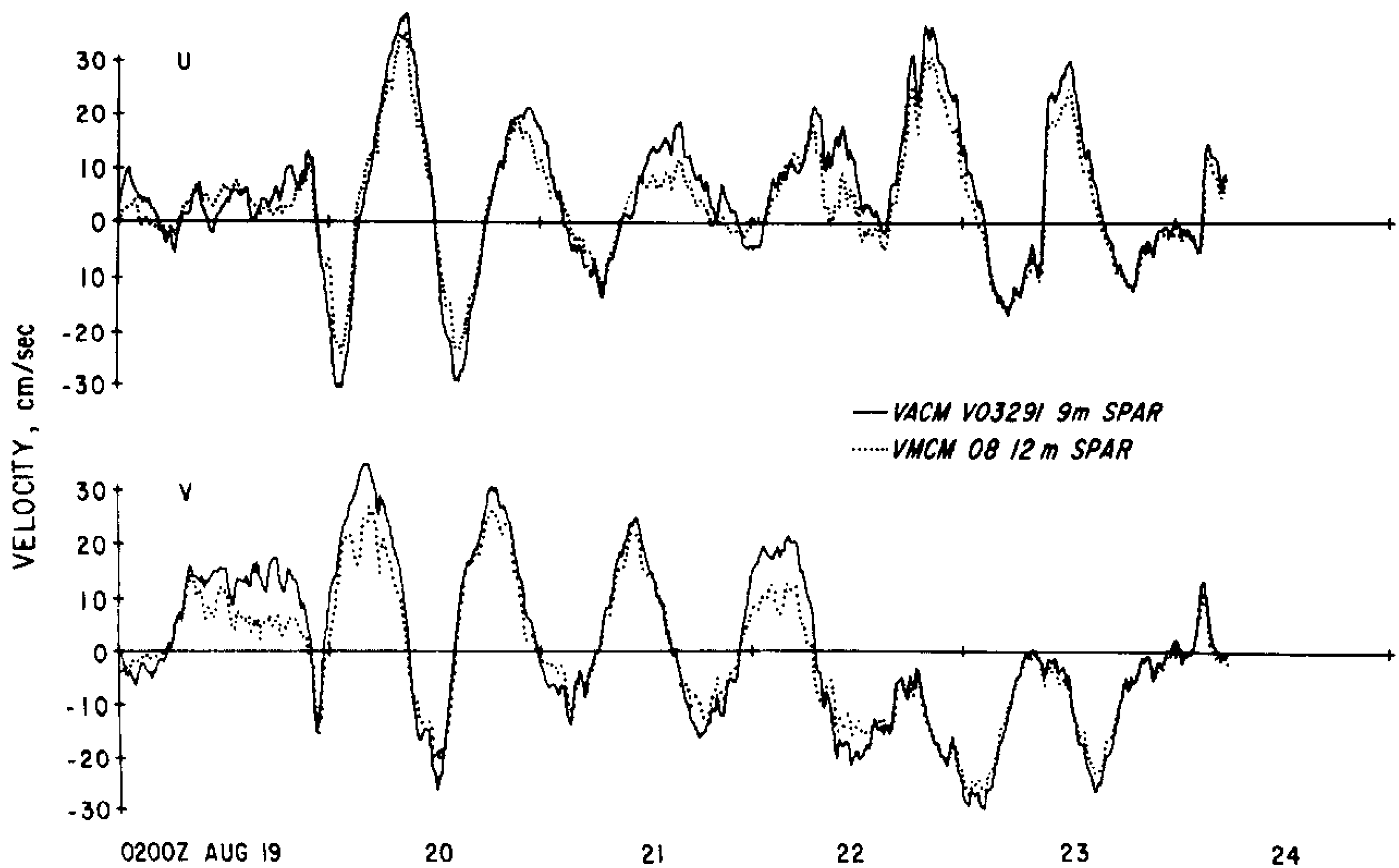

Figure 5. Intercomparison between VMCM and VACM meters.

DEEP OCEAN VELOCITY PROFILES FROM ELECTROMAGNETIC AND ACOUSTIC DOPPLER MEASUREMENTS

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ABSTRACT

An instrument is described for measuring profiles of horizontal velocity as a function of depth in the deep ocean. The method is a hybrid technique based on the principles of electromagnetic induction and acoustic Doppler and is mobile since not dependent on bottom-installed equipment. The EM method measures weak electric currents in the sea induced by the motion of the water through the earth's magnetic field. The resulting velocity profile reveals the velocity shears but is relative to an unknown, depth-independent reference velocity. The reference velocity is determined by acoustic Doppler measurements of the absolute velocity of the instrument as it nears the sea floor. The two methods are incorporated into a single freely-falling probe which measures and internally records the electric and acoustic signals and other variables such as temperature and vehicle orientation. The method yields velocity determinations every 5-10 m with an uncertainty of about ±1 cm/s. A round trip in 6000 m of water lasts about 3 hours. Data from this method have been used to study mid-ocean eddies, internal waves, and the Gulf Stream.

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INTRODUCTION

That the deep ocean is in constant motion is well known. Physical oceanographers have, however, only recently established a crude idea of the temporal and spatial energy spectra of the motion. The classical idea that the interior of the ocean is predominantly a sluggish and broad mean circulation has been proved invalid. In fact, fluctuations in the flow contain 10 to 100 times more kinetic energy than the mean circulation of mid-ocean gyres. The temporal and/or spatial variability, which we frequently denote as eddy variability, presents a formidable measurement challenge. By its very nature, the eddy field undergoes rapid temporal and spatial changes in momentum, kinetic and potential energy, density, and morphology.

Numerous other phenomena besides eddy motion are studied by physical oceanographers. The structure and dynamics of, for example, internal and acoustic waves, surface mixed layers, heat transport and mixing, and water mass tracing are areas of current research activity. We now, however, recognize that many oceanic phenomena are influenced if not dominated by mid-ocean eddies and cannot be easily studied in isolation.

To understand the generation, structure, and evolution of open ocean currents and waves requires extensive moored and mobile measurements. The observational task is to measure currents and passive quantities, such as temperature, at a number of levels between the sea surface and bottom. Current meter moorings support such measurements for long periods of time at discrete depths and geographical positions. Yet moorings are not well suited for all investigations. For example, conventional current meters and moorings are endangered when deployed in the upper 300-500 m and in intense currents such as the Gulf Stream.

An alternative approach is to obtain velocity profiles from a mobile platform rather than a stationary mooring. Velocity profilers yield nearly continuous profiles of current throughout the water column. Since the method is mobile, researchers can track a feature of interest and respond in real-time to the observations. On the other hand, mobile profilers are not easily operated at sea for more than several weeks; hence they do not yield a long time series of observations.

It is difficult, however, to obtain velocity measurements in the deep sea, especially from a mobile platform. The principal difficulty in such measurements is establishing a known and sufficiently stable reference or coordinate frame from which to make the observations. A variety of current sensors is available, but the utility of most sensors is limited by uncertainties in the reference frame through which the motion of the water is sensed. To a lesser extent, profiles of temperature, salinity, sound speed, oxygen, and other scalar variables are influenced by the motion of the observing platform. However, velocity measurements are just about useless when made at the end of a several kilometer-long cable suspended from a drifting ship.

Alternatives in Present Use. Two approaches to the problem of establishing a suitable reference or coordinate system for velocity profile measurements have been developed. The methods sense the motion of a freely-falling probe either through an array of bottom-moored hydrophones or through the earth's magnetic field. The acoustic methods use bottom-mounted hydrophones, connected to recorders ashore (Rossby, 1969, 1974) or bottom-moored transponders with data recording aboard the ship or in the falling probe (Pochapsky, 1976; Luyten and Swallow, 1976). As the probe falls and is carried by the horizontal flow, the travel times to the fixed hydrophones are used to compute the position of the probe. Velocity is calculated as the time derivative of position. This method is not highly mobile since it is restricted to operate within the previously established hydrophone array. The alternative method, which will be discussed later, uses the reference coordinate system provided by the lines of the earth's magnetic field.

Velocity Profiles from Combined EM and Acoustic Doppler Measurements. Our approach to deep ocean velocity profiling has been to develop a hybrid system operating from a freely-falling probe. Our method, which we call the Absolute Velocity Profiler (AVP), consists of instrumentation to measure electric currents in the sea arising from the motion of sea water through the earth's magnetic field. These measurements, which are made from the sea surface to the bottom, are augmented by acoustic Doppler measurements of the absolute motion of the probe as it nears the bottom. The EM measurements yield a profile of the horizontal velocity, but the profile is not of absolute velocity; rather, it is relative to a depth independent or reference velocity. This unknown reference velocity must be determined from an independent method, which in our case is based on acoustic Doppler measurements. Perhaps an illustration of how we use these two measurements would be helpful. In Figure 1, we show an EM-derived or relative velocity profile throughout the water column and the Doppler-derived absolute velocity of the vehicle near the sea floor. To eliminate the velocity offset on the EM profile, we simply shift the EM velocities to agree with the Doppler velocities over the operating region of the Doppler system ($\sim$250 m).

The advantage of this method is that it is mobile, requiring no bottom beacons or special shipboard systems. The data can be telemetered in real-time, although we rely on internal digital recording with shipboard analysis. The round-trip travel time is about 3 hours in 6000 m of water. It yields velocity measurements as frequently as every 5 m in the vertical.

The disadvantages of the method are that it is not well suited to the collection of long time series since it must be operated from a ship. The method depends on the magnitude and stability of the geomagnetic field. Hence, it cannot operate near the geomagnetic equator where the vertical component of the magnetic field vanishes, and it is subject to errors during periods of strong geomagnetic or magnetotelluric disturbances.

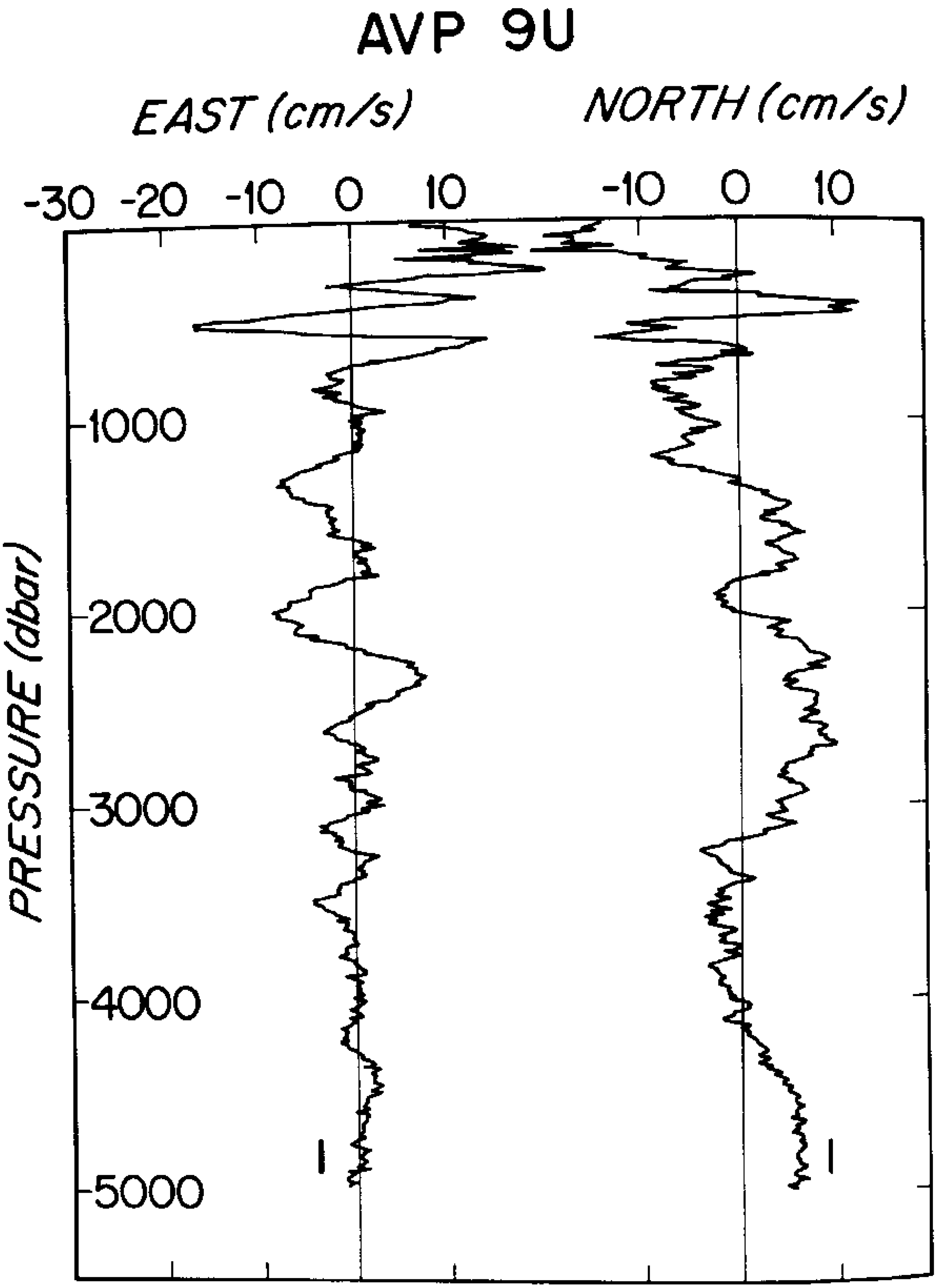

Figure 1. Relative velocity profile from the EM data for drop 9U (up). The absolute velocity components from the AD data are shown near the sea floor.

AVP SYSTEM DESCRIPTION

Basic Functions. The AVP, shown in Figure 2, consists of a cylindrically shaped vehicle from which several types of measurements are made.

Measurements are made of two, orthogonal components of the electric current density in the water. These electric currents are produced by the motion of the sea water through the earth's magnetic field. The measurement and interpretation of electric currents are discussed by Sanford, Drever, and Dunlap (1978). Thus, the surface-to-bottom velocity profile shown in Figure 1 is derived from measurements of the naturally occurring electric currents in the sea. The potential difference between the electrode posts is sensed and recorded.

The second type of measurements are of acoustic back scatter from the sea floor (Drever and Sanford, 1976). At the lower end, the AVP has a two-beam ultrasonic projector and a hydrophone. Two narrow beams of sound are directed toward the sea floor at an angle of 30° with respect to the vertical as shown in Figure 3. Due to motion of the AVP, the sea floor echoes undergo Doppler frequency shifts. The acoustic signals are heterodyned with the original carrier signal, and the resulting difference or Doppler shifted signal is recorded on an internal analog tape recorder. Spectral analysis of the analog tape determines the frequency shift and the corresponding velocity of the vehicle. The acoustic Doppler system operates within 250 m above the sea floor. The east and north velocity components are shown as the short bars on Figure 1.

The third class of measurements are of variables needed for the analysis or interpretation of the EM or Doppler data, such as orientation, pressure, temperature, and timing information.

DISCUSSION OF OBSERVATIONS

We would like to present some of what we have learned about velocity profiles in the deep ocean. Presently only a few profiles have been obtained from the recently completed AVP. However, numerous profiles have been collected with the EM technique alone without the Doppler capability.

Frequently, we collect several velocity profiles at the same location to reveal temporal changes. In Figure 4, we show two velocity profiles, the east and north velocity components versus pressure, where 1 dbar is approximately equal to the pressure increase due to 1-m depth increment. The notable features of these profiles, which were taken about 12 hours apart, are that much of the highly depth-variable structure changes between samples. In fact, many features have reversed or mirror-imaged between observations. The time variable part consists principally of inertial period internal waves. Also, the average of the two profiles is much smoother than either of the individual ones and reveals the low-frequency velocity profile. These aspects are common in our observations.

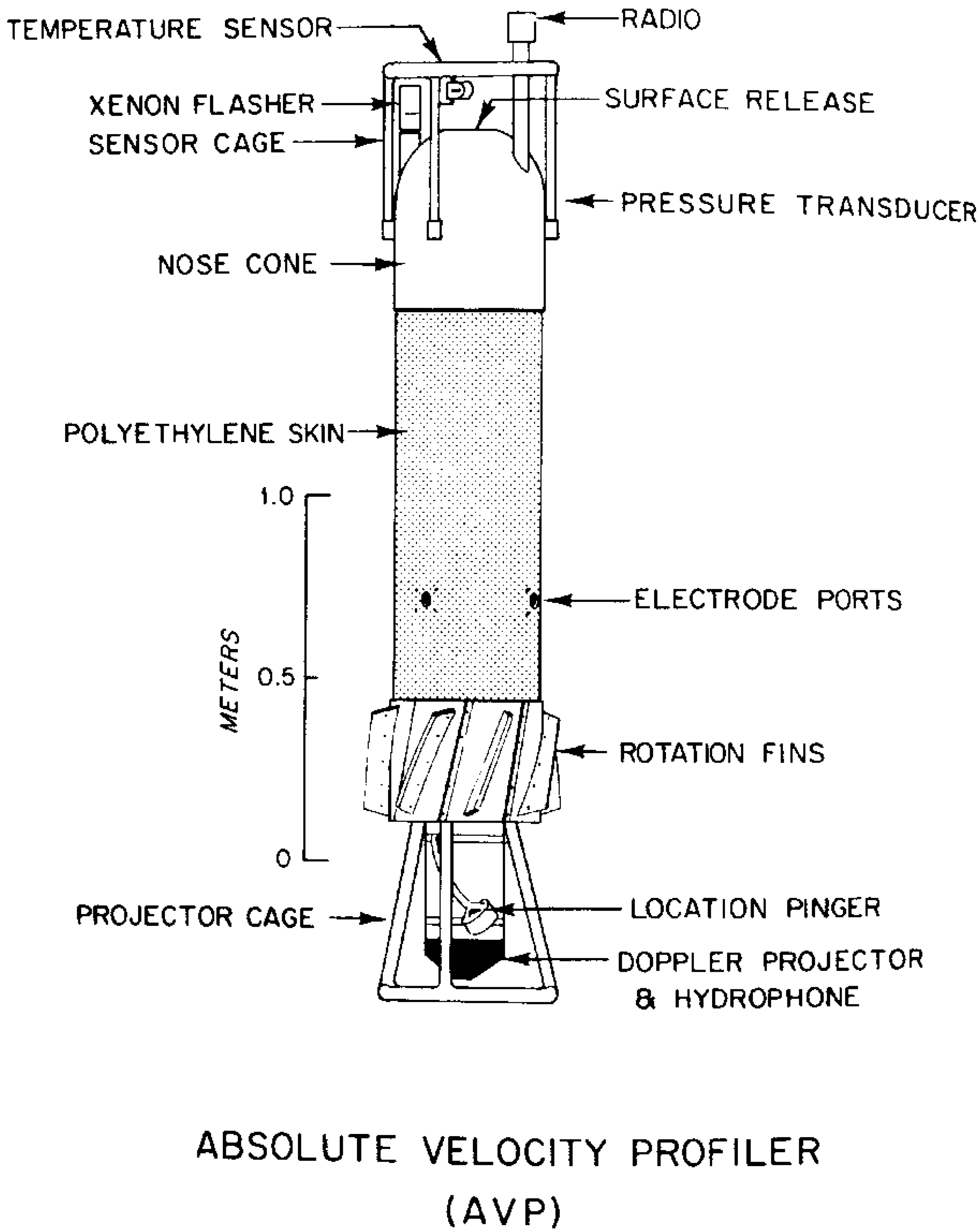

Figure 2. Absolute velocity profiler (AVP).

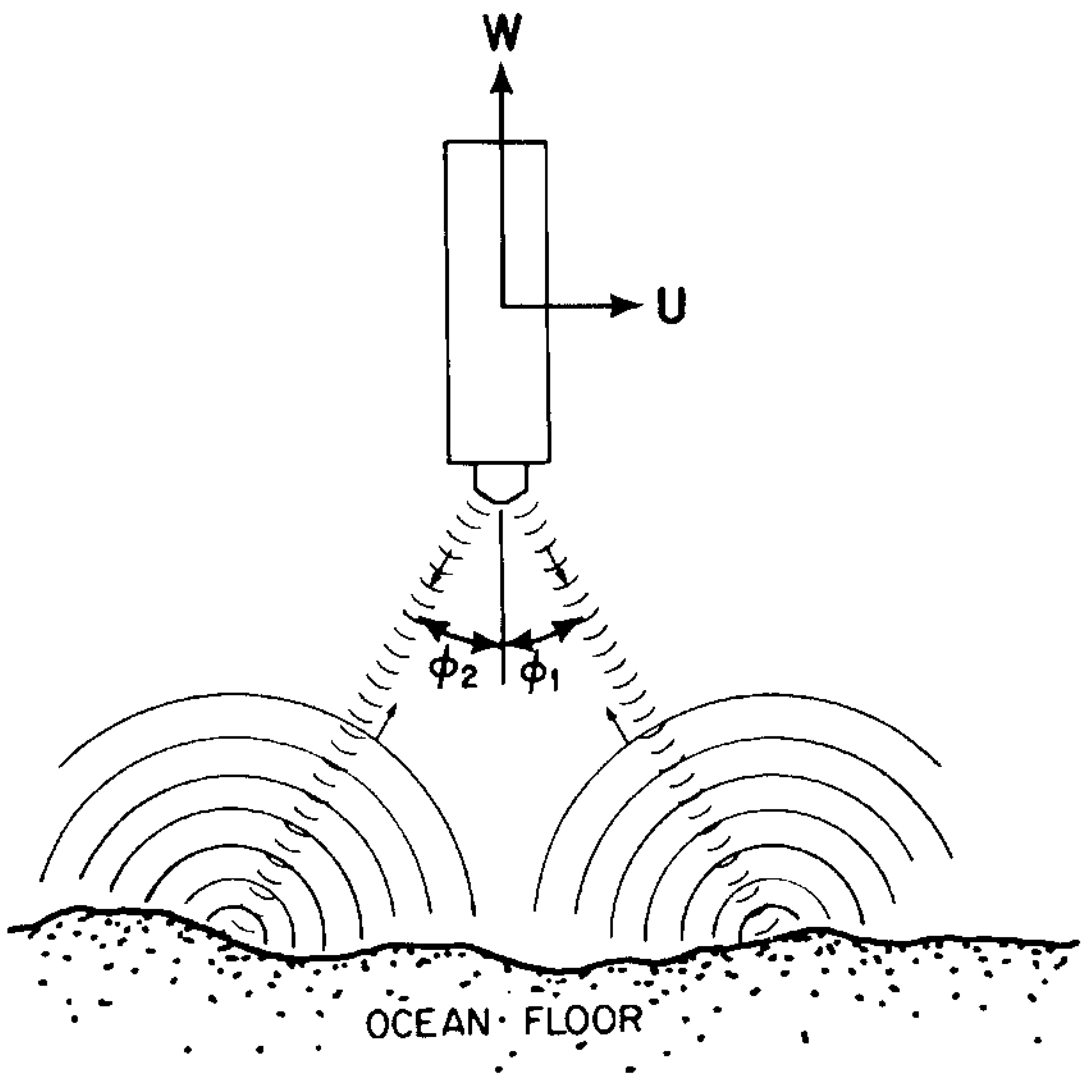

Figure 3. Schematic diagram of AVP acoustic transmissions.

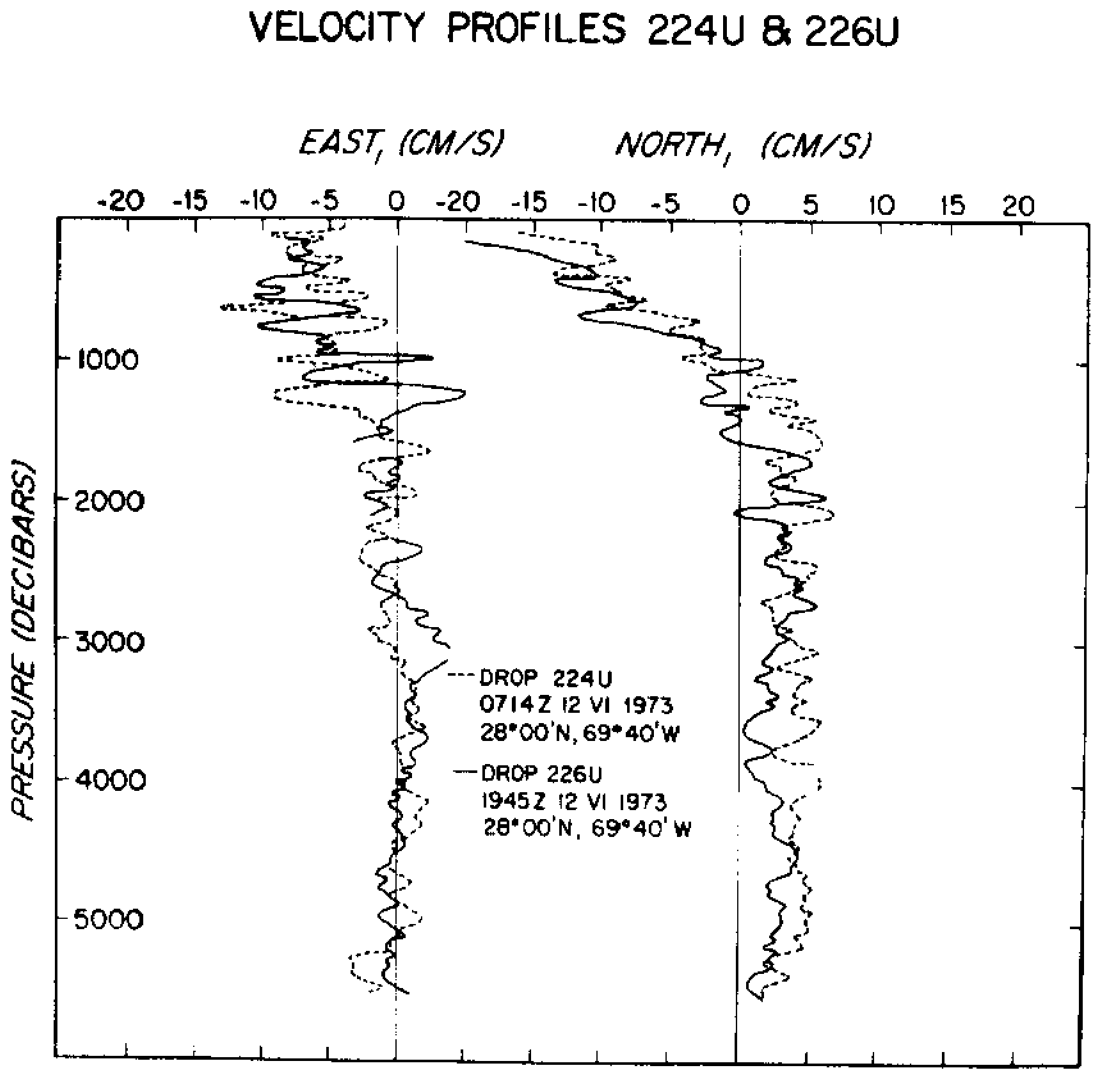

Figure 4. Relative or EM velocity profiles taken 1/2 an inertial period apart at the same location (from Sanford, 1975).

A longer time series at one location (ca-28°N) is shown in Figure 5. Again the temporal variability is evident, as are the strong velocity changes or shears between adjacent depth layers. A separation of the structure into time-dependent and time-averaged motions is shown in Figure 6. The average profile is simply the average at each 10-dbar level of the five profiles shown in Figure 5, while the other profiles are the individual profiles minus the average. About two-thirds of the time, variable kinetic energy is contributed by near-inertial period motions.

A dramatic view of the time-depth behavior of the inertial motions has been constructed by Leaman (1976). Leaman removed the mean from a 5-day time series of 20 profiles, just as was shown in Figure 6 for 5 profiles. Rather than presenting the data as we have in Figure 6, he contoured the zones of positive and negative values for the east and north components. His result is shown in Figure 7 for the east component. The tendency for the zones of positive or negative values to migrate upward in time demonstrates the presence of internal waves having upward phase speeds. The alternating signs at any level every 12 hours shows that the dominant period is approximately diurnal-inertial (24 hours).

Because of the mobility of the method, we can deploy two instruments at any horizontal separation to study spatial variability. We have several examples of profiles taken simultaneously at up to 15-km separation. Figure 8 shows two profiles taken about 100-m apart. The profiles are nearly identical; the differences between them are about the expected 1 cm/s r.m.s. noise of the method. At a larger separation, two simultaneous profiles will be more different, as shown in Figure 9.

CONCLUSION

The AVP is an operational hybrid acoustic Doppler and EM profiler having a measurement uncertainty of about ±1 cm/s r.m.s. It is completely mobile since it is not dependent on bottom moored beacons or hydrophones or moorings. It requires 2 to 3 hours, depending on water depth, to complete a round trip. Operation of the method is restricted to regions of strong vertical magnetic field.

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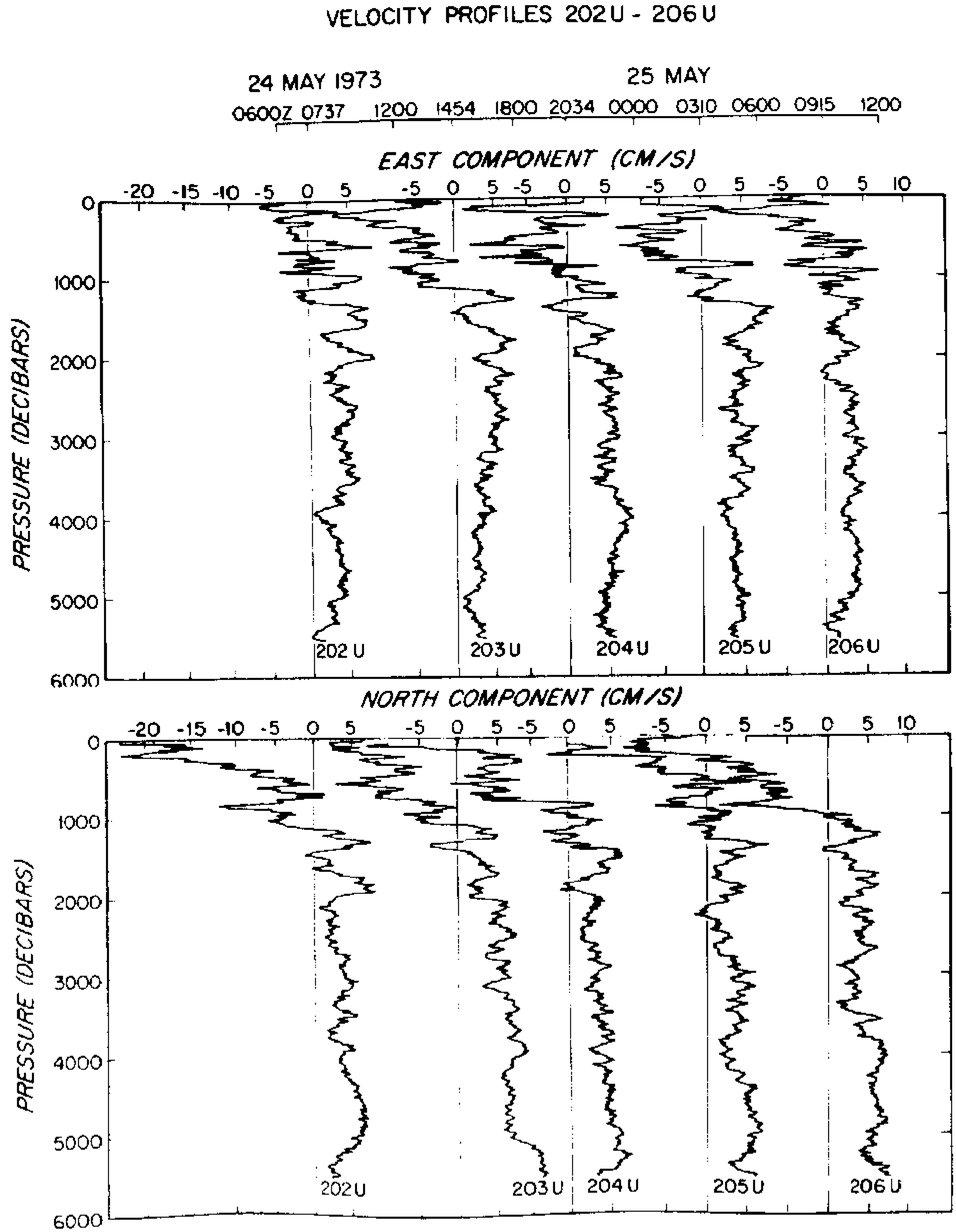

Figure 5. A 1-day series of EM-derived velocity profiles (from Sanford, 1975).

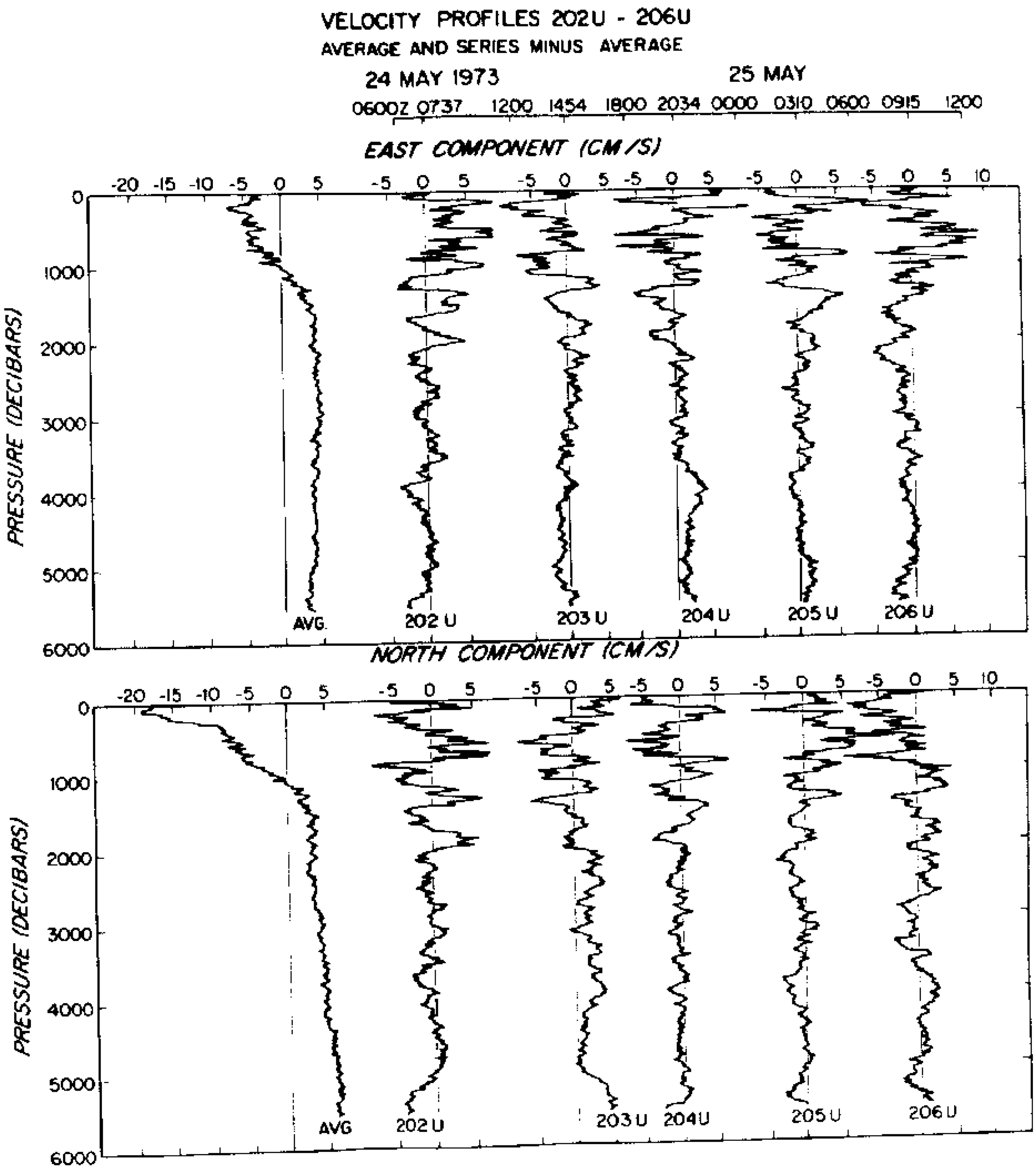

Figure 6. The time average and fluctuations of the 5-profile series shown in Figure 5 (from Sanford, 1975).

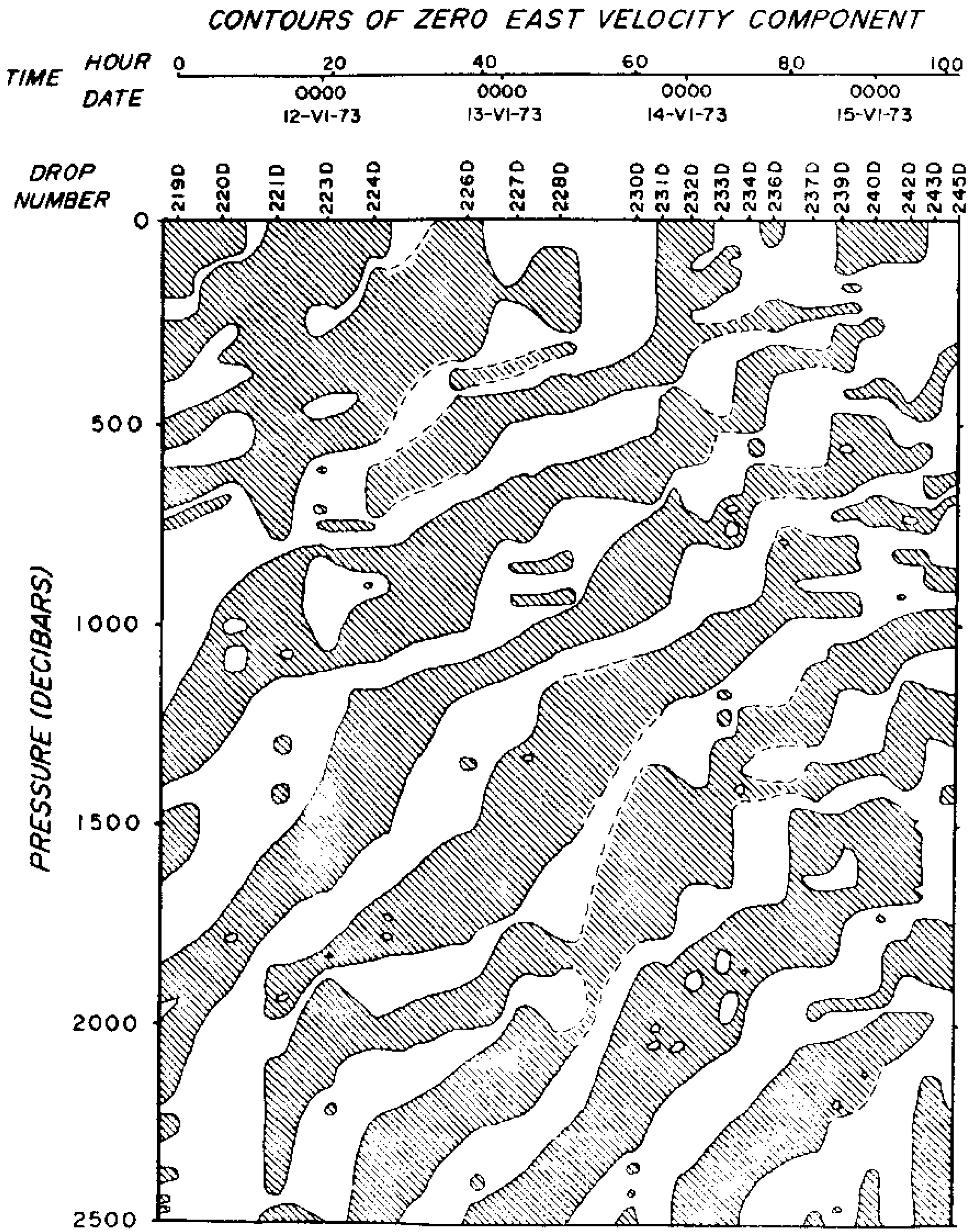

Figure 7. Contours of east velocity component after the 5-day mean velocity profile has been removed. Negative east components are indicated by hatched regions (from Leaman, 1975).

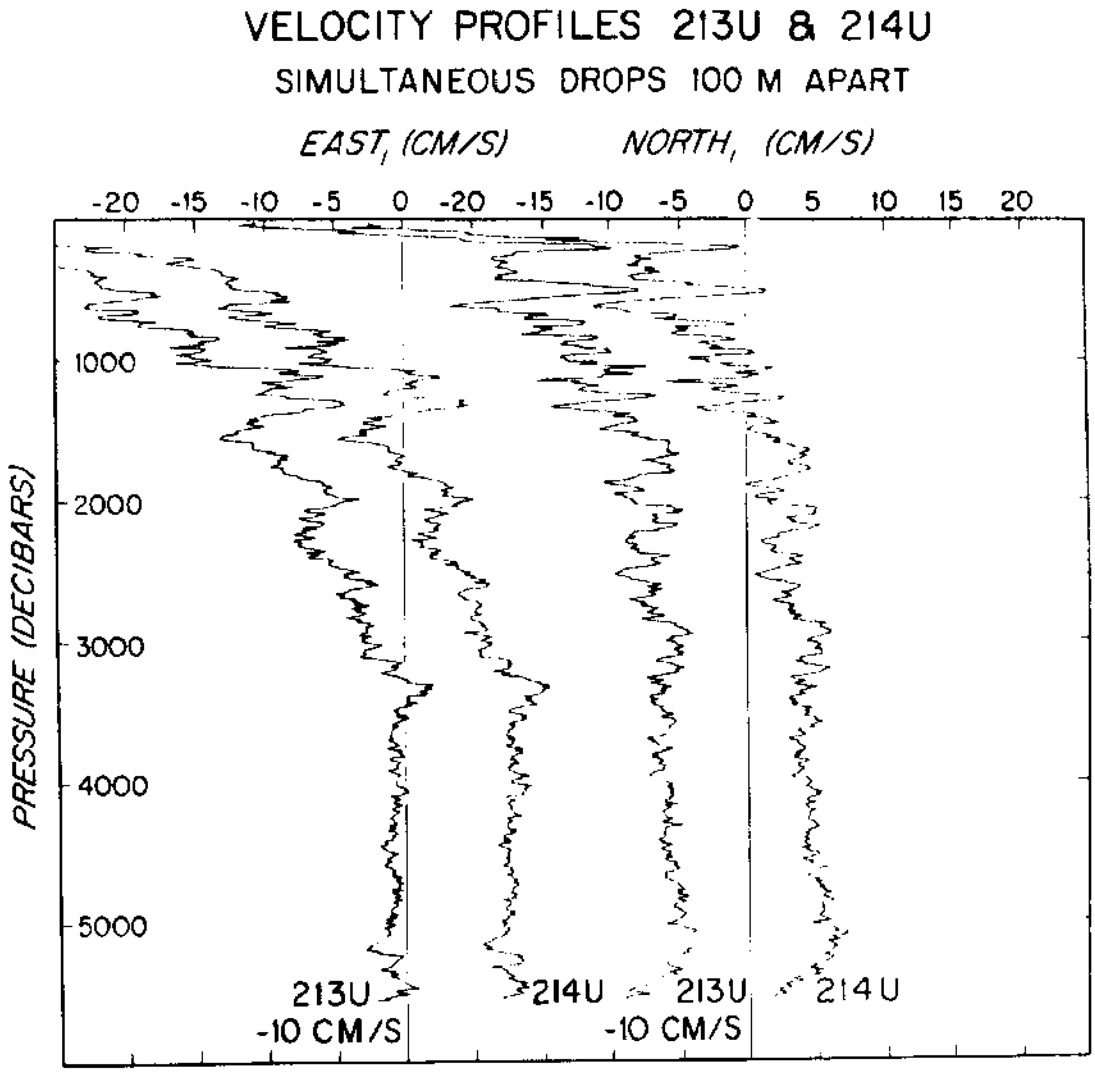

Figure 8. Two velocity profiles obtained from two EM profilers launched at the same time at a horizontal separation of 100 m. Profile 213U has been offset by 10 cm/s (from Sanford, 1975).

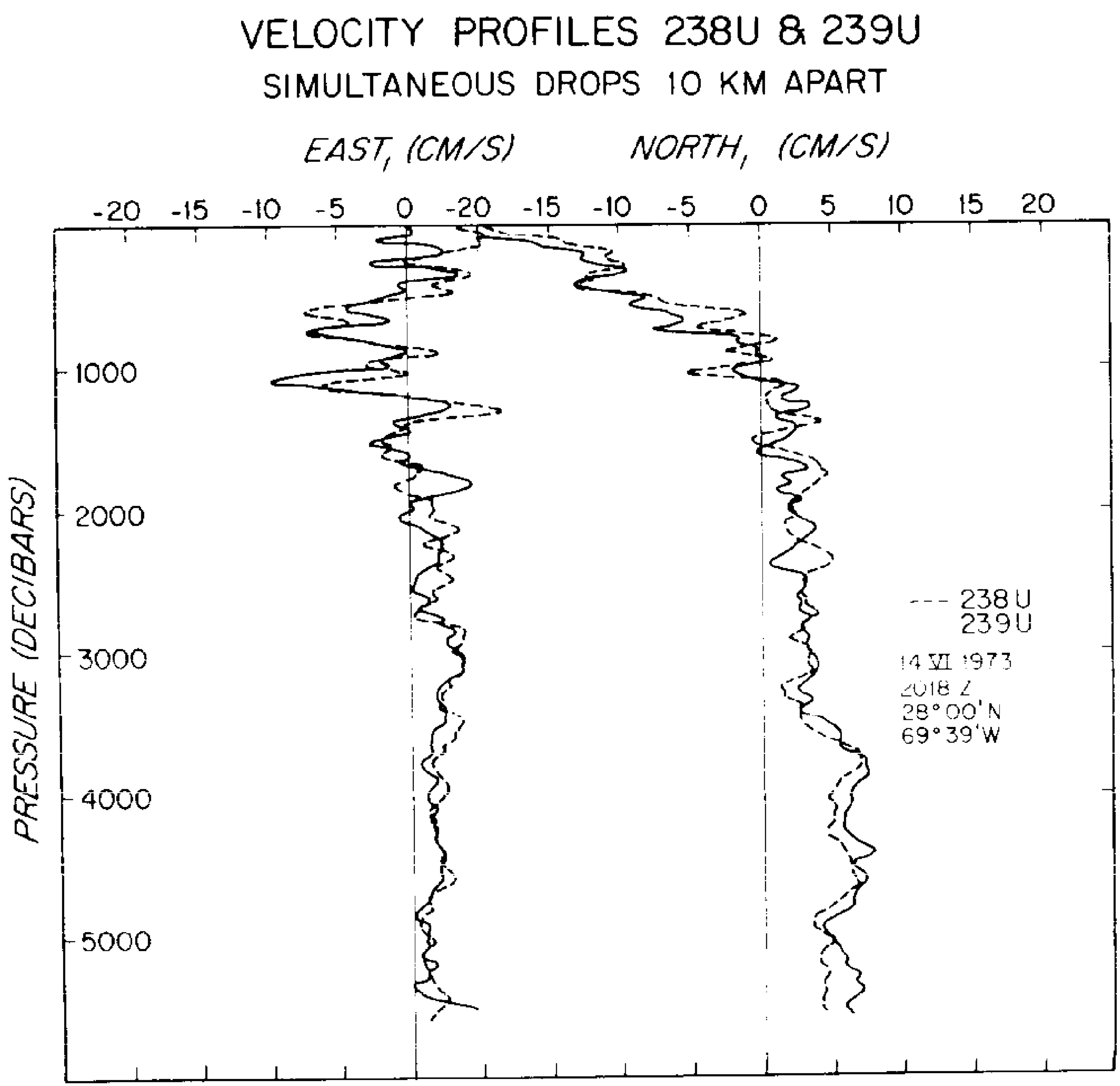

Figure 9. Two simultaneous velocity profiles taken 10 km apart. Profile variations of vertical wavelengths less than 100 m have been filtered.

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CMICE 76: A CURRENT METER INTERCOMPARISON EXPERIMENT CONDUCTED OFF LONG ISLAND IN FEBRUARY-MARCH 1976

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ABSTRACT

A current meter intercomparison experiment (called CMICE 76) was conducted about 6 km off the southern coast of Long Island near 40°47'N, 72°30'W during February and March, 1976. A total of 20 current meters were deployed on six moorings set in a roughly linear array parallel to the local coastline and topography. The instruments included the Aanderaa RCM-4, the AMF VACM, the Brookhaven National Laboratory spar buoy system using cylindrical and spherical Marsh-McBirney electromagnetic sensors, the EG&G 850 and CT-3, and the Chesapeake Bay Institute-modified ENDECO 105. Local mean water depth was 27.8 m and current meters were clustered near four depth levels (3.5 m, 7.4 m, 15.7 m, and 25.0 m). Wave data were also obtained at the array site, and 10 m wind and tidal data were obtained from nearby coastal stations. Intercomparisons of one hour vector average velocities measured with similar instruments deployed near the same depth level indicated sufficient horizontal homogeneity that most differences in the observed current data have been atrributed to real differences in instrument and mooring performance. Detailed discussions of the observed data, instrument and mooring characteristics and performance, and the effect of surface wave and wave-induced mooring motion on different measurement systems are presented.

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Before the recent series of current meter intercomparison experiments, physical oceanographers held a common impression that surface wave motion and mooring motion could generate spurious signals in current meter records. A group of coastal oceanographers at the November 1975 ASLO/MESA Mid-Atlantic Bight Symposium in New York felt, however, that there were insufficient details known on the performance of instruments under varying wave and mooring conditions. This lack of knowledge hampered not only the development of improved instrumentation, but also the informed choice of available instruments and mooring systems for particular applications. The CMICE 76 experiment was planned with the primary objectives to (1) add to the knowledge of these performance details and (2) to satisfy the scientific curiosity on the part of the participants as to how their traditional instrumentation and mooring systems performed in comparison to others.

The 20 current meters were deployed on six moorings in a line approximately parallel to local topography. The moorings were of three basic types: buoyant tethered spar, taut-wire subsurface float, and slack or compliant mooring with surface float (Figure 1). One of the taut-wire moorings (No. 5) had a surface spar buoy attached to the subsurface float. The moorings were in place in January and February 1976, during the season when vertical shears were expected to be a minimum. The mooring interval was sufficiently long to allow comparison of instrument performance under a variety of conditions, both low contamination stress (high mean currents, small surface waves) and high contamination stress (low mean currents, large surface waves).

The results have been collected in a report (WHOI-77 62) and will be summarized in a forthcoming publication. The principal analytical tools employed for comparison were (1) direct comparison via speed versus time overlays, (2) speed-speed scatter plots, (3) velocity stick diagrams for low-passed records, (4) velocity scatter diagrams, and (5) progressive vector diagrams.

The intent in the report was to provide analysis to allow the reader to extract relevant information on instrument and mooring performance and apply it to his particular current measurement problem. On one hand, the desire in the analysis was to avoid overspecifying criteria and needs and to avoid the attendant biases of the shallow-water oceanographers who were participating in the experiment. On the other hand, there was a desire to provide sufficient analysis to allow the reader to ascribe the observed performance differences to known sensor behavior.

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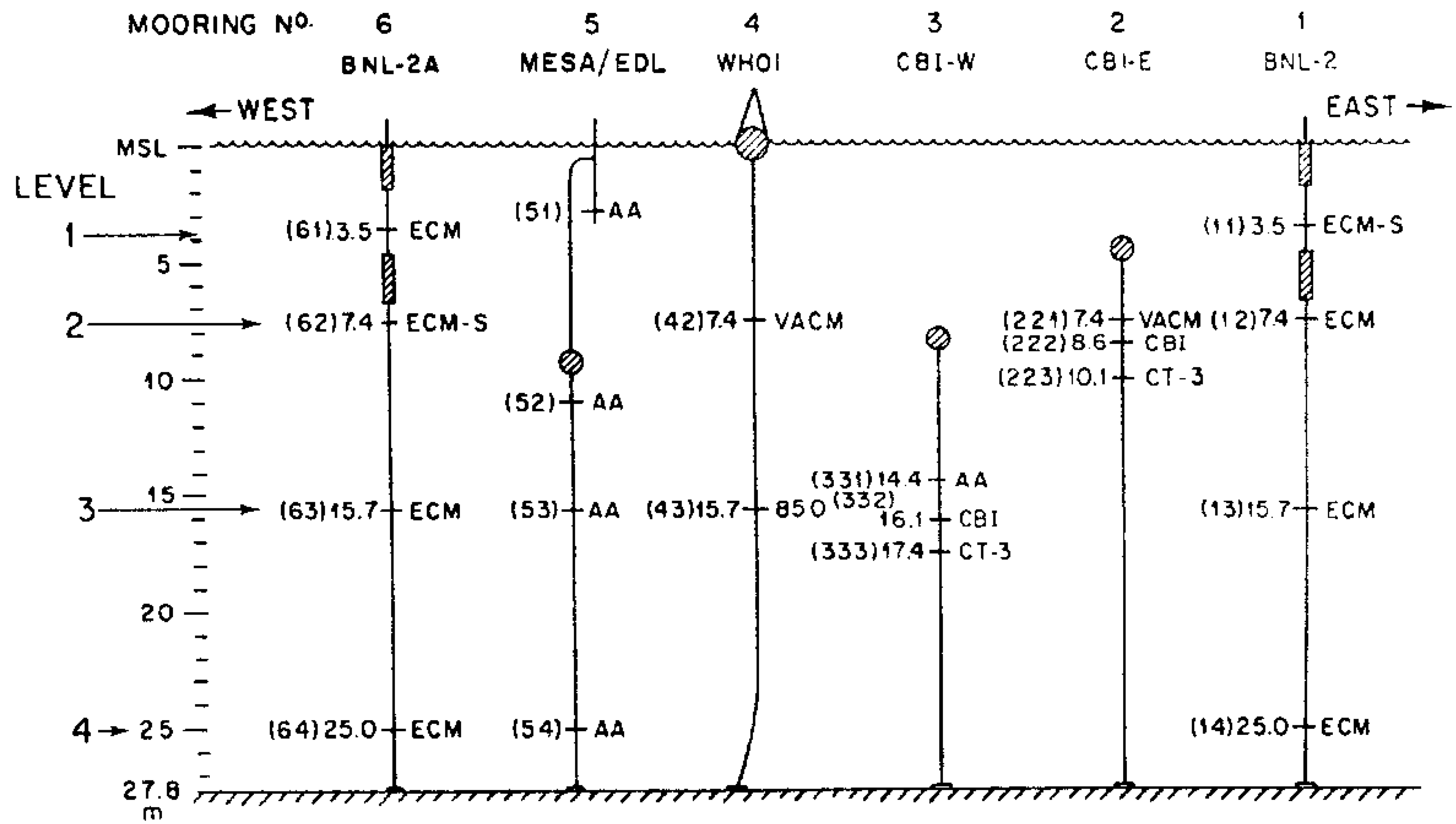

Figure 1. Schematic sideview of CMICE 76 array, showing locations of instruments and instrument code.

THE OCEANIC EDDY FIELD: COMMENTS ON EXPLORATION AND TECHNOLOGY

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ABSTRACT

The past decade yielded a substantial improvement in our perception of the oceanic eddy field, and some new ideas and information on the general ocean circulation. Eddies are observed to be most intense in the vicinity of particular strong currents, and eddy-resolving gyre-scale numerical models unanimously "predict" a similar spatial coincidence of energetic eddies and mean flow. These models are dominated by eddy-mean flow interactions, in both directions, and if realistic, imply that joint investigations of eddies and the general circulation are warranted. The observational segment of future programs in this area of research will probably be based on the use of essentially the entire technological spectrum, including both existing capabilities and likely new developments.

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In our opinion, the last ten years have witnessed a quantum jump in both descriptive and theoretical insight into the properties of low frequency variations (periods longer than a day or so, interchangeably referred to as eddies) in ocean currents and temperatures. The eddy field has been observed to be horizontally inhomogeneous in its fundamental properties such as energy level, Reynold's stresses, relative vertical structure, and spectral shape. This geographical inhomogeneity, involving for example orders of magnitude of variation in energy level and qualitative changes in relative vertical structure, is connected to the pattern of the general ocean circulation (Dantzler, 1976, 1977; Schmitz, 1976, 1977, 1978; Wyrtki, Maagard, and Hager, 1976). Results from numerical models have several similar general characteristics (Bretherton and Karweit, 1975; Holland and Lin, 1975a,b; Holland, 1976, 1978; Owens, 1975; Rhines, 1977; Robinson, Mintz, Harrison, and Sempter, 1977). In particular, gyre-scale eddy-resolving numerical models unanimously yield a spatial coincidence of energetic eddies and mean currents characteristic of the most basic observations of the field. Exploration of the distribution of the properties of the eddy field is in its embryonic stages, and we hope that the next decade will see a continued interest in this area of research.

These remarks are based on investigations at a variety of institutions using essentially the entire spectrum of measuring techniques available. With respect to our own experience using moored instrument technology, emphasis on quality control has been decisive. Subsurface moorings are now routinely deployed for a year or so with nearly 100% likelihood of retrieval. Approximately 90% data return has been achieved and maintained over the last four years, during which time our data base has exceeded that acquired in the previous twelve. The 90% figure for "overall" data return is based on 95% return from "broken-in" instruments and around 60% for first deployments. Equipment and quality control budgets are typically a small fraction of the total cost of published data.

We are also beginning to get reasonable direct estimates of the properties of time-varying fields at very low frequencies (or the general ocean circulation), although horizontal and temporal scales are not sharply defined. Classical descriptions of the general circulation (Worthington, 1976) focus on the baroclinic field, and the depth-independent component of the general circulation is relatively unexplored, although known to be important in the Gulf Stream and its re-circulation (Schmitz, 1977, 1978). Given the observation that the most energetic eddies are found where there is a significant mean flow, and given models dominated by eddy-mean flow interactions, predictions of the demise of general circulation oceanography (Munk and Worcester, 1976) seem cursory, and we hope that research in the next decade will continue to see attention paid to both scales of variability and their interaction.

Further exploration of the eddy field/general circulation will probably not be dominated by any single observational method or one group of scientists or one oceanographic institution. Broadly based contributions with respect to both personnel and methodology seem more probable. Candidates would be: (i) An evolving sequence of large-scale and long-term deployments of moored instruments (with continued emphasis on quality control). The capability for making such measurements in the upper ocean and in strong currents needs to be developed. The need for long-term near-surface data requires the ability to work around the fouling problem as well as average over surface gravity wave frequencies. (ii) Deployments of SOFAR floats and satellite-tracked drifters on general circulation scales. The major new development of the past decade, in terms of impact on oceanic eddy investigations and perhaps general circulation research as well, has been the SOFAR float system (Rossby and Webb, 1970, 1971; Rossby, Voorhis, and Webb, 1975; Freeland, Rhines, and Rossby, 1975). The very nice recent development of autonomous listening stations by Bradley (1977) makes SOFAR float deployments feasible on any scale in most oceans. (iii) We should benefit from enhanced shipboard and airborne survey capabilities, which should be oriented toward direct current measurements as well as conventional hydrographic observations. (iv) It seems appropriate to place a broad general priority on remote sensing, using for example acoustic and/or satellite techniques.

ACKNOWLEDGMENTS

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OCEAN ENGINEERING/CONSTRUCTION

Session Chairman: Richard I. Scarlet
EG&G, Environmental Consultants

THE INCOMPLEAT CURRENT METER

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ABSTRACT

Engineering and construction activities in the ocean require information on currents over a wide range of speeds, depths, and time scales. Many current measurement programs are hampered by lack of complete integrated systems to acquire the necessary data. Measurement accuracy is frequently degraded by mooring motions. Mooring suspensions for near-surface and near-bottom measurements are difficult or incompatible with other requirements. Data recording techniques limit deployment periods or undersample processes. Telemetry of data or system status is rarely available.

Unlike scientific studies, which may choose to focus on some aspects of the currents at the expense of others, engineering studies must determine all those features of the currents which will impact the intended activities or structures. Examples of the effects of all these instrument limitations on particular studies have been encountered in recent EG&G studies. Methods to surmount these difficulties have been developed, but better current measurement systems could provide considerable improvements.

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Engineering and construction activities in the ocean require information on currents over a wide range of speeds, depths and time scales. Many current measurement programs are hampered by the unavailability of complete and flexible systems to acquire the necessary data. Typical examples of these limitations are reviewed below. In almost all cases, methods are available to circumvent the particular limitations, but they are frequently costly and time-consuming. It is hoped that consideration of these problems will lead to development of better measurement systems.

At the outset, it is worthwhile to consider the accuracy requirements for the systems. Inaccurate measurements as input to engineering plans can lead to expensive overdesign, or dangerous (and ultimately even more costly) underdesign. But it is crucial to remember that it is the total system accuracy that counts. A bi-axial sensor with cosine response accuracy of 2% is fine, but it may have to be mounted in-line on a mooring that tilts up to 20°, leading to actual 6% errors. A sensor that is linear within 2% up to its peak reading of 200 cm/sec is likewise fine, but it is dangerously deceptive if speeds exceed 200 cm/sec. And data from excellent current meters, which can't be moored shallow enough, near enough to the bottom, or long enough, will have to be extrapolated, introducing new and unknown errors. Thus, in most cases, the accuracy of the actual sensors is not the limiting factor in the overall data accuracy.

Errors caused by tilt and other mooring effects (vibration, hydrodynamic shielding) are often a significant and unknown problem. Typical anchor, cable and float moorings will tilt, vibrate, and oscillate with short-period current fluctuations (such as internal waves). Information on these motions during a study is often unavailable, and their effects on the measurements are usually not known. Tilt sensing in the current meters, pressure (depth) sensing somewhere on the mooring, and various schemes of decoupling the meter from at least some of the mooring motions are partly helpful remedies. Instrument decoupling from tilt and vibration is an area in which there is much confusion, many claims, and few hard facts. Meters that are successfully tilt-decoupled may be "better" on simple tilt moorings, but "worse" on a mooring subject to vertical heave due to a surface float (such as tested for by NOIC).

Mooring dynamic response to internal waves is probably a more frequent problem than we now realize in continental shelf areas. Studies in several areas have shown internal wave currents well in excess of 1 knot. Mooring resilience at the relevant frequencies tends to cause under-recording of these currents, and data sampling and averaging schemes optimized for long deployments may average them out. This may not be a problem for research focused on much lower frequencies, but it can cause problems in engineering studies seeking to measure the largest total current. In general, the trend toward long-period averaging can lead to misleading results unless there is a solid data base to verify the absence of energetic shorter-period events.

Microprocessor control of data recording should lead to more powerful data sampling schemes to solve these problems. Similarly, they may help to solve the over-range and zero-speed problems that occur in many instruments. Undetected over-ranges can obviously cause an instrument to miss the data most important for engineering use. Most current meters can be set to handle fairly high speeds, but only at the cost of significant degradation of resolution. A common zero-speed problem is that recorded data frequently do not distinguish between true zeroes and electrical or mechanical malfunctions.

Measurements near the surface, in the presence of waves, are a difficult problem which will have to be addressed by significant further research. Many current meters are also very difficult to use near the bottom. Measurements less than a meter from the bottom are often desirable, but the shapes of current meters and anchors keep this from being a simple matter. This is a good example of a nuisance as opposed to a real technological block, as it is usually possible to "rig up something." But the cost in time and dollars should not be ignored, and it is typical of the problems that make it necessary for EG&G to maintain six different types of current meters in order to respond to most of our clients' needs.

As anyone who has worked with even two different types of current meters will probably appreciate, intercompatibility of recording formats is virtually non-existent. Even manufacturers who choose similar tape recorders generally change word and record lengths so extensively that tape readers and software have to be extensively modified to handle the data from the different sources. Now that computer manufacturers are beginning to achieve some limited degree of standardization, perhaps the same trend may begin in ocean instrumentation.

In fact, from a user's point of view, it is probably not too soon to appeal for the sort of measurement system approach to ocean instruments that is becoming common in the laboratory. A single "sequencer/recorder" on a mooring could communicate with multiple current, temperature, tilt, etc., sensor packages using an interface protocol suitably designed for oceanographic cable. This could also solve such problems as the difficulty of obtaining real-time data, or even system status, from an array in the ocean. Presently available electronic components make such a system approach feasible, but although some special systems show the beginning of a trend in this direction, considerable "push" will be needed to get our oceanographic instruments up to this state of the art.

OCEAN CURRENT MEASUREMENTS IN SUPPORT OF HYDROCARBON EXPLORATION AND PRODUCTION

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ABSTRACT

The exploration and production of hydrocarbons in offshore areas are affected by both average and severe ocean currents. Current measurements, for design information, are obtained either through joint industry programs or individual company efforts. The lengths of the measurement programs vary according to the specific application. Measurement programs typically use reliable, state-of-the-art moorings and instruments.

This paper discusses industry's need for current data, the required accuracy, and some typical examples of efforts. Also discussed are the concepts of proprietary data and the necessity for timely access to data obtained during government and government-sponsored measurement programs. Comments are presented as to how this conference can aid in fulfilling the mutual as well as exclusive goals of government, industry, and academia.

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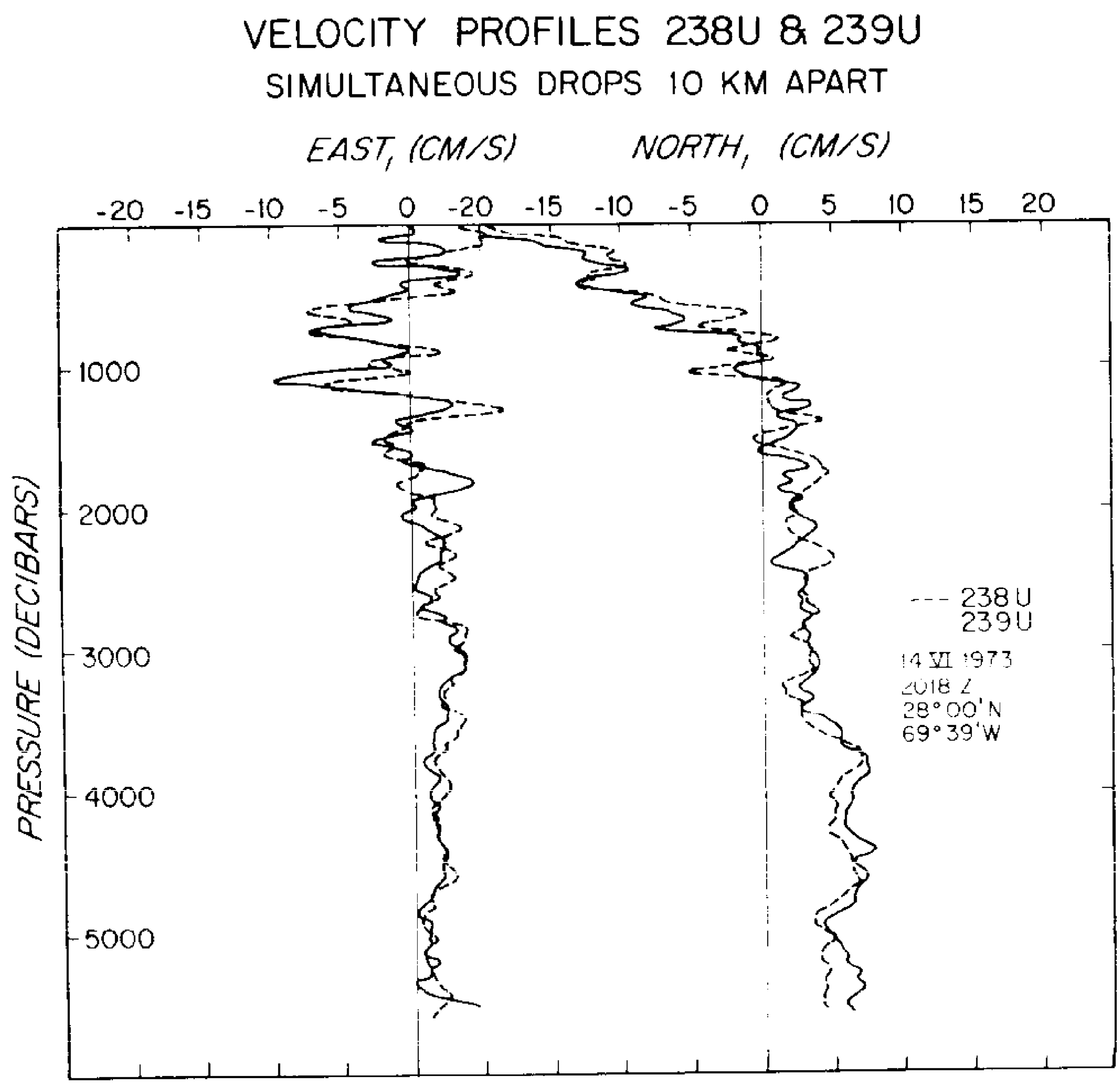

Figure 9. Two simultaneous velocity profiles taken 10 km apart. Profile variations of vertical wavelengths less than 100 m have been filtered.

Another use of current meters not directly related to currents is in the estimation of directional wave spectra. If a measure of the instantaneous current speed and direction is known in conjunction with wave staff data, the methods of Panicker and Borgman (1974), for example, may be used to obtain directional spectra.

ACCURACY

Accuracy is related to the nature of the given problem. Typically, accuracy requirements on current measurements for engineering applications are on the order of plus or minus 5% for speed, and plus or minus 5° for direction. Current speed values are important in the calculation of drag forces or lift forces since both depend on the square of the velocity. Therefore, an accuracy of 5% in the velocity measurements yields an accuracy of 10% in the force determination, which is usually considered adequate for engineering purposes.

Also, the accuracy requirement for currents is not very high because these values are averages on which confidence limits are placed. In the case of maximum extrapolated current values, confidence limits are placed around these estimates so that the absolute value of the current used for this purpose need not be known to within less than 5%. On the other hand, there are special cases where the accuracy requirements are much higher. In the determination of wave spectra or currents for wave force determination on a particular member, an accuracy on the order of 2% is desirable. In addition, current meters must respond reasonably well to flows which are not perpendicular to the axes of the meters.

HOW MEASUREMENTS ARE OBTAINED

Measurements are usually obtained through either a joint industry program or through the efforts of an individual company. One of the goals of this conference should be to enlist government-run, government-sponsored activities in the common endeavor and thereby broaden the overall data base. To date, the most notable industry effort has been the Ocean Current Measurement Program (Forristal et al., 1977) operated by Shell in the Gulf of Mexico for the past five years with funding from Shell, Mobil, Amoco, Exxon, Seadock, Brown and Root, Chevron and Pennzoil. In the North Sea, there has not been such a massive industry program. However, through the United Kingdom Offshore Operators Association (UKOOA), cooperation has been fostered among the oil industry, the government and the scientific community. UKOOA has set up a vehicle through which information and data may be exchanged. Measurements obtained by individual companies are thus accessible to other companies, the government and the scientific community under mutually agreeable terms. Exchange agreements typically cover access to reports of data analyses.

Mobil has developed three major measurement programs to date, two in the North Sea [in the Statfjord (500 ft) and Beryl (400 ft) fields], and one off the coast of Texas in the East Breaks (1100 ft) area. The purpose of all three programs has been the determination of operational and maximum design values for the construction and installation of platforms and other facilities. An attempt was made during the installation of the Beryl Condeep gravity platform to measure currents in real time using a current meter and its acoustic transmitter. Acoustic noise in the area prevented the transmitted signal from being received. As an alternative, meters were manually lowered over the side of the vessels for the eventual determination of the force on the platform at any instant in time during the installation. Current measurements at Beryl, taken at least at three depths, spanned a period of approximately two years, while measurements at Statfjord began in September 1977 and consist of two strings of three current meters each. The current meter string off the coast of Texas was operational for approximately a year and consisted of measurements at four depths. Unfortunately, Hurricane Anita passed very close to the station and subsequently, the string was reported missing. Attempts at recovery are still being made.

INSTRUMENTS

Figures 1 and 2 show typical remote current meter installations as well as an installation on a fixed platform. Remote instruments are used if the platform is of sufficient size to seriously disturb the flow or if no fixed structure is nearby. The remote string is least desirable because it is relatively unprotected, and thus subject to damage by fishing boats, supply boats, and other boat activity in the area. Also, it does not provide real time information. At this time, a satisfactory, economical system is not available for transferring real time current information from remote strings to a fixed location.

A variety of types of instruments are used in current meter strings. Out of the wave zone, Mobil typically uses Savonius rotor meters. At Statfjord, two devices have been placed near the surface in an attempt to eliminate transient contamination. One is a new meter, an acoustic device, and the other is a specially modified meter with a Braystoke-type impeller.

Mobil prefers to rely on electromagnetic meters in the wave zone because of their faster response. In the East Breaks area, a Savonius rotor, a ducted meter, and two electromagnetic devices were placed near the surface to gain reliability and to provide a basis for comparison of the instruments in the wave zone. Results of this deployment are being analyzed and should be available soon.

A major problem in loss of data stems from the reliability of the recording systems and batteries within the current meters. The main cause of lost data, however, is trawler and other boat activity in the area.

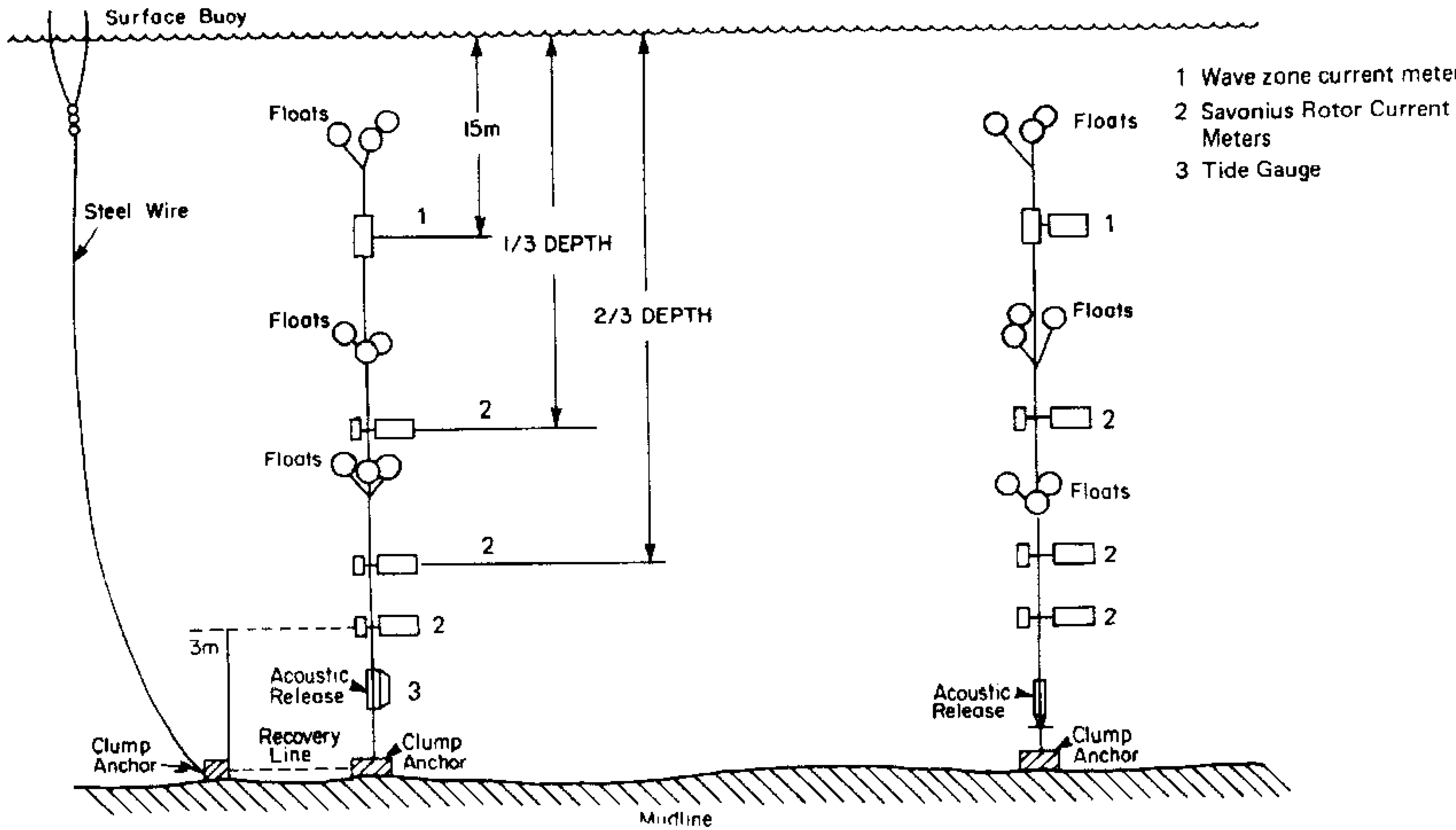

Figure 1. Typical Instrument Arrangements for Anchored Systems.

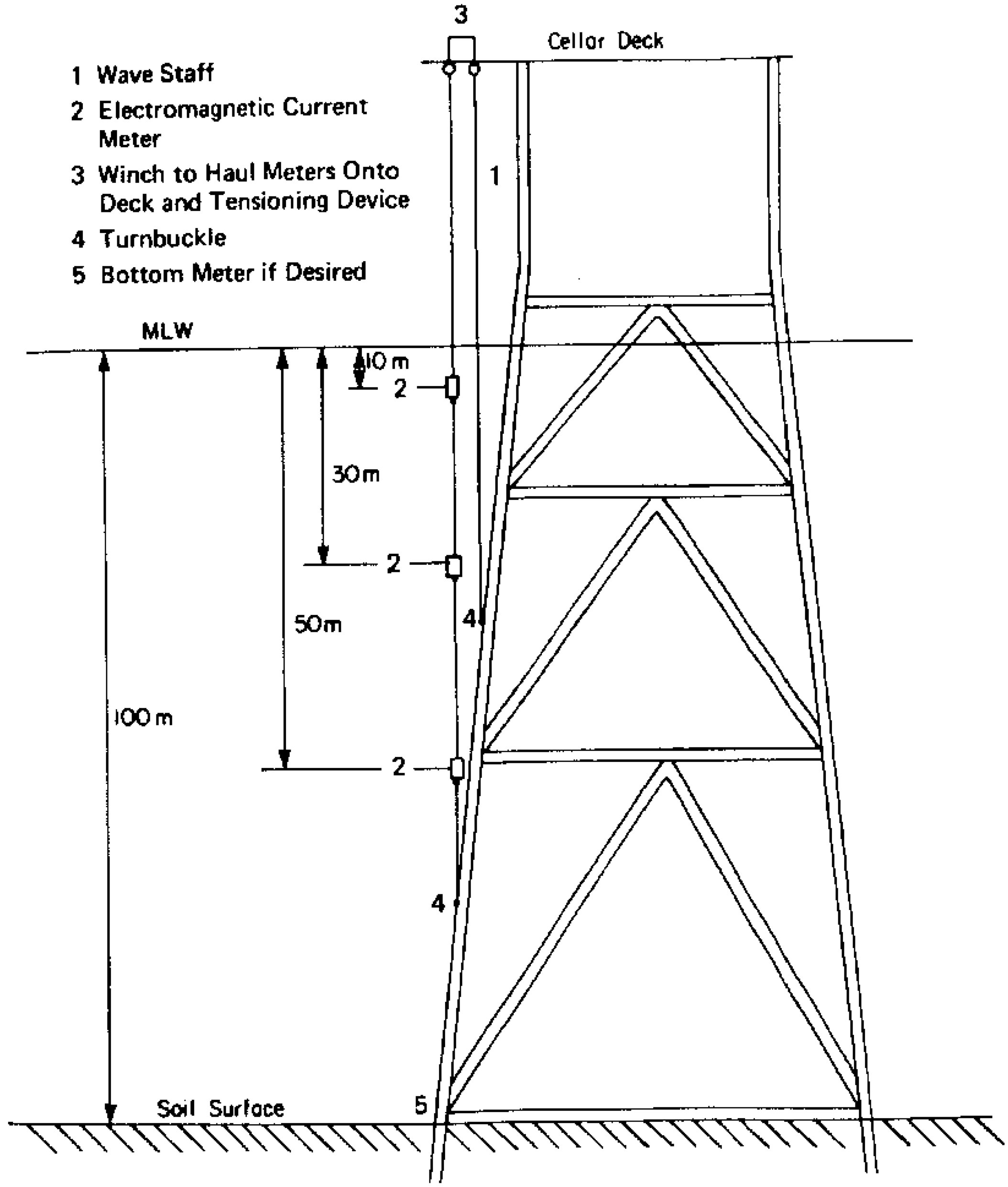

Figure 2. Typical Platform Instrumentation Mounting Scheme.

A U-shaped mooring is used to provide three alternatives for recovery of a current string. The acoustic release is the preferred method of recovery since the instruments are separated from the mooring itself. The anchor and balance of the mooring are then retrieved independently. If the acoustic release fails, recovery is accomplished by retrieving the entire string, starting with the surface marker buoy. The third mode of recovery is to drag for the recovery line; this method is a last resort, as there is a good chance of instrument damage or mooring loss.

RECOMMENDATIONS

All in all, we are pleased with the performance of instruments that are presently available for use out of the wave zone, although a less expensive, non-mechanical device would be preferred.

Telemetry of real time data is one of the problem areas left to conquer. An efficient, relatively cheap telemetering meter that can be used in the presence of acoustic noise and radio interference does not exist to our knowledge. The most room for development in the current meter realm is in the development of a three-dimensional current meter. Such a meter would have a large variety of uses and would improve force calculations greatly.

The greatest benefit that can possibly come from this working conference is for us to recognize each other's objectives. These objectives, which sometimes overlap, vary from individual to individual, institution to institution and company to company. We can all accomplish our objectives with minimal investment through cooperative programs if we do not lose sight of the fact that current measurements are gathered for particular purposes. Cooperation among the interests represented here should be encouraged so that valuable time and manpower are not wasted trying to meet duplicate objectives through duplicate programs.

Perhaps the most important issue that requires further explanation is the insistence on the part of the industry that data remain proprietary. One reason for this policy is the improvement of a company's competitive position. Another reason is to assure funding of joint industry programs of a similar nature in the future, not to keep information hidden. The practical incentive for joining these expensive programs is access to the data. Until a better means of funding is devised, these two reasons will determine industry's attitude. Joint funding schemes between government and industry would present a strong case for making the data available to all.

Another point in need of clarification concerns the availability of data from government- and university-funded programs. Such data are sometimes invaluable to the industry, as they are often the first such data in an area. Such efforts include the BLM programs in the Bering Sea, Gulf of Alaska, Georges Bank, and the Baltimore Canyon.

A problem arises since data are not released in a timely manner, because of the number of offices that the information has to go through before it finally reaches NODC, where it can be released. We find it difficult, at best, to obtain data of this type in less than three to six months. Our intention is not to deprive anyone of his legitimate claim to authorship or right of publication; we simply wish to obtain the information vital to the estimation of safe, reliable design values.

SUMMARY AND COMMENTS

We conduct an evaluation in each new area to determine the level of ocean current information needed. Based on this evaluation, a decision is made as to the value of a measurement program. The measurement program may be on a short-term (less than one month) or long-term basis (full year or longer), depending upon the particular need for the data. If data in a new area exist, the measurement program is geared to the construction and installation of production facilities. To eliminate duplicate efforts, cooperation among the three groups involved--government, academia and the offshore industry--is needed. The key to effective current measurements in determination of values for all purposes is cooperation. Money, manpower and resources are limited, and cooperation is essential to make optimum use of all of these.

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CURRENT MEASUREMENT INSTRUMENTATION SENSORS FOR INDUSTRIAL APPLICATIONS: REQUIREMENTS, PROBLEMS, AND PROPOSED SOLUTIONS FOR THE NEXT GENERATION OF INSTRUMENTS

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ABSTRACT

Industry commonly uses current measurement data to properly design and safely install marine structures. The ocean engineer's information requirements emphasize maximum current velocities and durations, with less stringent requirements placed on the data's absolute accuracy and resolution. While reduced accuracy is acceptable, the data acquired must truly represent the ocean dynamics. In this type of application, the reliability and system cost, not sensor accuracy, become the trade-off considerations by which the current sensor components of a system are selected. This reliability is expressed not only in system design but also in instrument ruggedness, ability to detect failures before installation, component reliability and commonality, and ease of servicing at sea. Our experiences have shown major deficiencies in the areas of power supplies, tape transport reliability and commonality, and errors derived in the encoding and translation process. All of the deficiencies cause errors that may not be entirely evident without rigid data processing controls.

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DATA FOR INDUSTRIAL APPLICATIONS

Important in the design and installation of marine structures, such as offshore platforms, pipelines, and storage devices, are the acknowledgment of and allowance for the environmental conditions present at the installation site. The designer, therefore, must have available, reliable estimates of the magnitude of the most severe wind, wave and current conditions likely to be encountered by the structure during its design life. This represents a critical area for the designer because of the consequences associated with under- or over-estimation of these design values. Over-estimation of these extreme values results in overdesign and increased and unacceptable expense. Underdesign invites disaster in the form of a damaged or lost structure and/or loss of life.

The estimation of the design values can be obtained by several methods. These methods include literature reviews of historical data from the site, hindcasting of wind, waves and surface currents from the abundant synoptic weather maps, and extrapolation of observed data in time and space. Often the designer will elect to use a combination of methods.

Wind and waves lend themselves well to hindcasting and extrapolation methods. Currents, however, because of their great variability and because of their dependence on water column characteristics, are not as easy to hindcast. Additionally, historical data for a specific site are few and often do not include the entire profile. Clearly, in applications where most or all of the structure lies below the wave zone, measurement programs must be initiated.

The length of a current measuring program depends on the general nature of the currents at the installation site. For example, if the maximum currents are associated with the tides, then data from one lunar cycle may be sufficient; if a general circulation pattern is dominant, then measurements representative of each season may be necessary. In the case where great horizontal variability is observed, it may be necessary to deploy several current-meter arrays to achieve adequate coverage. As more data are acquired from an area, a more reliable design estimate value can be derived.

To provide the designer with useful data, Interstate Electronics Corporation uses a variety of statistical and data reduction routines which produce the data in a form tailored to the designer's needs. Some examples of Interstate's presentation include tabulated raw data, frequency-of-occurrence diagrams, current shear, daily minimum-mean-maximum plots, spectral energy density plots, progressive vector diagrams, and scatter diagrams. From these data presentations, it is a simple matter to determine maximum current velocities and seasonal trends.

Before any of this can happen, however, a current measuring system must be successfully deployed and recovered with the data intact. The best way to ensure data recovery and reliability is by carefully selecting the array components, especially the current meters themselves.

SELECTION CRITERIA

The single major criterion used in the selection of current meters in industrial applications is reliability. Reliability is expressed as the ability to:

- Measure correctly in the installed environment.
- Withstand installation and retrieval.
- Survive multiple servicing actions with reasonable maintenance.
- Maintain calibration for reasonable periods.
- Perform as expected and desired.

Installation Environment. All meters have drawbacks when exposed to the operating environment. Savonius rotor sensors are sensitive to wave or mooring-induced motions; electromagnetic, acoustic and optical sensors are prone to mechanical degradation as are Savonius rotors; most meters are vulnerable to physical damage of a varying degree.

The ultimate instrument to fit the varying environment throughout the water column will most likely be a non-mechanical, bi-axial flow sensor that is sampled at a rate allowing measurement of wave, tide and mooring motions in addition to "steady state" flow in order to quantify and describe all the energy sources.

Mechanical Reliability Under Stress. The single most damaging factor to current measurement systems is the vulnerability of meters to physical abuse during installation and retrieval. A current meter should not have sensors that protrude severely or attach to a string in such a manner that invites mechanical overstress. Sensors, especially mechanically coupled rotors, must be protected as much as possible; and hangers, eyes, and connecting rods must be designed for installation with minimal deck gear. As most damage is caused by the inability to control instruments out of the water, size and weight should be kept as low as possible. If a meter is light and has handles, it will be subject to less damage during handling sequences.

Multiple Servicing Reliability. The previous criteria can be related to any ocean-current measurement system,but the need for reliability of a meter under use in an industrial application may be somewhat unique.

Economics usually do not allow the total replacement of meters for each servicing period, which can be as short as monthly over a multi-year program. A meter that can withstand these requirements of installation and recovery month after month, with minimal parts and minutes of work to effect repairs and replace expendables, is an absolute necessity.

Calibration Stability. Industry lacks the resources to determine the stability of a current sensor before purchase and installation. This area is one that is lacking in information, that tends to be ignored, and is a "seat-of-the-pants" feeling to most users. Generally, if a sensor maintains mechanical integrity, does not get sloppy in operation, or does not foul severely, it is expected to maintain calibration.

Performance to Specification. This is another area in which few in industry have the capability to detect problems correctly before use. Manufacturers are assumed to deliver as advertised, and knowledgeable users purchase from concerns with a good track record.

COST AS A BASIS FOR SELECTION

The cost of an instrument should not have a bearing on selection if the end result is the highest quality data obtainable. In some cases, this is a valid premise, but in industry, cost can drive an organization out of the market. A properly designed system would preferably consist of current meters by the same manufacturer to ease the data analysis burden. If this were the case and a sensor is required in the wave energy zone, all the meters would have to be electromagnetic or acoustic meters that cost approximately twice that of a Savonius rotor meter. If the persons reviewing the proposal for such a system do not appreciate the data analysis problems, cost becomes a hurdle that will trip the technically responsive company. Because industrial applications require responsive attitudes in the cost to perform, the sensor cost becomes nearly equal to reliability as a basis for selection.

DEFICIENCIES OF PRESENT SENSORS

State-of-the-art current meters have performance capabilities far beyond the past generations of equipment. This capability is not always realized because of failures, either partial or total, of components critical to proper data collection. Interstate Electronics Corporation's experience has shown major deficiencies in the following areas:

- Power supply failures (total).
- Inadequate power supplies.
- Sensor damage due to inadequate protection.
- Tape transport reliability.

Power Supply Problems. In situ instruments require storage cells for completely remote operation. Over the past 18 months, Interstate has experienced some ten meter-months of data loss due to battery failure; this from some 80 meter-months of installation. A failure rate of some 10% or greater cannot be considered acceptable when caused by a single common component. Approximately five meter-months were lost due to failure of battery totally at some point in the installed period. In one case, a battery had correct values at installation onboard, ran for several cycles on deck, then failed at installation, a time period of only 40-50 minutes. The remaining lost data were from an instrument with an improperly designed power source that could not record for the planned installation period.

Sensor Damage. A major number of failures caused by mechanical damage can be forestalled by proper handling, but several of our failures have been caused by inadequate protection and instrument bulkiness that did not allow handling, under prevailing sea conditions, with the required care to forestall damage.

Tape Transport Reliability. Data losses caused by tape transport failure have been a minor problem, and are usually due to electronics failures that cause stoppage of the transport or recordings that are undecipherable or erratic. The last mode, erratic recording, can lead to the use of invalid data. Unless a properly conceived data quality program at the encoding level runs in conjunction with data analysis, such errors as partial records, missing records, or bit shifts in the data may not be readily apparent.

Suggested Solutions. Commonality is one approach to a solution to lower failure rates of power supplies and tape transports. If the majority of current-meter manufacturers could be convinced to use the same power source and tape transport, their suppliers would invest to provide the best batteries and transports for oceanographic applications available at present state-of-the-art. Certainly if the desired product is specified, the market area is large enough, with all in situ instruments included, to spur development.

Sensor damage is a more difficult area to cover in a commonality approach, but if an instrument proves more reliable in a mechanical nature and is reliable in other areas, the bulk of purchases will shift to that instrument. Manufacturers should pay more attention to competing instruments and should establish a user's forum for timely discussion of problems that crop up.

ADDITIONAL PROBLEMS AND SOLUTIONS

Following are several problems related to translation of data after recording that cause inaccuracies and difficulty in comparing data.

Data Translation. From the raw data tape, a transcribing process is usually required to format data to a computer-compatible form. A company using the full range of meters needed for commercial work will most likely need transcribers for: 1/4" reel-to-reel tapes; cassette tapes (two or three versions); 8-track tapes; "Scotch" cassettes, and probably others. In addition, recording densities, tracks and formats vary within each type. We need to standardize on one or two data storage device types so the transcription process is less complicated and less costly.

The final problem we at Interstate have been faced with is in the recording intervals available on different instruments. On a string placed in the Gulf of Mexico, we used three types of current meters: an electromagnetic, a propeller-type, and several Savonius rotor meters. The EM recorded at 17.006-minute intervals (1024 seconds), the propeller-type at 3.75 minutes, and the Savonius rotor meter at 10 minutes. The ability to compare data at similar times at the same level of confidence is lowered by this mismatch in recording intervals. Commonality, please.

CURRENT MEASUREMENT: AN IMPORTANT CONSIDERATION IN THE DESIGN, CONSTRUCTION, AND OPERATION OF OFFSHORE FACILITIES

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ABSTRACT

The movement of the offshore industry into frontier areas and harsher environments has given way to increasing concern over current-induced forces for design, construction and operation of offshore facilities. The historical approach to design current determination is slowly being replaced by computational techniques which consider all components of currents with their respective time of occurrence and direction. From a construction standpoint, there is an increasing requirement for near real time data that will be helpful for facility installation. For facility operation, the need is for a good statistical base as well as near real time data for critical operations. This paper discusses industry's current data requirements as related to the design, construction and operational phases of offshore facilities.

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INTRODUCTION

The advancing state of engineering technology has provided the oil and gas industry the capability to safely develop hydrocarbon resources in many varied offshore environments. The capital investment, however, has been tremendous. Because of this investment as well as the concern for human safety, there is a continuing effort to better understand the offshore physical environment. The movement into frontier areas with harsh environments such as the Beaufort Sea or Gulf of Alaska provides even more incentive for investigating the environment and defining the results in terms of the effects on design, construction, and operation of offshore facilities. No longer is there necessarily, a gradual move to deeper and deeper depths within a specific area, as was the experience in the Gulf of Mexico. Offshore the U.S. East Coast, a frontier area, initial exploratory drilling will begin in water depths from 200 to 400 feet. There will be no gradual learning of the environmental conditions in this area; either sufficient measurement of environmental parameters before development will be obtained or conservative estimates of these parameters will be made. Though both approaches will yield structurally safe facilities, the marginal increase in cost of facilities based on conservative estimates of environmental criteria as compared to environmental criteria based, in part, on measured data, can often justify the cost of measurement programs. Basically, measured data often allow a lowering of various design, construction and operational requirements without any increase in risk.

This philosophy is particularly applicable to current speed and direction. Because of difficulty of accurate measurement, conservatism is generally the rule for current specification, at least for the quasi-steady components (components other than wave-induced currents). With the advent and subsequent field development of new instrumentation, as well as better understanding of mooring behavior, the current environment can be better defined.

DATA REQUIREMENTS

The design, construction and operation of offshore facilities are affected substantially by the current environment.

Design. Though those involved in design often speak of the design wave height, indirectly the inference is to water particle motions which produce the force. Design of offshore facilities has historically been based on forces as determined by the Morrison Equation[1] which considers the wave-induced water particle velocity and superposition of other forces caused by such current components as tide (astronomical, wind,

[1]With exception of large structures such as the Condeep platforms where diffraction theory is used.

pressure), density, wind, etc. effects. Since adequate theories exist to describe the wave-induced currents throughout the water column for a particular wave profile, emphasis has commonly been placed on wave measurement. Estimates for the components of current other than the wave-induced component have followed from limited measurement programs or various hydrodynamic/numerical models. Further, the magnitudes of these components are often conservatively overestimated and, in view of the lack of directional and temporal information, have been assumed to act in the same direction at the same time.

Given an acceptable level of risk--confidence that the force produced by a certain combination of events (in the present case, simultaneously existing current components) will not be exceeded during a particular time interval--what then actually constitutes the most severe current-induced force? The most valid answer will be based on the joint probability of occurrence for all possible components and the resultant force produced by this joint occurrence. Additional difficulties are introduced since these components are not necessarily independent of one another, i.e. there could be a relationship between the extreme wave-induced and extreme wind-driven current.

The adequate definition of the magnitude, direction, interrelationship and thus the joint probability of occurrence of all these components is the major requirement from a design standpoint. To meet these requirements, reliable, accurate instrumentation and subsequent measurement programs to either empirically determine design current parameters or verify theoretical and statistical models are needed.

Construction - Operation. Construction and subsequent operational requirements for current data are classified together because of the similar nature of information needed. Additionally, only the quasi-steady current is treated here since the oscillatory wave-induced current is normally defined by the wave height/period environment.

The first requirement is for a statistical data base on which decisions regarding the timing of various phases of construction or operations can be based before the actual initiation of the tasks. In such areas as offshore Brazil near the Amazon River mouth, or in Cook Inlet, Alaska, tidal current velocities of greater than 3 m/sec are not uncommon. Construction or operations such as platform launching, pipeline laying, etc. can become critical in these situations. Ability to predict potential problems before construction or operations begin is most desirable.

A second requirement, real time current data, has recently become a tool substantially benefiting offshore construction and operations. During the launching of the lower section of the Cognac "A" platform in 1030 feet of water (Gulf of Mexico), currents were monitored with a profiling current measurement system. Continuous measurements over the water column were acquired every two hours and were monitored in real time aboard the construction barge. If adverse conditions had been detected, then the launching and subsequent lowering would have been delayed. Other construction/operational tasks such as laying pipeline, running the BOP stack or riser, etc., often make use of real time current data for input to on-site decisionmaking.

In summary, the basic data requirement is an accurate description of the current environment for defined regions. Data must be adequate to supply information for design, construction and operations. Instrumentation must be flexible enough to provide for accurate and reliable real time as well as historical data.

INSTRUMENTATION/MEASUREMENT REQUIREMENTS

The requirements for water current instrumentation, deployment intervals and sampling can be quite varied. Given the particular current parameter desired, e.g. tidal, wave-induced, etc., and the environment where this parameter is to be measured, the type of instrument and appropriate mooring can be specified. If instruments can be mounted on fixed, stable facilities with minimal interference from the facility, so much the better. If moored arrays are to be used, then an appropriate mooring must be specified, with subsequent mooring behavior predictable. As a part of the mooring specification, the decision between surface and subsurface flotation must be made. Surface flotation will provide for instrument mounting nearer the water surface but the ensuing wave-induced motions of the mooring can result in grossly inaccurate data. Instruments attached to subsurface mooring arrangement will experience less of the oscillatory wave effects, but will not be capable of measuring currents very near the surface. Surface mooring location will be easier to monitor and retrieve. Subsurface moorings must depend on acoustic or timed release mechanism, but the chance of outside interference with the mooring is substantially less. The use of acoustic slant range interrogation of subsurface arrays has helped to solve some of the problems associated with position monitoring, but the range of these devices is limited and occasionally the existence of a thermocline will cause problems with signal reception.

Instrument specification and associated sampling intervals will depend on the depth of measurement with respect to total depth, the particular current parameter to be measured, and the physical characteristics of the environment where the measurements are to be made. Beardsley, et al. (1977) give an excellent summary of current meter intercomparison results in a water depth of 25 meters during the recent CMICE project. In this study, Savonius rotor, impeller and electromagnetic sensors with substantially different sampling techniques and moorings were evaluated. Though there was no comparison with an absolute standard, the work does provide significant information that should be helpful in instrument selection.

Data output from current sensors will be either some average or instantaneous value of current speed and direction. Data averages will either be scalar or vector averages over a particular interval as determined from a continuous sampling mode or a burst sampling mode. The latter mode computes averages by considering a predetermined number of values of speed or direction sampled at or over specified intervals. Average values of current speed and direction will give values of the quasi-steady current over a defined time interval (e.g., five minute current speed). The sampling intervals for either the continuous or burst sampling modes must be carefully specified so as to eliminate aliasing problems which might be encountered because of the presence of wave-induced velocities. Continuous sampling instruments must have long enough sampling intervals so as not to introduce an erroneous net wave-induced velocity. To eliminate a similar error in the burst sampling instruments, there must be a sufficient number of data points sampled at adequately short intervals between points.

Instruments capable of supplying instantaneous values of current speed and direction require a high response to changes in the physical environment. The electromagnetic current meter is presently the primary instrument used for instantaneous current speed and direction measurement. It operates on the principle that an electric field will be induced in a medium that is moving relative to a magnetic field. Response of electromagnetic instruments is typically less than 0.5 seconds. Thus, there is sufficient response to measure wave-induced water particle velocities. In some instruments, data can be internally processed to yield average current values. If actual time history of current speed and/or direction is desired for long intervals, then the amount of data that must be collected requires transmission by RF link or hard wire to data acquisition facilities.

In summary, then, current measuring instruments will either provide average or instantaneous values of current speed and or direction. The instrument specification very much depends on measurement location and what current component should be measured. This, in turn, will dictate the appropriate sampling technique.

ECONOMIC IMPACT

The economic impact of currents on offshore facilities is commonly related to wave-induced currents. However, even the quasi-steady current forces can significantly influence project cost. Figure 1 illustrates the change in concrete material cost due to an increase of design bottom current for various depths and constant design wave height.

For offshore developments in deeper water depths, e.g. the Cognac project, the quasi-steady current will be the major current force in the deeper portion of the water column. The facility design and subsequent

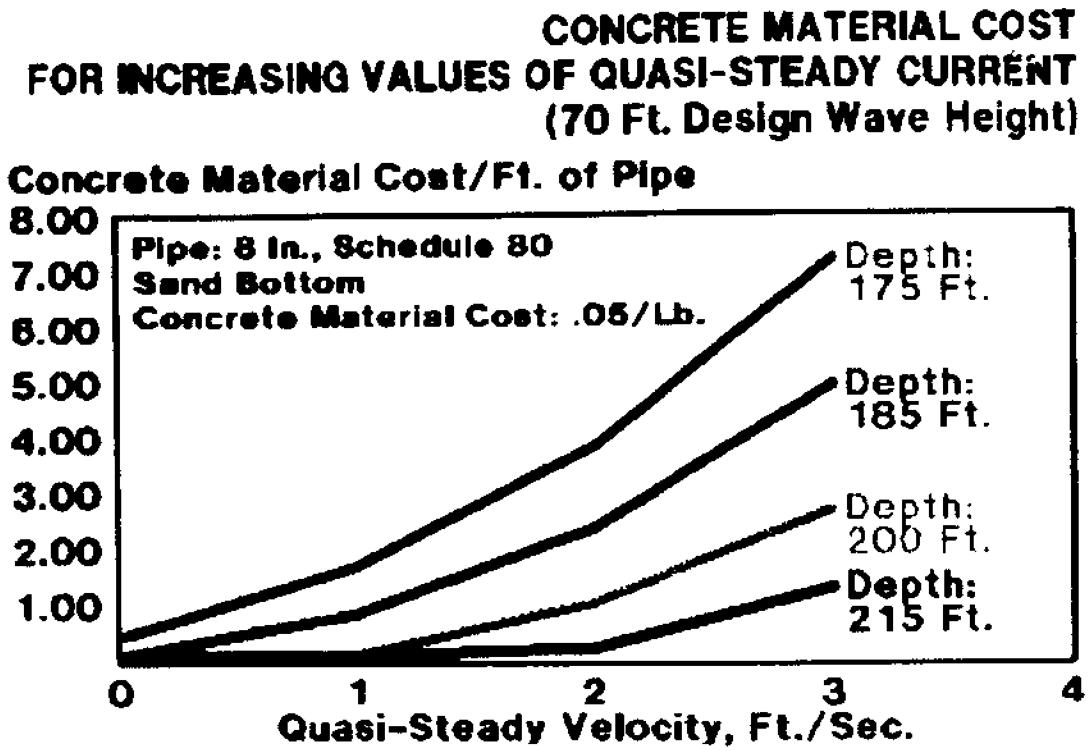
CONCRETE MATERIAL COST
FOR INCREASING VALUES OF QUASI-STEADY CURRENT
(70 Ft. Design Wave Height)
Concrete Material Cost/Ft. of Pipe
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
Pipe: 8 In., Schedule 80
Sand Bottom
Concrete Material Cost: .05/Lb.
Depth: 175 Ft.
Depth: 185 Ft.
Depth: 200 Ft.
Depth: 215 Ft.
0
1
2
3
4
Quasi-Steady Velocity, Ft./Sec.

Figure 1

cost will be considerably more dependent on design values of the quasi-steady current speed and direction than facilities in shallower depths. In regions subject to severe currents, downtime of construction/operational activities can cost many thousands of dollars per day.

SUMMARY

The current environment is an important consideration in the safe and economical design, construction and operation of offshore facilities. Within each development area, it is necessary to investigate this environment and assess the impact on facilities. Decisions can then be made as to whether or not measurement programs should be implemented. If measurement programs are undertaken, the primary considerations will be mooring and instrument characteristics as well as data sampling and deployment intervals. Generally, the increased confidence in the various current criteria produced by measured data could provide for lowering of the criteria with no appreciable increase in risk. Additionally, the temporal and directional characteristics of various current components can be better estimated, which in turn will allow the determination of more realistic probability distributions.

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WATER CURRENT MEASUREMENTS FOR MARINE PIPELINE DESIGN

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ABSTRACT

The stability of a marine pipeline which is exposed to lateral currents is one of the major concerns of the pipeline engineer. The design velocity in the bottom boundary layer dictates the amount of concrete weight coating which must be applied to maintain stability during the worst lifetime current conditions. As this submerged weight requirement has considerable effect on material cost and installation techniques, one of the early steps in designing the pipeline is calculation of the design currents. This value is traditionally derived from steady current data obtained along the pipeline route. The typical requirements of this data base are discussed.

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INTRODUCTION

The proper design of a marine pipeline requires that the submerged weight be sufficient to resist lateral sliding in the maximum expected current during the life of the pipeline. Additionally, stability must be achieved during the entire period of installation, and in many cases, this may be the more severe requirement because of the void and untrenched status of the pipeline. Accordingly, one of the early elements in the pipeline design sequence is assessment of the steady current flow patterns along the pipeline route. Specifically, sufficient current data must be obtained to determine the peak steady velocities to which the pipeline will be exposed during the construction season and the entire design life. To this end, an array of current meter moorings is deployed along the pipeline route at certain intervals. The central objective of this effort is to identify the peak monthly velocities caused by tidal, density and wind forcing. Coincidental to this effort, the characteristics of the construction period (say three months) and lifetime (100-year) significant waves are derived using statistical techniques. The measured steady current data are then combined with the design wave-induced velocity to yield the final design current which dictates the submerged weight requirement for the selected return period.

Another element in the pipeline design sequence is the analysis of various types of installation methods and their associated risks. In this scenario, the requirement exists for complete velocity information throughout the entire water column, and typically real-time data are required during the actual installation. Although there is a distinct requirement for these types of measurement programs by the pipeline community, they are not viewed as unique to the construction industry, and as such, the focus of this paper is on the measurement of steady bottom currents by deployed recording instruments. The primary objective in the following discussion is to acquaint the reader with some of the techniques presently used, and to identify areas of potential hardware enhancement.

DATA REQUIREMENTS

As noted in the preceding section, the main purpose for obtaining current measurements is to assess the flow regime in the bottom boundary layer over a large spatial scale. This type of measurement program is, therefore, unique to the offshore industry in two ways. First, several different types of flow regimes can be encountered along a single pipeline route. This does not ordinarily present any measurement difficulty, but it does require that the spacing between moorings be made small enough such that local flow variations can be identified. Selecting an appropriate number of current meters to define the flow regime along the route is analogous to the vertical spacing requirement for fixed level current meters on a single mooring. The second feature unique to measurement programs for pipeline design is that no attempt is made to measure wave-induced velocities. The presence of such signals can, in fact, cause an overestimation of the true current unless they can be filtered from the velocity record.

Characteristics of a hypothetical measurement program designed to measure bottom boundary layer currents are compared with presently available instruments in the following paragraphs. Comparison is made in terms of the following considerations:

- physical characteristics
- sampling period
- sampling and recording rate
- accuracy
- range of measurements
- data logging
- data format
- options
- reliability
- cost

The remarks are summarized and presented in Table 1.

Physical Characteristics. The general arrangement of a current meter mooring designed for monitoring boundary layer currents consists of a pair of recording instruments placed as close to the bottom as physically possible. Usually this is 1 to 2 m, depending on whether or not an acoustic release is used and the expected intensity of sediment bedload. As upper ocean measurements are needed for correlation of data, additional current meters are often included at the top and middle of the mooring. This adds relatively little expense to the major costs incurred for vessel support. The major requirements in terms of physical characteristics are the ruggedness and compactness of the instrument. As the deployment operation itself is often the proving ground for instrument survivability, instrument designs enabling the use of small sensors, vertical axial symmetry, and reduction in package dimensions are desirable in terms of physical characteristics. This is especially true for use in the offshore petrochemical industry.

Sampling Period. As noted earlier, the phenomena of interest are due mainly to tidal, density and wind forcing. The length of the measurement program, therefore, depends on the dominant forcing mechanism expected. In areas where the regime is essentially tidal, a minimum record length of 30 days is considered adequate. In order to quantify a density signal, however, which may be significant in estuarine regimes, several 30-day records obtained throughout the year are desirable. In lieu of such a vessel-dependent program, a single 60-day record taken during the construction season or peak fresh water discharge is sufficient. The measurement of wind-induced bottom currents requires the most ambitious commitments, as in deep water, a wind-induced signal may not occur except in extreme atmospheric events. The approach taken here is often to generate the theoretical wind-induced bottom current on the basis of a suitable model. Bottom current measurements in depths greater than 50 m taken during storms are obtained largely by good fortune.

TABLE I

DESIRABLE SPECIFICATIONS FOR CURRENT METERS USED FOR MARINE PIPELINE DESIGN

CRITERIA	PRESENTLY USED	DESIRABLE	REMARKS
PHYSICAL CHARACTERISTICS	31.5" x 24" 42 lbs. in air	smaller size, symmetry about mooring axis	physical compactness required for deployment ease
SAMPLING PERIOD	30 days	30 to 90 days	practical limits due to biofouling and mech. failure
RECORDING RATE	15 min.	15 min. to 1 sec burst sampling controlled by microprocessor	
SAMPLING RATE	continuous speed integration over recording interval, vane response-10s	capability of 1/s rate for speed & direction	requires vane length of 6"
ACCURACY	+ or - 8 cm/s	+ or - 8 cm/s rel. to absolute std. + or - 10^{o} for dir.	present accuracy satisfactory
VELOCITY RANGE	3-120 cm/s	3-120 cm/s	
DATA LOGGING	film, pressure sensitive paper tape	mag. tape or bubble memory	ruggedized tape cassette is presently most suitable
DATA FORMAT	various	RS 232 or 8 bit binary	
OPTIONS	none	pressure record, acoustic transducer for real time data	
RELIABILITY	60 - 70% data return	70 - 80% acceptable	
COST	$4,000 - $5,000 per unit	same	

Attesting to this is the lack of historical current data collected during hurricanes. A potential solution to this measurement problem is to maintain very long-term (one year) moorings or simple, short-term arrays which can be deployed when an extreme event is imminent. In most cases, long-term deployments are not economically attractive, because the ratio of data recovery to cost drops sharply after 30 days of deployment. This is due chiefly to the following effects:

- biofouling, resulting in unreliable data
- premature battery drain
- corrosion of instrument or mooring resulting in flooding or mooring loss
- failure of data logging transport mechanism

Improvements in instrument design directed at these problems are considered prerequisite to practical deployment for periods in excess of 30 days.

Sampling and Recording Rate. In this discussion, sampling rate refers to the frequency at which reliable velocity and direction data can be obtained from the sensors. Recording rate refers to the frequency of data logging. For purposes of establishing the 100-year design criteria, measurements are generally made in depths greater than 60 m, and as such, are free of wave-induced signals. In these areas, Savonius rotor current meters have been used successfully with 15-minute recording rates. In this case, the recorded speed is the time averaged scalar quantity, and the recorded direction is the instantaneous value. Accordingly, the sampling rate and the recording rate are identical. In areas where the oscillatory motions are a significant fraction of the total energy, a sampling interval of 1 second for both speed and direction is desirable. In this manner, vector averaging can be achieved and the wave motions can be identified. In either the steady or oscillatory current case, the proper recording period is essentially a function of data storage and length of deployment. Typically, 15-minute intervals allow 30 days of recording; however, a wide range of recording intervals should be available to allow optimizing data recovery for a given deployment period. As one of the sources of error in current measurement is the uncertainty of the fraction of orbital energy present, a desirable feature in recording current instruments is the use of a microprocessor to permit burst sampling of speed and direction at various intervals, depending on the velocity fluctuations. A 60-second burst of data at 1-second intervals obtained even once every 12 hours greatly reduces the uncertainty inherent in measurements in the wave zone.

Accuracy. The instruments used for pipeline current surveys are calibrated to the manufacturer's standard before each deployment. The allowable error is ±8 cm/sec and ±10° for the speed and direction sensors. These somewhat relaxed accuracy specifications stem from the built-in conservatism in the methodology used to compute submerged weight. The major problems associated with accuracy, however, have not been noted to be related to calibration, or manufacturer's accuracy specifications, but have instead been caused by the following:

- biofouling on speed sensor
- presence of wave signals when Savonius rotor is used without vector averaging

- tilt of instrument (when tilt sensor is not installed)
- influence of mooring line motion
- lack of true cosine response to direction of flow in instruments having fixed geodetic orientations

Biofouling of the speed sensor has been found to be particularly severe on near-bottom installations. Biocides incorporated into exposed components have greatly reduced the problem with microfouling, but macroscopic free-drifting debris remains a hazard.

The problem of wave noise has been virtually eliminated by vector averaging, but because of the cost premium for this feature, several manufacturers have introduced alternate methods of filtering the wave data. For real time measurements in shallow (5-meter) water, a bi-directional ducted propeller has been used in conjunction with a long stabilizing vane. The intent is to keep the heading of the instrument constant in the wave field, while a low pass filter removes the high frequency signal from the propeller output. In one deployment, it was found that the long tail vane presented a serious deployment difficulty, and yet it was not long enough to stabilize the heading of the instrument. Subsequently in this operation, the speed filter was bypassed to allow raw data to be recorded, thus partially overcoming the problem.

The remaining three sources of inaccuracy have been suitably addressed by the manufacturing industry except in the case of mooring line motion, which is not a particular problem associated with near-bottom measurements.

Velocity Range. The velocity range typically encountered in the bottom layer is 5-100 cm/sec, even in strong tidal flows. The maximum velocity threshold which is desirable is 3 cm/sec and is achieved by most presently available instrumentation.

Data Logging. Presently used film recording data loggers are considered inadequate for effective reduction and analysis of data. Considerable time and effort are wasted while films are scanned and transposed to paper tape by the manufacturer. Although simple schemes such as Rustrak impact recorders allow immediate review of the data upon instrument retrieval, magnetic tape cassettes are considered to be the most efficient storage medium. With the advent of low cost micro-processors, the need to have the data reduced by the manufacturer is essentially eliminated. Data playback can be achieved at sea if necessary, using an audio tape deck, interfacing circuitry and an X-Y plotter.

Data Format. A suitable format for recording on magnetic tape must include, in addition to speed and direction data, time and reference information. Due to the somewhat standard use of RS 232 as an interface medium for minicomputers, this format is recommended. Additionally, this format enables data to be transmitted directly via a standard Telex terminal.

As noted earlier, in situ filtering of current data has, in the past, introduced errors which were not otherwise present. As data filtered prior to recording can never be regained, it is recommended that all raw data be recorded and filtering be implemented using computer techniques which preserve original data.

Options. A parameter which has been useful when analyzing velocity data is the pressure signal. A low pass filter allows the tidal elevation to be determined, thus aiding in the determination of the velocity characteristics. Another option which has been useful is the availability of a real time data transmission link. This can be accomplished via acoustic signals, inductive coupling through the mooring wire to a surface transmitter or a hard wire connection. Real time data have traditionally relied on the latter, which are subject to severe handling, wave conditions at the interface and leaking connectors. The results obtained from this arrangement have been fair at best.

Reliability. It has been found that the existing data return rate for instruments carefully deployed is 60 to 70%. This figure represents the rate of good data returned to the quantity of data expected according to deployment length, sampling rate and battery life. Although the instrumentation community has responded well to most industry needs, improvement is still required in the following specific areas:

- improve reliability of tape transport mechanisms in the presence of vibration or shock loading. This is especially true of current meters which do not use cassettes;
- reduce the number of external moving parts to minimize the effects of biofouling;
- reduce battery drain in both sampling and quiescent modes.

A minimum data return of 70 to 80% is considered acceptable in most cases for pipeline design.

Cost. Generally, the cost per current meter which can be supported on a current meter survey is about $4,000. Since a significant portion of the survey cost is due to the provision for a means of recovery, either acoustic release or surface line, it is anticipated that a small, integrated package combining the anchor, flotation, acoustic release and current meter would be readily suited for bottom current measurement programs. A device such as this would presumably offer significant savings in hardware cost over the present cost of $10,000 for a single meter mooring.

CONCLUSION

From the large selection of instrumentation, the requirements of the pipeline engineer tend to dictate the use of the simpler, less sophisticated equipment. Only with these instruments are the large-scale current monitoring programs such as those requiring 10 to 20 current meters, economically tenable. At present, no instruments have been identified which are uniquely suited for pipeline applications. Hypothetically, such an instrument would have some or all of the following features incorporated at various cost premiums:

- solid-state recording medium consisting of addressable banks of magnetic bubble memories capable of storing 10^6 bits;
- electronic, as opposed to mechanical, sensing of current speed and direction. This would reduce the effects of biofouling;
- acoustic transducer which would serve as a telemetry link for real time data;
- acoustic release mechanism which could optionally be incorporated into the instrument and would utilize the telemetry transducer;
- microprocessor to allow the recording rate to be optimized in situ depending on the time scales and magnitudes of the velocities encountered;
- self-contained diagnostics in Read Only Memory which may be exercised by the technician just before deployment;
- small, axially symmetric physical package; and
- cost $5,000 to $6,000.

CURRENT MEASUREMENTS IN SUPPORT OF FIXED PLATFORM DESIGN AND CONSTRUCTION

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ABSTRACT

Storm-driven currents can be an important part of the design hydrodynamic flow field for fixed platforms. In addition, the currents which exist during platform construction can significantly affect the installation. Planning for the installation of a large platform off the Mississippi Delta was facilitated by climatological current data collected with electromagnetic and Aanderaa meters, which were supported from a semisubmersible drilling rig and from a subsurface mooring. In addition, Cyclesondes and electromagnetic current meters were used to provide real time current data during the installation of the base section of the structure.

Once a platform is in place, it provides an excellent site for the study of near-surface, storm-driven currents and waves. The fast response time of electromagnetic current meters makes them seem ideally suited for this application, and their effectiveness has been demonstrated through five years of experience at three sites in the Gulf of Mexico. Early problems with reliability of the meters during long-term, unattended operation have now been mostly eliminated. During tropical storm Delia, surface currents over 2 m/sec were measured. The electromagnetic current meters also provide information on the kinematics of storm waves. Comparison of the measured particle velocities with wave theories shows that the directional spread of the wave energy is important. The measured particle velocity spectra agree with the predictions of linear theory to within a few percent over the energetic frequency range, increasing confidence in the current measurements.

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INTRODUCTION

Offshore oil operators are interested in current measurements because the design of oil production platforms is governed by the hydrodynamic forces which are expected to occur during their lifetimes. These forces are dominated by the storm waves, but during the storms, there should also be substantial wind-driven currents. Since the forces are roughly proportional to the square of the water velocity, the additional effect of the current is worse than additive.

Unfortunately, there is much less quantitative information available for wind-driven currents than for wave heights. Even very long time series of current data would not be sufficient to reliably estimate for design purposes a climatology of extreme currents. Thus the climatology is usually produced by hindcasting the wind-driven currents that would have been produced by historical storms. The role of current measurements is then in the development and verification of wind-driven current models.

Once a platform is in place, it makes an excellent site from which to make measurements of near-surface currents in storms. At the expense of some interference with the free stream flow, a mounting system can be devised which is very rigid even in extreme waves. Fast response time, solid state current sensors can then be used to accurately measure the total flow. We began implementation of this measurement philosophy in 1971 with a pilot study at Station 1 (Buccaneer) shown in Figure 1. The next year, the program was extended to an Ocean Current Measuring Program (OCMP) at the three stations shown in the figure. The stations were maintained nearly continuously through the 1977 hurricane season, making measurements in the three storms shown in Figure 1 as well as in Anita and Babe in 1977.

The currents measured in tropical storm Delia were discussed by Forristall et al. (1977), and the wave kinematics and directional spectra in that storm are described by Forristall et al. (1978). Reports on measurements in the other storms will appear in the future. Here, we give a reasonably detailed description of the taut wire mooring system to be used for the current meters, and discuss the experience we have gathered on the reliability and accuracy of the electromagnetic current meters used in the project.

Information on currents is sometimes also needed during the construction phase of an offshore engineering project. The Cognac platform is being assembled from three shore-fabricated sections at a site off the Mississippi Delta. The details of the installation are dependent on the current profile at the site. To help plan for the installation, climatological current data were collected using electromagnetic current meters supported from a semisubmersible drilling rig and Savonius rotor meters on a subsurface mooring. During the installation, profiling current meters and near-surface electromagnetic meters were used to provide real time data. All of the various types of instrumentation worked well in the functions for which they were intended.

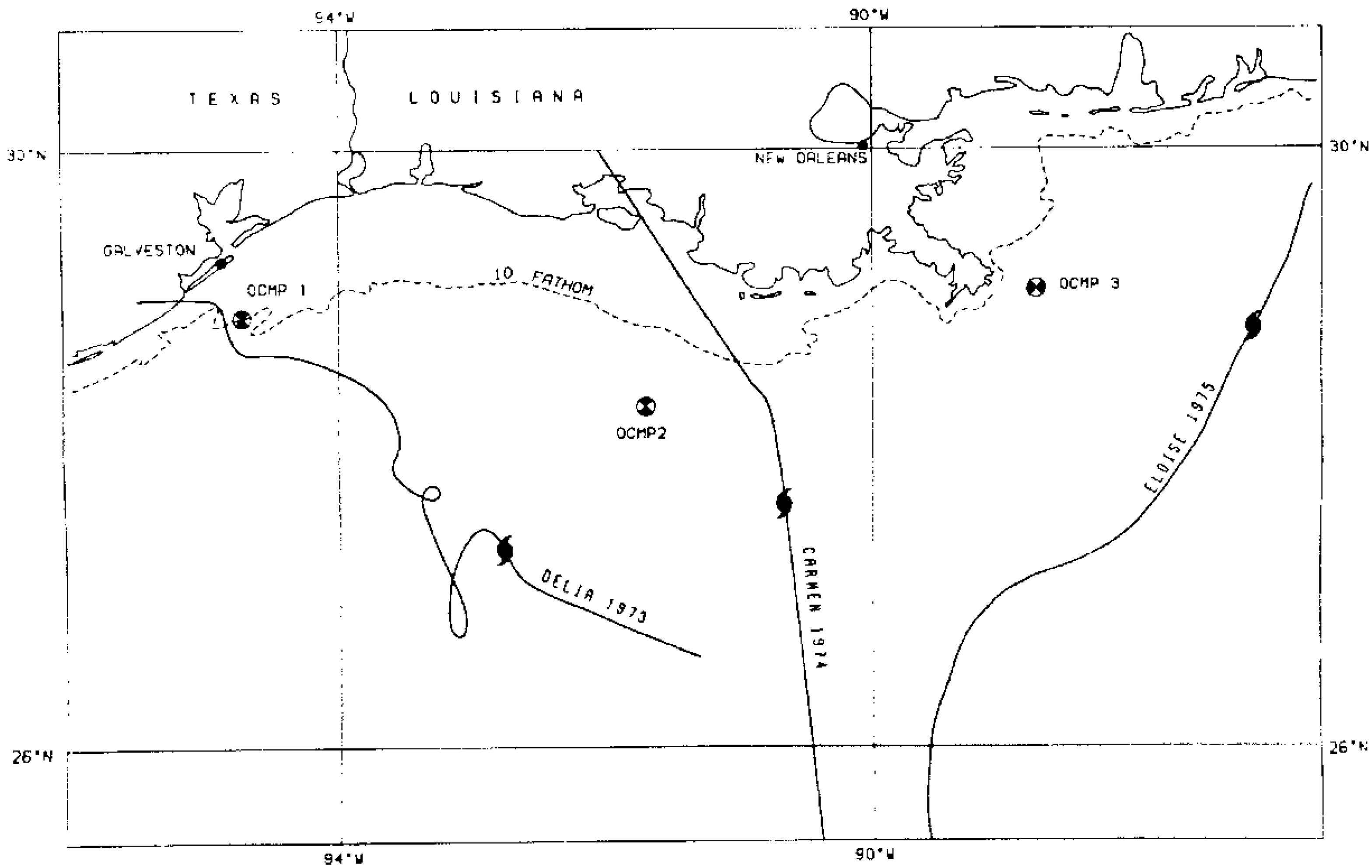

Figure 1. Ocean Current Measuring Program station locations and tracks of storms affecting the stations.

TAUT WIRE SUPPORT SYSTEM

The support system for the platform-mounted current meters must hold them as rigidly as possible with minimum interference to the flow, while also providing access to the meters. The system designed to meet these constraints is shown in Figure 2. It consists of a single wire rope stretched over an upper and lower sheave to form a pair of taut wires. The tension in the taut wire pair can be adjusted to a desired value with the spring-loaded tensioning device on the upper sheave. The lower sheave is mounted on the platform where an accessible work area is provided. The current meter probe is clamped into a frame which supports it midway between the taut wires. These frames are designed differently at each station so that the probe is held in a vertical position and in a north-south orientation. The current meter frame itself slides freely on the wire rope. It is held in place on one side only by cable clamps above and below a cross member. When the upper sheave is rotated, the frame is raised or lowered on the taut wire pair. In this fashion, the meter array can be placed at any desired depth. There would be nothing more to the support system if the meters were self-recording. However, they are not; therefore, their cables must be routed safely with small tension loads while preserving the vertical mobility of the current meter frames.

The conductor cables cannot be routed up one of the taut wires because this results in asymmetrical wave forces on the wire pair. These asymmetrical loads were observed in the pilot study where the cables were all routed up one side of the taut wire pair, and they produced unacceptable torsional motions at the current meter frames. To overcome this problem, the current meter cables are now routed up a central "messenger" wire. This small-diameter wire rope is left very slack, and the conductor cables are closely routed along it. The deliberate large catenary in the messenger line causes the hydrodynamic loads on the cable bundle to be distributed as lateral loads in the braces that are placed every ten feet along the messenger. This prevents the tension in the messenger from exceeding a safe level, and the messenger prevents the conductor cables from being tensioned under load. When the cable bundle must be routed past one current probe in order to reach the lower ones, the cables are routed outside the taut wire on a bridle constructed for this purpose.

Because of differences in platform structure at the three stations, the configuration of the taut wire system is different at each station. At Station 1, two platforms about 200 feet apart are connected by a bridge which is used to support the taut wires (Forristall et al, 1977). At the other two sites, the water depth is much greater and single platforms are used. The taut wires must then be supported by the platform itself, with the attendant problem of interference with the flow. Figure 3 shows the configuration at Station 3, with the wave staff and current meter taut wires mounted outboard of the south face of the platform, the direction from which most storm-generated waves and currents are expected to arrive. However, with calm seas and a

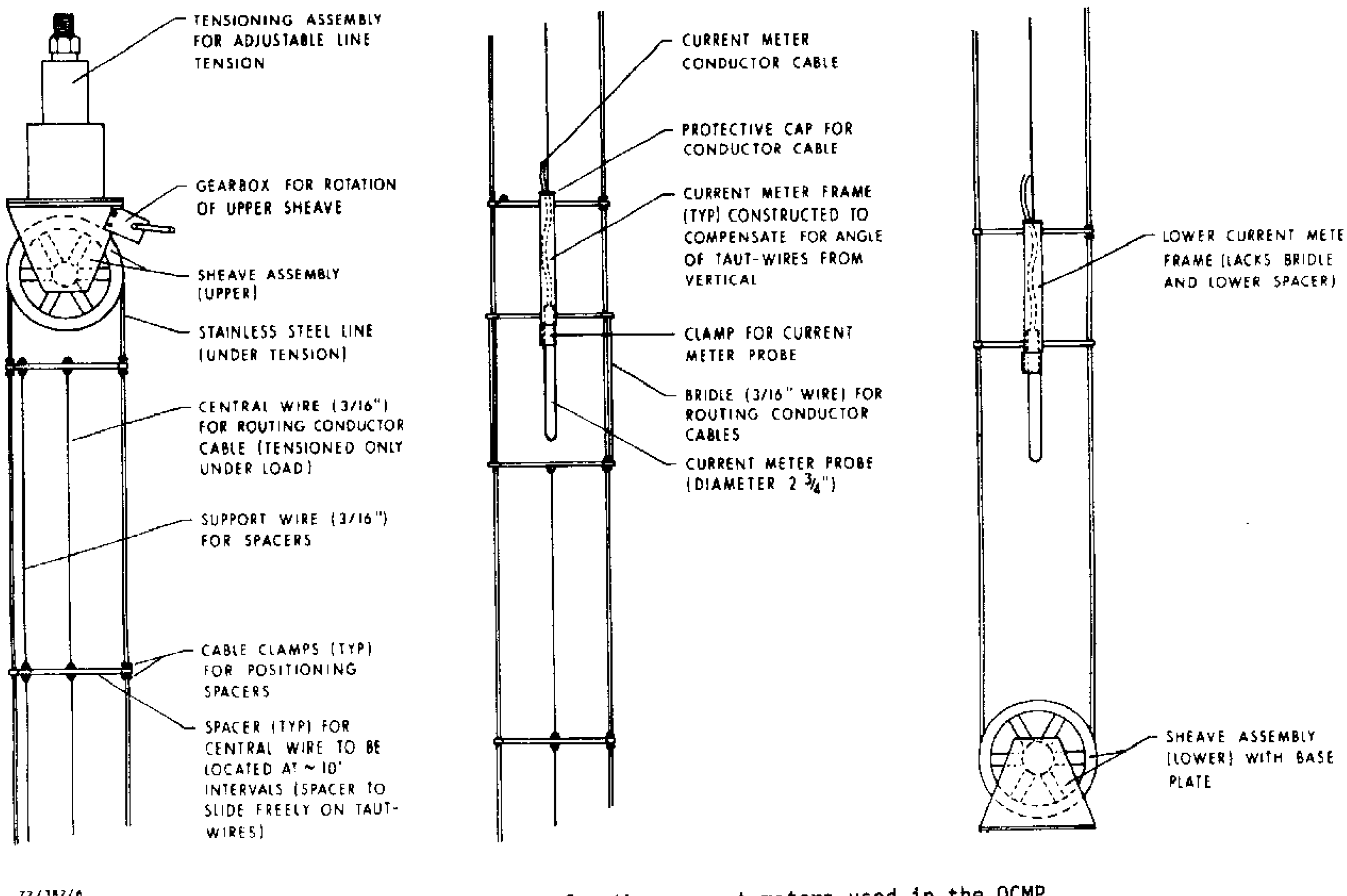

Figure 2. Support system for the current meters used in the OCMP.

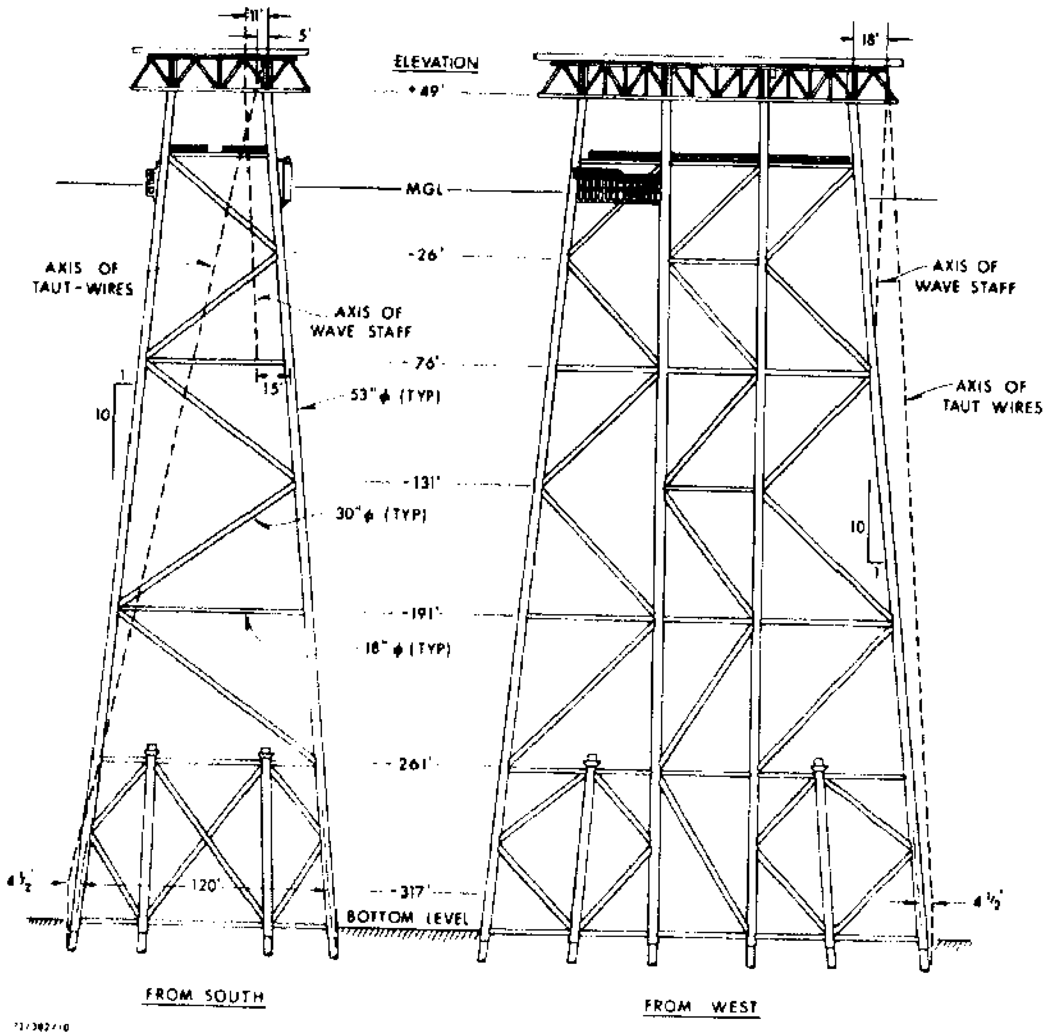

Figure 3. Taut wire and wave staff installation at OCMP station 3.

two ft/sec current setting toward the east, we have observed eddies from the southwest platform leg crossing the current meter string and causing oscillations up to two ft/sec in the output. During more normal conditions of wave-dominated flow, the same problems do not seem to exist, but the possibility of such interference is still disturbing.

The taut wire system is complicated, and the installation of current meters is time-consuming and tedious. A hand crank is shown at the top sheave in Figure 2, but it has been necessary to use a two-ton chain hoist to move the wires at Station 3. Replacement of current meter probes and their cables takes on the order of 10 man-days. However, the system has many advantages. As we shall see in the next section, the taut wires provide a nearly rigid mooring system for the current meters, even in extreme storm waves, while creating minimal interference with the measured flow. Having the current meter probes hard-wired to the surface signal conditioners and recorders means that the status of the instruments may be easily monitored. Finally, the taut wires can be used to pull the current meter probes to the surface, eliminating any need for divers and greatly reducing the cost of maintenance.

MOTION ANALYSIS OF THE TAUT WIRE SYSTEM

Although the taut wires are far more rigid than any mooring system that can be used away from a bottom-founded structure, they will still have some motion in storm waves. Wave and current forces are considerable even on so slender a structure, and the resulting motions will cause errors in the recorded velocities. It is thus important to be able to predict the magnitude of the motion and correct for it if necessary.

To a reasonable approximation, the taut wire system shown in Figure 2 may be considered as a single string with variable properties along its length. If we take the x-axis running down the string and let the vector $\underset{\sim}{y}$ (x,t) represent displacement of the string in the plane perpendicular to the x-axis, the equation of motion for the string is:

$$m\ddot{\underset{\sim}{y}} = T\underset{\sim}{y}'' + T'\underset{\sim}{y}' + \underset{\sim}{F} , \qquad (1)$$

where T is the tension in the string, m is the mass per unit length, $\underset{\sim}{F}$ is the hydrodynamic force per unit length, and the primes and dots represent differentiation in x and t, respectively. Equation (1) is an approximation valid for small vibrations; that is, we neglect the vertical component of the motion.

The hydrodynamic force is determined from Morrison's equation,

$$\underset{\sim}{F} = \frac{1}{2} C_d \rho A \underset{\sim}{v} |\underset{\sim}{v}| + C_m \rho D \underset{\sim}{a} , \qquad (2)$$

where C_d is the drag coefficient, ρ is the density of water, A is the cross sectional area of the system, C_m is the added mass coefficient, D is the volume of water displaced, and $\underset{\sim}{v}$ and $\underset{\sim}{a}$ are the velocity and acceleration of the water relative to the system. Since the system responds essentially in a forced mode, arbitrarily determined initial conditions will only affect the solution near time zero and we can assume:

$$\underset{\sim}{y}\ (x,\ o) = \underset{\sim}{y}'\ (x,\ o) = 0\ . \tag{3}$$

In practice, the effects of the arbitrary initial conditions disappear in a few seconds, which is fortunate since there are a priori means of discovering the true initial conditions.

If we divide the cable into lengths Δh and take time in steps Δt, the variables can be written in the form:

$$\underset{\sim}{y}\ (x,\ t) = \underset{\sim}{y}\ (i\Delta h,\ j\Delta t) = \underset{\sim}{y}_i{}^j\ , \tag{4}$$

$$i = 1,\ \ldots,\ n$$

$$j = 1,\ \ldots\ .$$

With this notation, the usual finite difference approximations for the derivatives are:

$$\underset{\sim}{y}' = \frac{1}{2\Delta h}\ (\underset{\sim}{y}^j{}_{i+1} - \underset{\sim}{y}^j{}_{i-1})$$

$$\underset{\sim}{y}'' = \frac{1}{(\Delta h)^2}\ (\underset{\sim}{y}^j{}_{i+1} - 2\underset{\sim}{y}^j{}_i + \underset{\sim}{y}^j{}_{i-1}) \tag{5}$$

$$\ddot{y} = \frac{1}{(\Delta t)^2}\ (\underset{\sim}{y}^{j+1}{}_i - 2\underset{\sim}{y}^j{}_i + \underset{\sim}{y}_i{}^{j-1})$$

$$T' = \frac{1}{2\Delta h}\ (T_{i+1} - T_{i-1})\ . \tag{6}$$

To avoid numerical instability by round-off error amplification in an explicit finite difference method, the maximum length of the time step must be limited by:

$$\Delta t < \min_i\ \{\Delta h\ \sqrt{m_i/T_i}\}\ . \tag{7}$$

Unfortunately, in the present problem there is another source of instability which is more difficult to eliminate. In equation (2), the hydrodynamic force is a function of the relative velocity between the system and the water, which is exactly the information given by a current meter suspended on the taut wires. This means, however, that the calculated motion of the system has no effect on the hydrodynamic force so that there is no damping in the equations. Thus, the solution is unstable in a very fundamental sense. What is to be done?

The measured relative velocity is $\mathbf{v}$. If we let the true reference frame water velocity be $\mathbf{w}$ and the velocity of the water be $\mathbf{y}'$, then clearly

$$\mathbf{w} = \mathbf{v} + \dot{\mathbf{y}} \; . \tag{8}$$

The solution of equation (1) can be written symbolically as a functional of the relative water velocity so that:

$$\dot{\mathbf{y}} = F\,(\mathbf{v}) \; . \tag{9}$$

As we have seen, this formulation leads to a lack of the physically expected damping and thus numerical instability. But note that from combining equations (8) and (9):

$$\dot{\mathbf{y}} = F\,(\mathbf{w} - \dot{\mathbf{y}}) \; , \tag{10}$$

and if $\mathbf{w}$ is given, this system can be solved by a finite difference scheme. Unfortunately, we do not know $\mathbf{w}$; indeed, it is to be the final result of our calculations. However, if $\dot{\mathbf{y}}$ is small compared to $\mathbf{v}$, it is reasonable to make the approximate $\mathbf{w} \approx \mathbf{v}$ in (10), to get a first approximation of the motion:

$$\begin{aligned} \dot{\mathbf{y}}_1 &= F\,(\mathbf{v} - \dot{\mathbf{y}}_1) \\ \mathbf{w}_1 &= \mathbf{v} + \dot{\mathbf{y}}_1 \; . \end{aligned} \tag{11}$$

Successive approximations will then have the form:

$$\dot{\mathbf{y}}_k = F\,(\mathbf{w}_{k-1} - \dot{\mathbf{y}}_k)$$

$$\mathbf{w}_k = \mathbf{v} + \dot{\mathbf{y}}_k$$

For our purposes, numerical experiments have shown that $\mathbf{y}'_2$ is close enough to $\dot{\mathbf{y}}_1$ so that the first approximation is sufficient. Forward differences for the velocity vector and backward differences for the magnitude of the velocity in equation (2) were taken to prevent further instabilities.

The original taut wire system at the pilot Buccaneer station was rather simple, with the current meter frames clamped to one of the taut wires and the cables to the meters routed up the same taut wire. Since the hydrodynamic forces on the cable bundle are much greater than those on a single cable, one side of the system deflected farther than the other, thus twisting the meter away from its intended direction and introducing a directional error into the measurements. The problem was significant; at Buccaneer, we observed at least 20° of twist in 10-foot seas.

Analysis by the finite difference scheme showed that the twist problem would become enormous during hurricanes, with over 60° of twist in 40-foot waves. It would be very difficult to correct for such deflections in the study of either currents or wave particle motions. Thus, the cable bundle was reluctantly moved to a position between the taut wires, although this greatly complicated the design and installation. Some random asymmetry could remain, particularly where the cables must be routed around the meters, but it should be small. To get an idea of how a small symmetry would affect the system, we made a series of computer runs in which the system was symmetrical except for five feet of conductor cable on one taut wire next to the top meter. Figure 4 shows the predicted deflection, additional tension, and rotation for such a model of the taut wires at Station 1. The motions of the taut wires at the deeper water stations were actually less, since it was possible to clamp the taut wires to the platform near mean water level, where most of the wave force occurs.

An example of the effect of the taut wire motion on the measurements is shown in Figure 5, which shows the recorded and corrected velocity vector history during a 10-foot wave at the pilot station. Since the taut wire system was still unsymmetrical then, the figure actually represents a worst-case analysis for most of the OCMP data. The crosses and solid dots show the tips of velocity vectors at 0.5-second intervals, with the circled numbers the time in seconds since the start of the record. The measurements are represented by the crosses and solid line and the corrected measurements by the dots and dashed line. Although the wave field is confused and twist effects were present in the taut wires, the correction for the taut wire motion seems basically to produce a phase shift in the record which is less than the digitization interval. Thus the system seems to be rigid enough that the use of the correction program is not required, which is fortunate, since it is extravagant of computer time.

RELIABILITY AND ACCURACY OF ELECTROMAGNETIC CURRENT METERS

From our viewpoint, the most desirable feature of the electromagnetic current meters has been their very fast response time which permits accurate and explicit filtering to get the true current. Since the meters have no moving parts and are not subject to biological fouling, they also hold the promise of better reliability than meters using mechanical rotors. However, the induced voltages measured by the electrodes on the meter probes are very small, which means that the meters are sensitive to the slightest seawater leakage or shifting contact resistance. This type of problem usually produces a very noisy signal and is easily diagnosed even with the meter in the water, but it is still serious for any program that relies on long-term, unattended deployment. Early in the OCMP, such problems occurred in cable splices, underwater connectors, and in the probe electrodes. All of the fundamental design problems now seem to be cured, but successful manufacture and deployment of electromagnetic meters still require constant attention to detail.

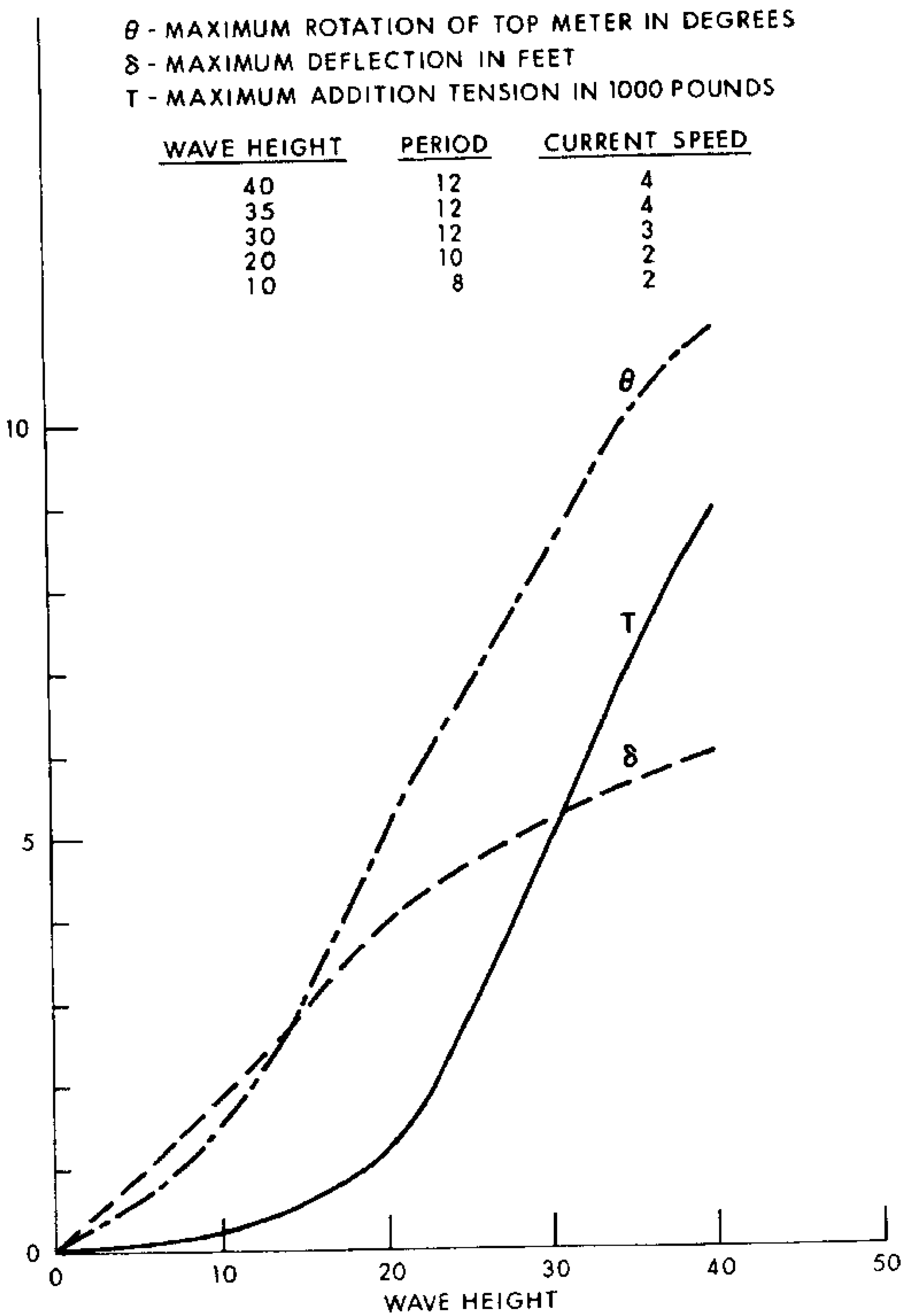

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Figure 4. Motion of slightly asymmetrical taut wires at OCMP station 1.

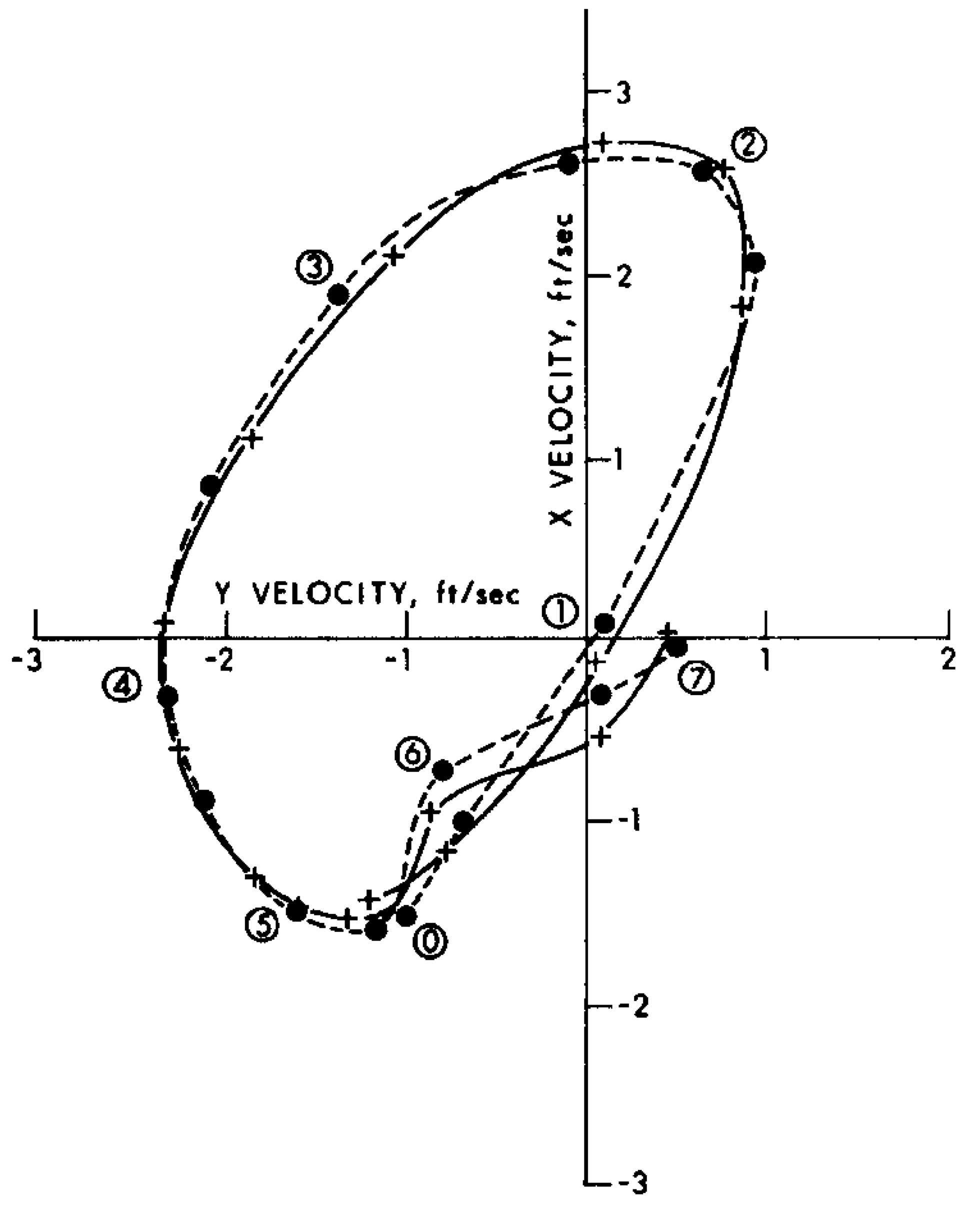

Figure 5. Comparison of recorded and corrected velocity data from OCMP station 1 in a ten-foot wave.

Tank tests of cylindrical electromagnetic current meter probes have shown that the meters do not have a perfect cosine response; that is, the meter output for flow off the central axis is slightly less than it should be. This is an example of a type of problem that really presents no difficulty once the true response is accurately known. The measurements can be easily corrected for the response during data processing, and this has been done for all the OCMP storm data we have studied. The meters also include an internal calibration circuit which is switched on automatically once a day and which provides a check on the gain of most of the amplifiers in the circuitry.

We have performed no laboratory tests on the meters to define their accuracy, but some of our data provide a rare check on the total accuracy of the current meter and taut wire system during storm conditions. The simultaneous measurements by a wave staff and high frequency response current meter can be used to estimate the directional wave spectrum as discussed by Bowden and White (1966). Forristall et al. (1978) show how the calculations can be modified to take into account the Doppler shift caused by strong currents, such as those in tropical storm Delia. An example of such a directional spectral estimate is shown in Figure 6, where the curves delineate a surface whose height is proportional to the spectral density at a given frequency and direction of propagation. Such measurements are important in the study of the generation and propagation of wind waves.

One of the most important results of the spectral analysis is an observed value of the transfer function between the surface elevation and the subsurface velocity. A comparison of this measured value with that predicted by linear wave theory sheds some light on current meter performance. Figure 7 shows the ratio between the measured and theoretical transfer functions at Buccaneer at one time during tropical storm Delia. CM1 was at -13 feet, CM2 was at -33 feet, and CM3 was at -58 feet. For the part of the spectrum that had energetic motions; that is, below about 0.17 Hz, the measurements almost always agree with linear theory to within 10 percent, which would be very high accuracy for a current meter system operating under storm conditions. However, it is far from certain that linear theory accurately predicts storm wave kinematics. There are trends in the data which persist over various depths, meters, and times which may be symptomatic of nonlinear phase locking between harmonics. It would be interesting and important to further study these nonlinear effects, but calibration tests which would prove sufficient accuracy in the current meter system would be very difficult.

CURRENT MEASUREMENTS FOR CONSTRUCTION PLANNING

The type of current data required to support a construction project and the problems encountered in obtaining the data can be much different than for a design project. The differences involve timing, accuracy

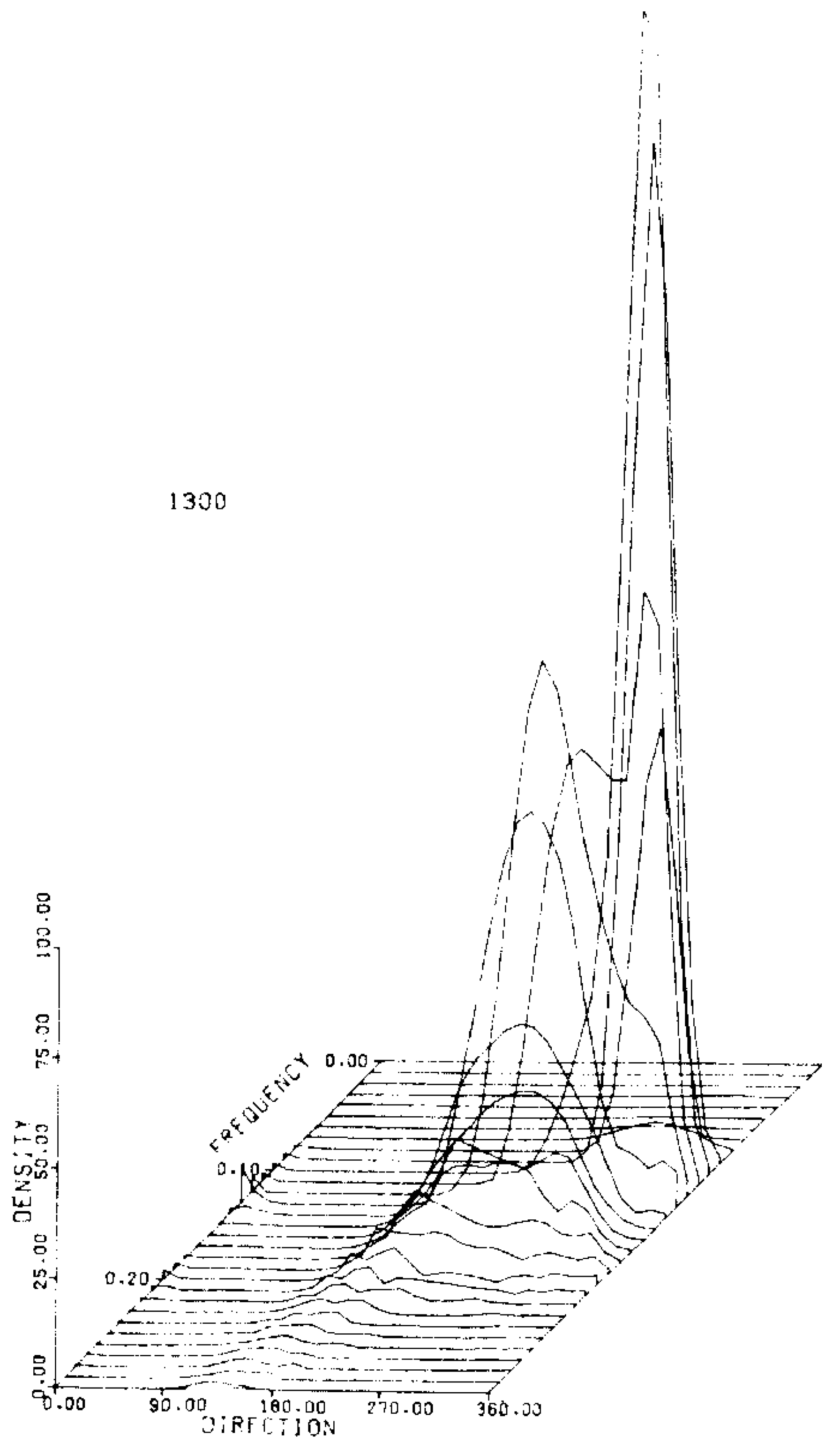

Figure 6. Directional wave spectrum measured at OCMP station 1 during Delia at 1300 CDT, September 4, 1973.

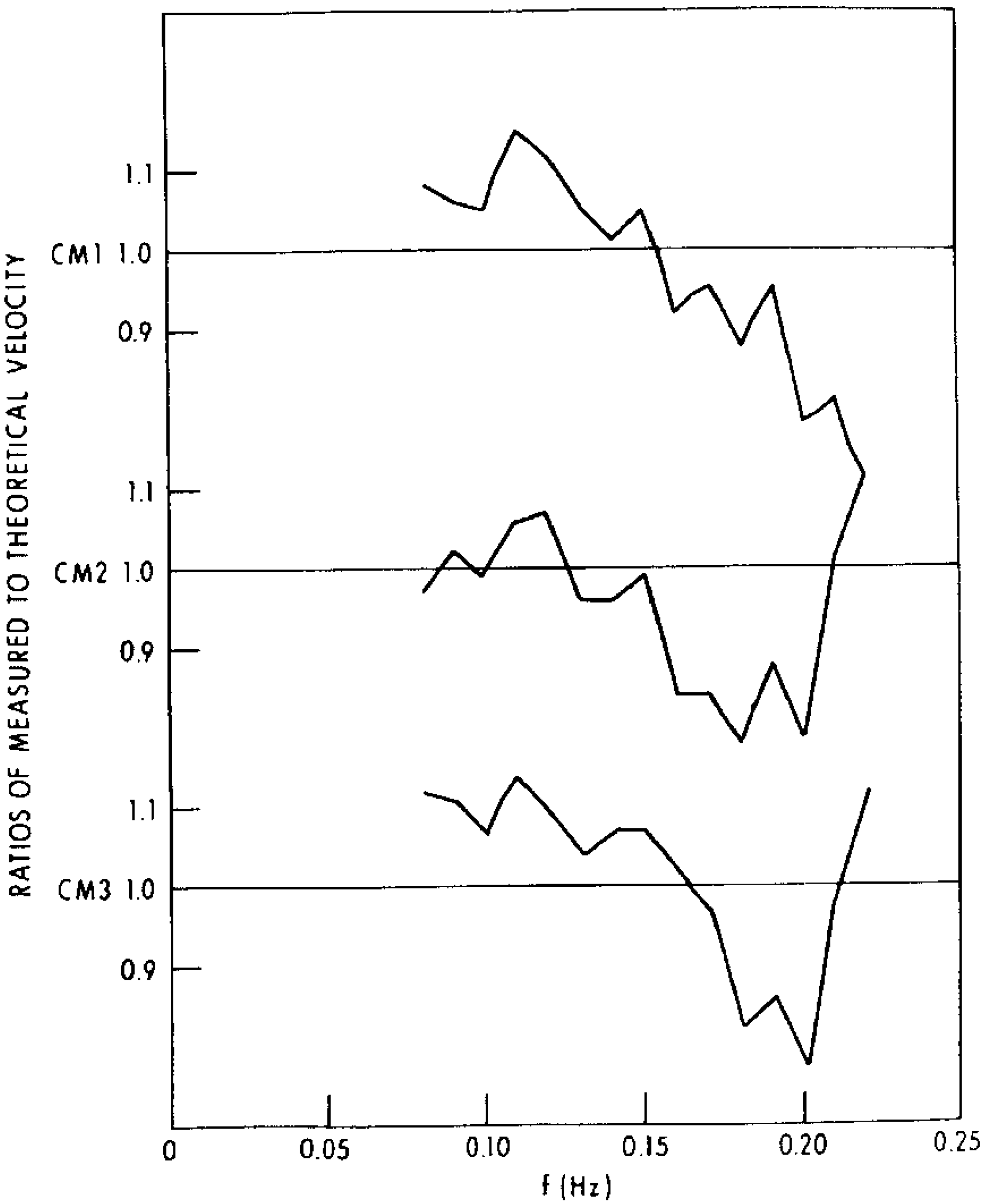

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Figure 7. Ratio of measured to theoretical velocity at OCMP station 1 at 1200 CDT, September 4, 1973.

requirements, and sensor location. A construction project has a set time schedule which can be delayed only at great cost. The rigidity of the schedule indicates that reliability is an extremely important factor in the selection of any instrumentation. Absolute accuracy is not as important as in many design studies, but repeatability between instruments is very desirable. The construction engineer cannot readily calculate the forces caused by a given current profile during a specific phase of the operations. However, if a particular current speed causes problems, it is important that the meters repeat that value when the same current occurs so that proper plans may be made. As in design studies, confident measurements of strong currents are much more important than accuracy at low velocities. Construction activities usually take place in locations where no fixed structures yet exist, so the taut wire mounting system previously described cannot be used. Real time data is imperative during construction, and this leads to additional difficulties.

Current measurements are not always needed during offshore construction. For many projects, the currents which could occur at the site present no problems to the construction activities. However, the unique nature of the Cognac project, as well as its site near the mouth of the Mississippi River, produced an impressive variety of current measurements. When completed, the Cognac platform will be 1050 feet tall and support up to 66 oil wells. The platform is being constructed from three prefabricated sections 12 miles south of the mouth of the Mississippi. The bottom section or jacket base section (JBS) was installed in the summer of 1977, and the remaining two sections will be attached to it in the summer of 1978.

Strong currents could adversely affect several phases of the construction. The JBS is approximately 400 x 400 x 200 feet and had to be lowered to a specific location and orientation. Then, 24 piles, each eight feet in diameter by 600 feet long, were lowered into pile guides on the JBS and driven with an underwater hammer. Physical and model studies indicated that moderate currents could cause vortex shedding on the piles, making this phase of the work difficult if not impossible. The middle and top sections will then be lowered and mated to sections already in place. Positioning will be affected by whatever current profile is present. The mooring system of the lowering barges must also resist all environmental forces during the operations, including the forces due to surface currents.

Current measurements at Station 3 of the OCMP showed that currents were strong enough to be of some concern in the general area of the Cognac project. However, the current regime was unpredictable, with large spatial and temporal variability. It thus seemed prudent to also make measurements at the site and season planned for the actual operations. A preliminary measurement program was conducted from the semisubmersible drilling vessel Pacesetter II while it was at the site during the summer of 1975. The vessel was rigged with a winch-operated Marsh-McBirney 555B electromagnetic current meter to obtain data at various depths, and a Marsh-McBirney 724 to obtain near surface data (Figure 8).

The winch-operated current meter was to obtain data from the 500, 700, 850, and 1000-foot water depths every hour and a profile at 100-foot increments at least twice per day. All data were recorded from visual readings of the meters. The near-surface (-15 feet) data were obtained hourly from visual readings using a 30-second output filter on the meter. An example of a current profile is shown in Figure 9.

Near-surface measurements were obtained without equipment problems from July 21, 1975, until program termination on September 15, 1975. The only data loss occurred during rig moves or when personnel were not available to read the meter. Some erroneous data were obtained during periods when the prop wash from supply boats affected the meter.

Deep measurements were much more difficult to obtain. The meter was run down the guidelines to the Blowout Preventer (BOP). This location produced some conflict between rig operations and current measurements, with the rig operations naturally taking precedence. In addition, data were lost due to problems with the winch, electromechanical cable, and the current meter power supply and preamplifier.

The measurements indicated that currents could possibly cause problems during the Cognac installation. Most of the energy was sub-inertial, uncorrelated with the local wind, and could not be predicted with presently available techniques. Plans were thus made to make further climatological measurements in the summer and fall of 1976. Since no exploratory drilling vessel was at the site at that time, a taut wire mooring with subsurface buoyancy and five Aanderaa current meters was used (Figure 10). The system was deployed in July 1976, with monthly service visits. Data recovery from the system was excellent until the mooring could not be found on the last monthly service in January 1977.

The current measurements made during the summers of 1975 and 1976, allowed the barge mooring system design to be finalized and gave the construction engineers an idea of the strength and persistence of the currents encountered at various depths. The measurements also gave the engineers some insight into the rapidity of current changes in the area so that they might be able to anticipate the advent of dangerous conditions by monitoring real time current information. Plans for making real time measurements during the installation were thus formulated.

REAL TIME CURRENT MEASUREMENTS DURING CONSTRUCTION ACTIVITIES

Real time acquisition of current data both near the surface and at various depths was necessary. The system devised to meet these needs

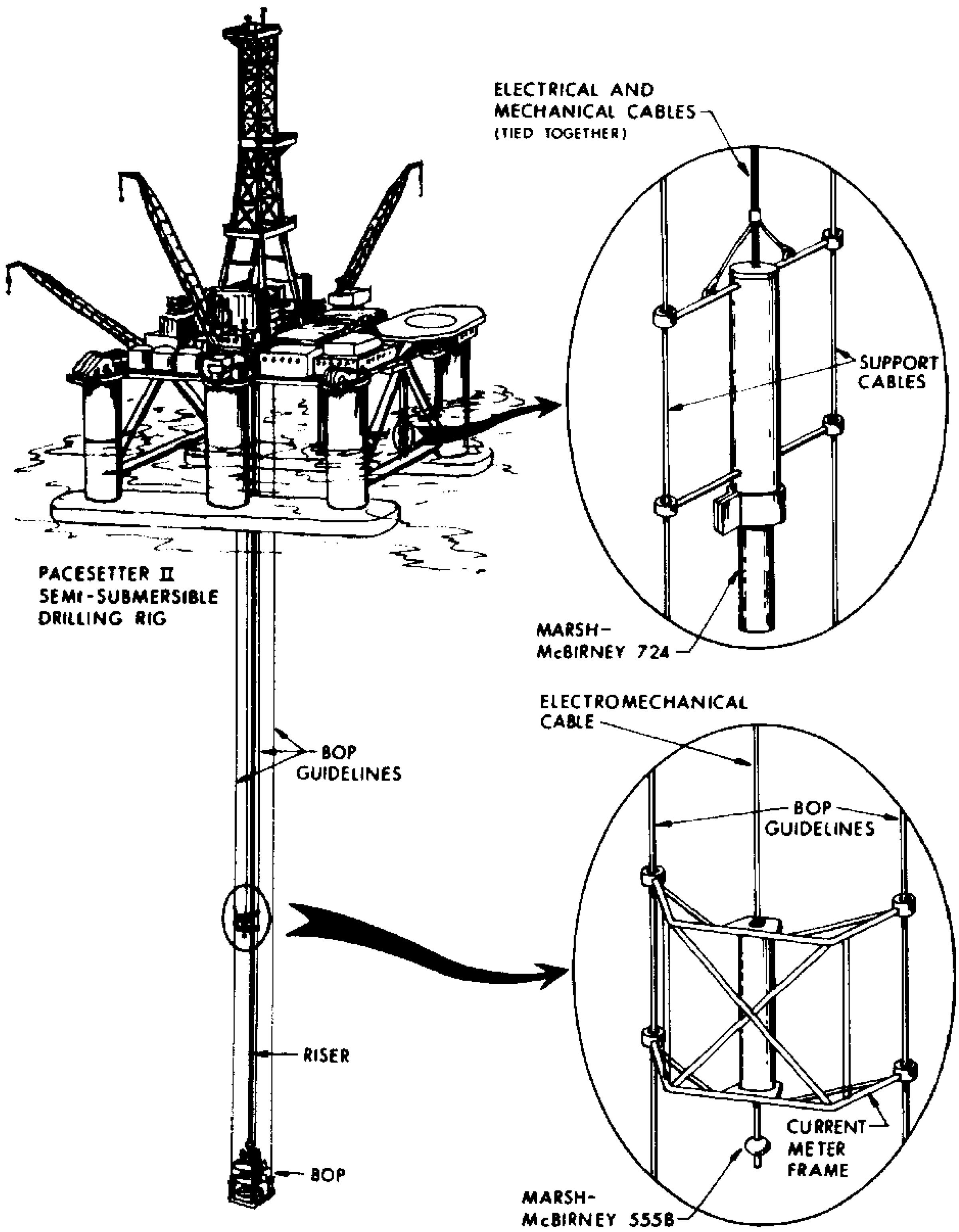

Figure 8. Current measuring configuration on the Pacesetter II.

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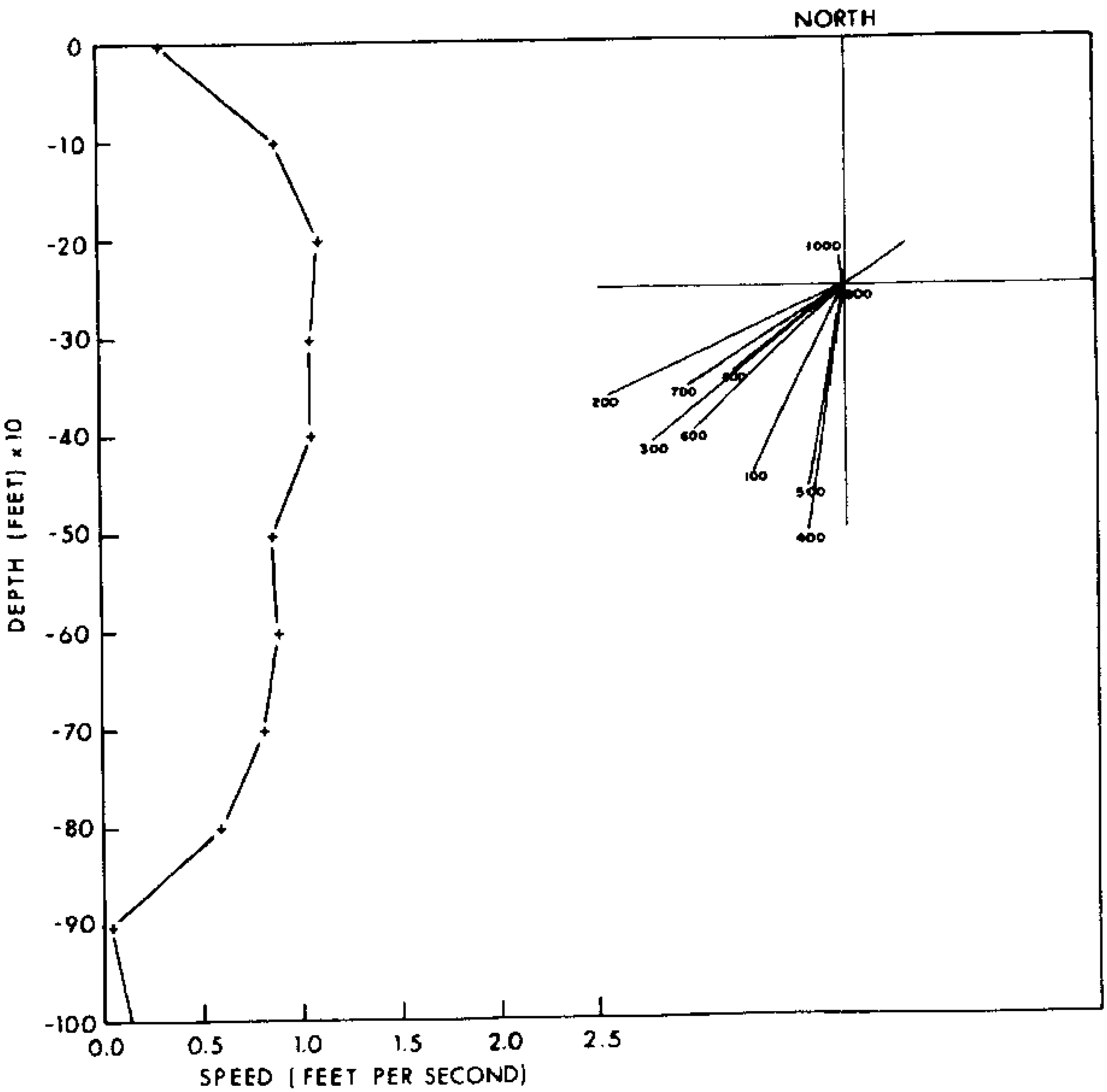

Figure 9. Current profile measured from the Pacesetter II on September 13, 1975.

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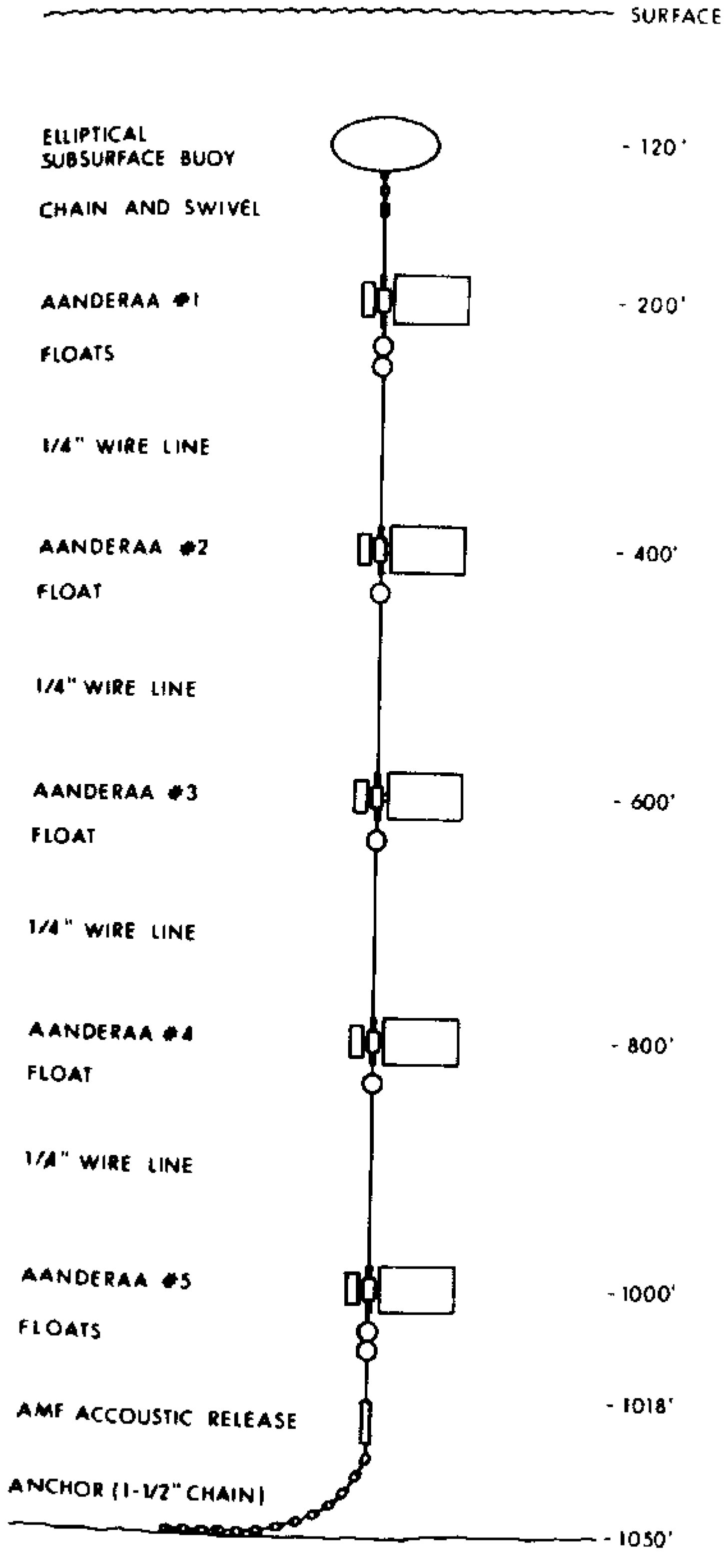

Figure 10. Aanderaa current meter mooring used in the Cognac site survey.

included two barge-mounted Marsh-McBirney 524 electromagnetic meters, two buoy-mounted Cyclesondes, and a backup winch-mounted Cyclesonde (Figure 11). The barge-mounted meters were hardwired into the barge control room and the Cyclesonde data were telemetered from their buoys. The near-surface meters provided continuous data, while the Cyclesondes took a current profile every hour, alternating between moorings.

Since Cyclesondes had not previously profiled to a depth of 1000 feet nor been used in an area where current magnitudes up to 100 cm/sec might occur, the manufacturer had to design essentially a new instrument. The instruments were field tested in the Atlantic Ocean off Florida and were then calibrated in the ONR tow tank at Bay St. Louis, Mississippi. The tests showed that with individual calibration curves for each instrument rotor, the accuracy in the tow tank was two to three cm/sec rms. Use of an average calibration curve for all rotors reduced the accuracy to five percent of the reading for the planned measurements, which was still sufficient for construction operations.

At the beginning of July 1977, the Cyclesondes were installed on their moorings at the Cognac site and began obtaining current profiles. Measurements were made until early October, when the 1977 phase of the construction activities ended. There were some instrument failures, but the redundant systems ensured that current profiles were almost always available. An example of a Cyclesonde current profile is shown in Figure 12 to indicate the complicated vertical structure often observed.

During late August when the site was abandoned because of approaching hurricanes, the Cyclesondes were left on their moorings. After the storms, one of the instruments could not be located. The other was found at the bottom of its mooring. Unfortunately, a mistake made during the retrieval of the mooring resulted in the loss of this instrument also.

The surface meters performed well with no problems occurring with the meters themselves. However, data were lost on several occasions when boats ran into the frames holding the meters, causing the cables to be severed. These problems demonstrated the wisdom of choosing independent moorings for the Cyclesondes.

The 1977 phase of the Cognac installation was completely successful, and there is every reason to believe that the operations in 1978 will go just as smoothly. A similar real time current measuring system is planned for the 1978 operations.

A wide variety of different meters were used in support of the Cognac construction activities. Each of them worked well in the particular situation for which it was best suited, and no existing current meter would have been appropriate for all situations. One of the most important tasks of the instrumentation engineer is thus to choose the proper instrument for the job at hand.

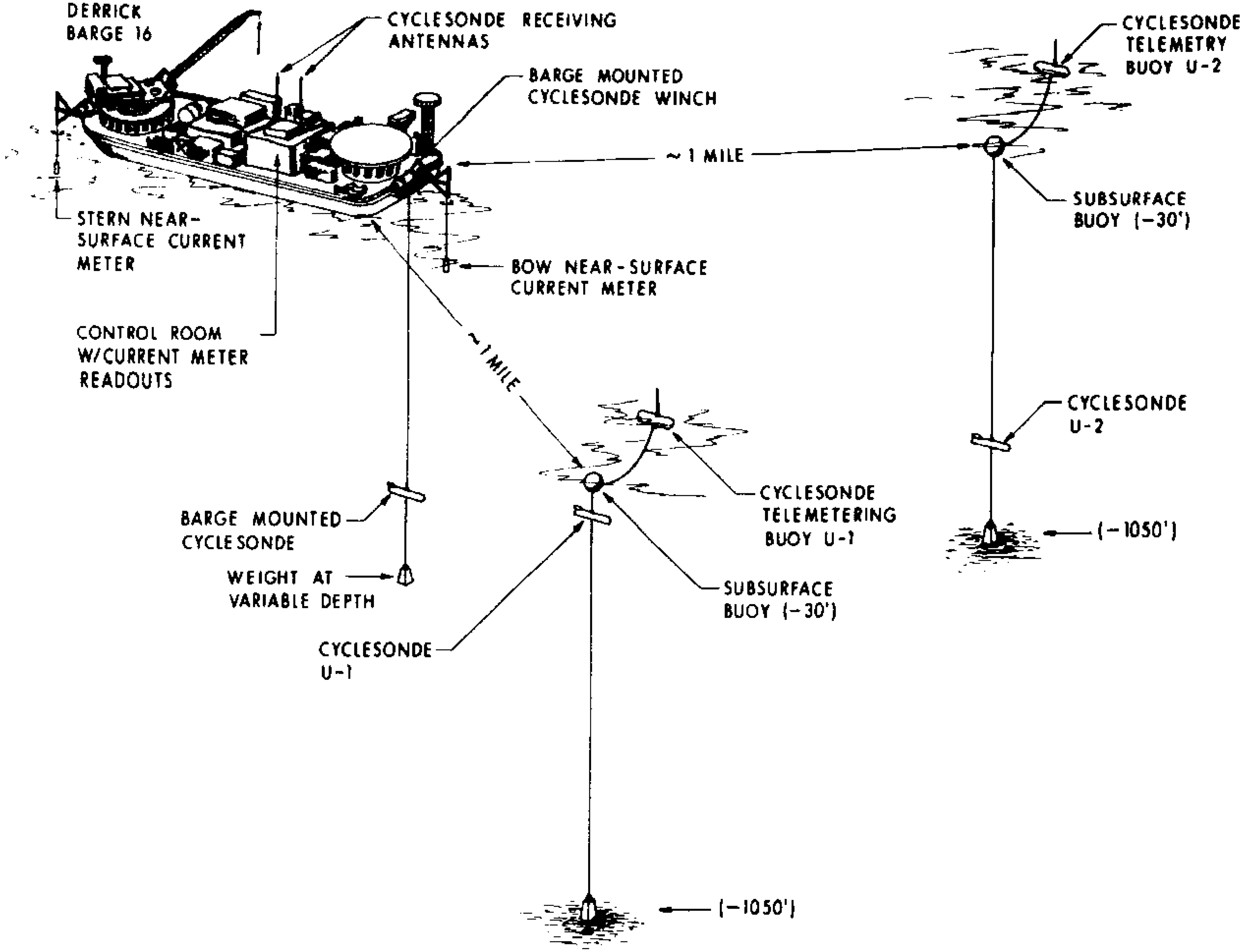

Figure 11. Real time current measuring system.

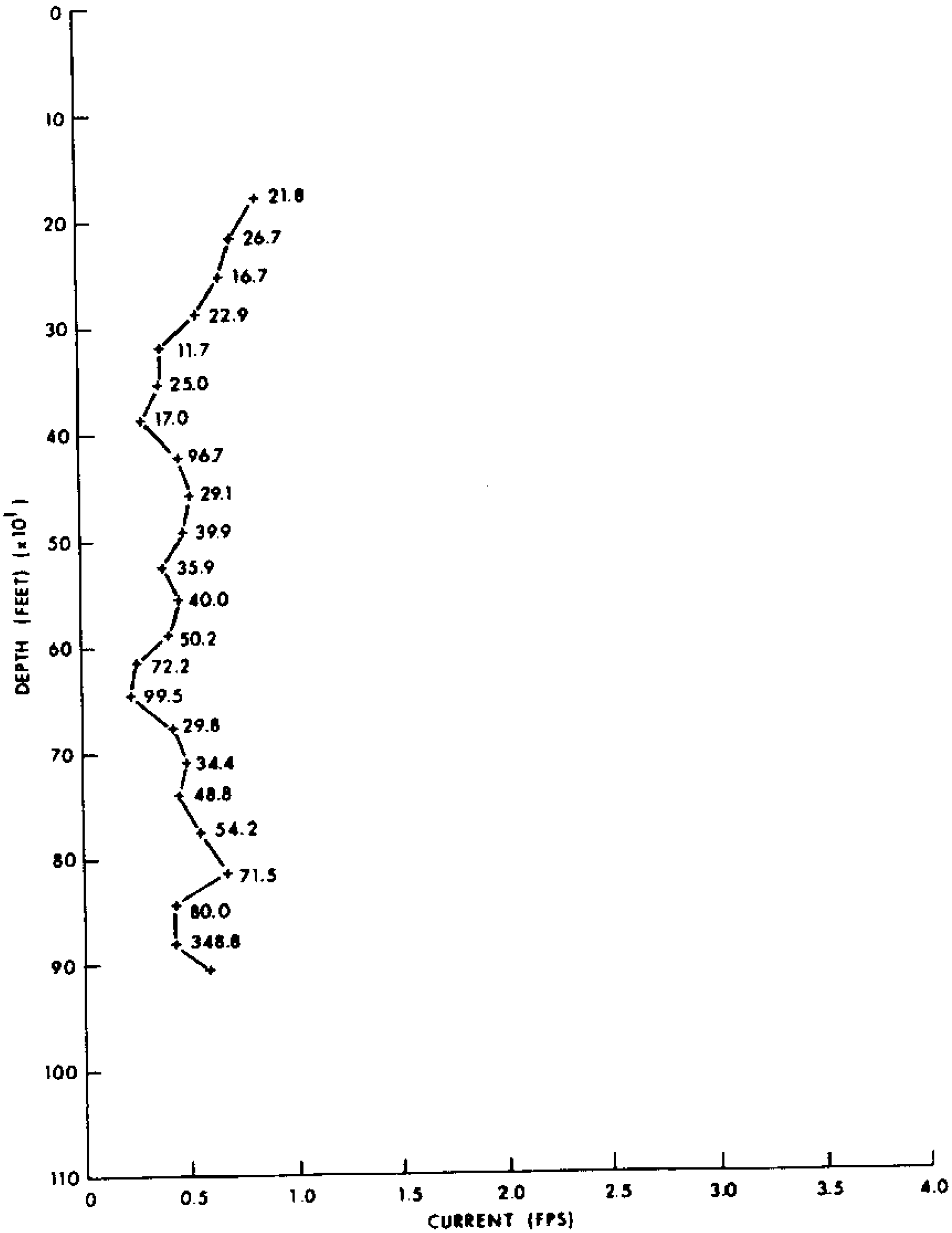

Figure 12. Sample Cyclesonde current profile measured during the Cognac installa

ACKNOWLEDGMENTS

J. M. Hall was largely responsible for the design of the OCMP instrumentation system and T. E. Long worked untiringly to make the instrumentation work as it was designed. The OCMP was managed by Shell Development Company with financial support from Amoco, Brown and Root, Chevron, Exxon, Mobil, Pennzoil, Seadock, and the U.S.G.S. None of the work described here would have been possible without the active support and encouragement of the Southern Region and Head Office Civil Engineering Group of Shell Oil Company. The crew of the Western Pacesetter II was very helpful while the current measurements were being made from their vessel. C. F. McFarlane and M. Lewes of Interstate Electronics Corporation were largely responsible for the measurements by the string of the Aanderaa meters and P. Skipp and C. Abbott of Marine Profiles Inc. operated the Cyclesondes.

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ENVIRONMENTAL IMPACT ASSESSMENT

Session Chairman: J. O. Blanton
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MEASUREMENTS OF COASTAL CURRENTS IN THE ASSESSMENT OF ENVIRONMENTAL IMPACT

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ABSTRACT

Pollutants ejected into the ocean environment are dispersed and transported by the water movements induced by wind forces, tides, bottom topography and shoreline configuration. Whether the pollutants have an impact on the environment depends primarily upon where they are carried and how much they are diluted along the way. We expect current measurements to tell us not only the trajectories followed by a given pollutant, but also the variations in the trajectories and the variations in the currents that affect the dilution of a pollutant. This information is provided by techniques that follow the movement of water (Lagrangian) and ones that measure water movement past a given point (Eulerian). This paper focuses on the latter, primarily because instrumentation measuring currents at fixed points can provide the required length of records over many months. This yields information on seasonal changes in circulation as well as detailed data on variations occurring over several seconds or minutes.

Current measurements must provide data on variations over seconds to hours to properly assess the dilution characteristics of circulation. These must also be made under a wide range of conditions to provide information on the changes in the characteristics from day-to-day and season-to-season.

Basic current regimes that govern transport and dispersion of material repeat themselves at a given location. Unattended current meters that record rapidly over periods of several months are required to determine the frequency of occurrence as well as the energy associated with such regimes.

WORKING CONFERENCE ON CURRENT MEASUREMENTS, JANUARY 1978. SPONSORED BY THE NOAA OFFICE OF OCEAN ENGINEERING AND THE DELAWARE SEA GRANT COLLEGE PROGRAM.

INTRODUCTION

Environmental impact assessment requires answers to three basic questions: (1) What are the chemical and physical characteristics of the pollutants and what are their rates and locations of input?; (2) How are the pollutants transported, and how are their concentrations changed from point of input throughout their journey in the ocean environment?; and (3) What are their effects on the environment, knowing the concentration that a pollutant would have at a given time and place? Knowledge of water circulation gained from actual measurements becomes crucial in determining how far and where pollutants are carried and how much they are diluted in the receiving waters. The answers to these questions will change with the winds, tides, and seasons.

We will concentrate on the measurements of currents in nearshore zones of the continental shelves and inland seas, including the Great Lakes. The development of energy resources and the production of energy in the coastal zones of the world affect other uses, such as recreation and food production. The coastal zone environment and man's use of that environment are strongly influenced by water circulation, thermal structure and the environment's capacity to disperse pollutants.

A variety of techniques are used to determine circulation regimes in nearshore waters. The initial diffusion and spreading of wastes from input locations are governed by small-scale, turbulent processes occurring over periods of several seconds to an hour or more. Lagrangian-type measurements are particularly useful at this scale if experiments cover a sufficient variety of environmental conditions. The larger-scale dispersion and transport of pollutants are governed by processes that are repeated over periods of hours to days. It is on these scales that recording current measurements at fixed locations play a dominant role. The weather cycles last several days and can completely change the direction of coastal currents. More important, the structure of the currents is likely to change during a weather cycle, a structure which could govern whether or not a pollutant is trapped against the shoreline or rapidly dispersed seaward. Determining the frequency of occurrence of these and other coastal current regimes becomes a major factor in assessing the likelihood of environmental impact. Such information is required to evaluate the output of hydrodynamic models of coastal currents, that are also an important tool in environment assessment.

CHARACTERISTICS OF COASTAL CIRCULATION

The coastal zone is unique in terms of circulation (Figure 1). The outer shelf and slope regions are influenced by the open ocean circulation. As distance to shore decreases, the ocean influence diminishes. The inner-shelf regime contains a top and bottom friction layer, separated by an interior zone. The interior is thought to attain some degree of geostrophic equilibrium after initial impulses from wind stress and

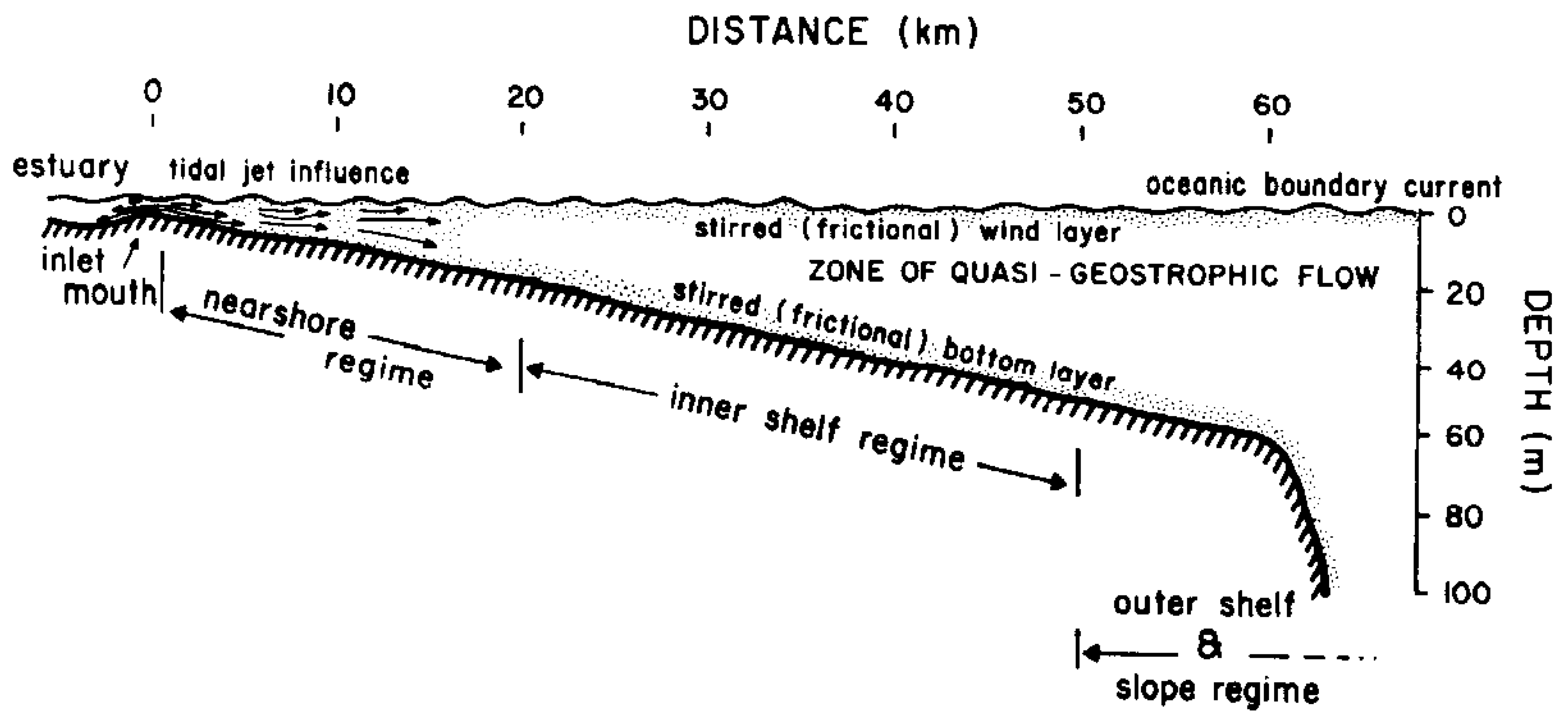


Figure 1. A schematic view of the circulation regimes on a "typical" continental shelf. The surface-wave influence in shallow nearshore zones requires that current meters respond to the wave-induced motion as well as turbulence generated by bottom roughness.

fluctuating boundary currents at the shelf's edge. The two friction layers are merged in the shallow water close to shore. Here is a zone of fast, shore-parallel currents and strong tidal currents. The bottom can be shallow enough to be stirred by large surface waves. The shoreline can be rugged, straight and smooth, or indented by estuaries.

A wide variety of processes account for the structure of coastal currents. The currents near the coast often have a jet-like structure (Charney, 1955; Csanady, 1971). The lateral shear across these currents plays an important role in dispersing material. Zones of maximum shear should be defined if effective dispersion of material is required.

Coastal currents are confined to a relatively narrow band some 10 to 20 km wide. Within this band, currents must adjust to the presence of the shoreline, where they are constrained to flow alongshore. Here, tidal and inertial currents whose vectors rotate in near circular motions far offshore are constrained to rotate in elongated ellipses. The inertial oscillations in the Great Lakes are effectively filtered out within 10 km from shore, where most of the kinetic energy in coastal currents occurs at frequencies less than 0.5 cycles per day (Csanady, 1971; Blanton, 1974). By contrast, off open ocean coasts, tidal currents appear dominant right up to the shoreline. The orientation of the major axis of the tidal ellipse is probably alongshore off straight uninterrupted shorelines, but the major axis can be perpendicular to shore near many tidal inlets (EG&G, 1974).

Reversals in shore-parallel currents within 10 to 20 km from the shore can cause wide fluctuations in water temperature. Currents flowing with the coast to the left in the Northern Hemisphere bring cold subsurface water into the coastal zone (upwelling). When the current reverses (coast to the right), the cold water is replaced by warm surface water (downwelling). During the change from upwelling to downwelling and *vice versa*, there may be large masses of inshore water exchanged with offshore water (Csanady, 1974). Upwelling and downwelling events represent a major process affecting the use of the coastal zone. They affect significantly the proper location of power plant and water intake lines, as well as the location of waste water outfalls.

Turbid water off coasts with high runoff appears confined within the same 10 to 20 km from shore (Manheim *et al.*, 1970; Bigham, 1973; Blanton and Atkinson, 1977; and Murray, 1977). Suspended material is transported up and down the coast by the shore-parallel currents. Off estuaries and inlets where the material is injected and where the major axes of tidal ellipses are most likely perpendicular to shore, tidal currents apparently play a fundamental role in governing the magnitude of offshore displacement (Figure 1). Under these conditions, the excursion of a water parcel is predominantly offshore for a little more than six hours before its motion turns shoreward. Root-mean-square tidal velocities between 30 to 60 cm/s in the offshore direction (representative of the east coast of the United States) would cause excursions between 7 to 14 km over one-half a tidal cycle. It appears likely that tidal currents act to confine material ejected into the coastal zone to distances on the order of 10 km.

CLIMATOLOGY OF COASTAL CURRENTS

Before credible assessments of environmental impact can be made, we must determine the characteristics of the nearshore currents and the frequency of occurrence of those characteristics that lead to effective dispersion and dilution, as well as those that lead to the opposite effect (Murthy and Blanton, 1975). Some years of study requiring current measurements at several locations are required before a current climatology for a coastal region can be determined. Recent studies have indicated that lateral velocity gradients can be large (Blanton, 1974; Blanton and Murthy, 1974). These gradients are as effective as turbulence as a dispersive process (Kirwan, 1975). Current measuring programs must also attempt to measure the magnitude of such gradients across the coastal zone.

A current climatology for a specified region is made up of three basic elements (Murthy and Blanton, 1975): (1) periods of stagnation or low currents, (2) periods of shore-parallel currents lasting 24 hours or longer, and (3) current reversals occurring between periods of shore-parallel currents of opposite direction. Each of these elements will be discussed, using an actual time-series of currents measured from two moored current meters only 1 km apart (Figure 2).

Stagnant Currents. The time period from 6 to 7 August was characterized by weak currents of less than 4 cm/s. Such slow, nearly stagnant flow regimes may last for several hours up to several days. These episodes may be thought of as interludes between well-defined longshore flow episodes (Blanton, 1974). Weak or stagnant flow can produce severe conditions which retard the dispersion of pollutants. Csanady (1970) and Murthy (1972) have demonstrated that dye accumulates in the area of injection. The effect was increased with slow onshore drift, whereby the dye pool was transported to the shoreline and trapped there. Areas where such conditions frequently occur are clearly undesirable for the disposal of wastes or accidental spills.

Shore-Parallel Currents. Steady shore-parallel currents result in regular effluent plumes. The concentration distribution across the plume is reasonably predicted by Gaussian diffusion models (Csanady, 1970). The zone of contamination around the plume's source can be estimated by knowing the average current speed, the current's persistence in a given direction, and the turbulent fluctuations of the current. A 3 to 4 day episode of steady currents appeared on 26-29 July (Figure 2). After this, steadier currents followed (30 July-2 August) but from the opposite direction.

These steady episodes are significant in defining upwelling and downwelling cycles. The steady currents of 26 to 29 July were

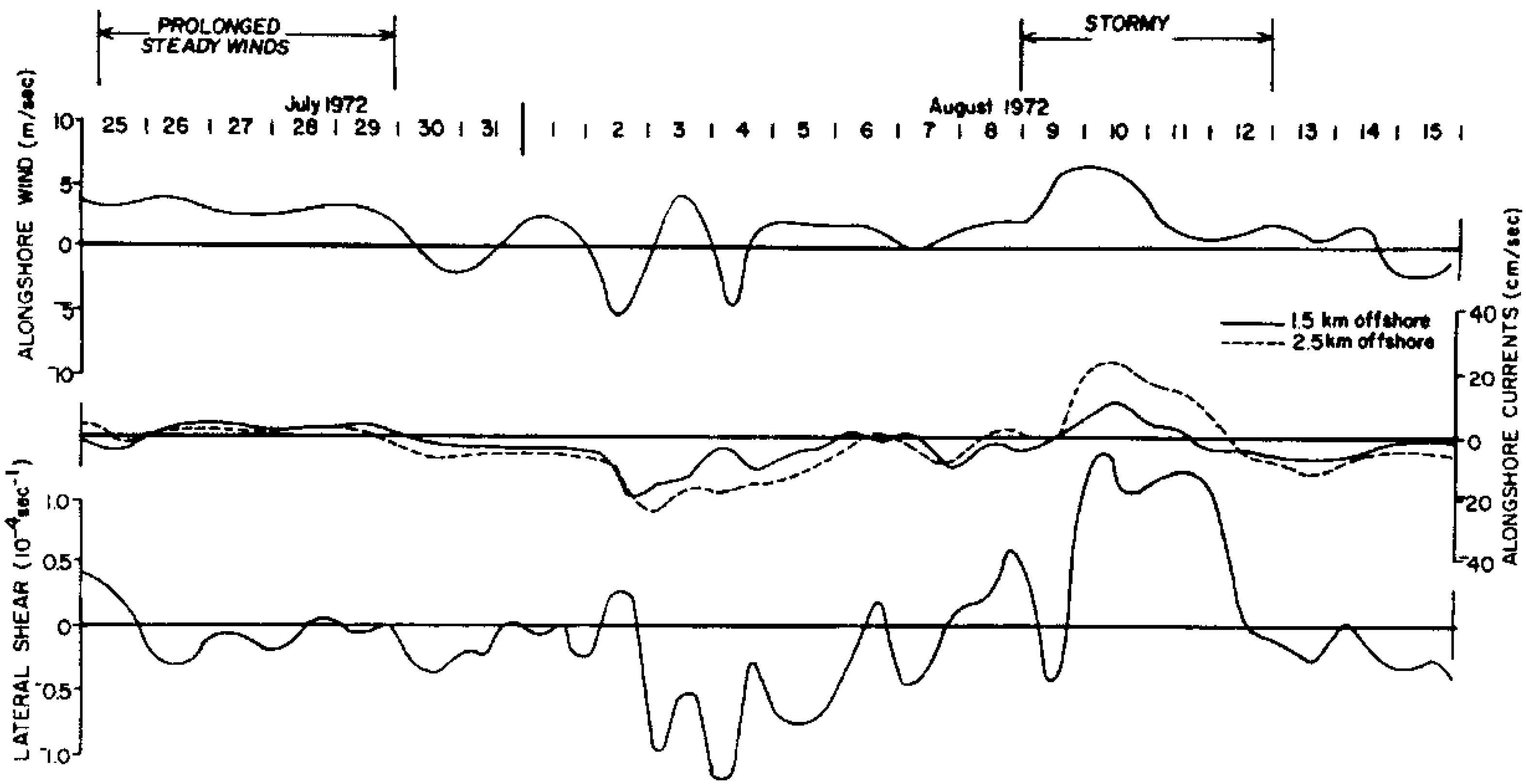


Figure 2. A series of alongshore winds, currents and lateral shear in a zone within 3 km from the north shore of Lake Ontario (from Blanton and Murthy, 1974). The data result from hourly values that have been smoothed to remove all fluctuations of 18 hours or less. Currents 1.5 km and 2.5 km offshore were measured at depths of 10 m in water depths of 13 m and 20 m, respectively. Current meters used were Plessey (Model M021).

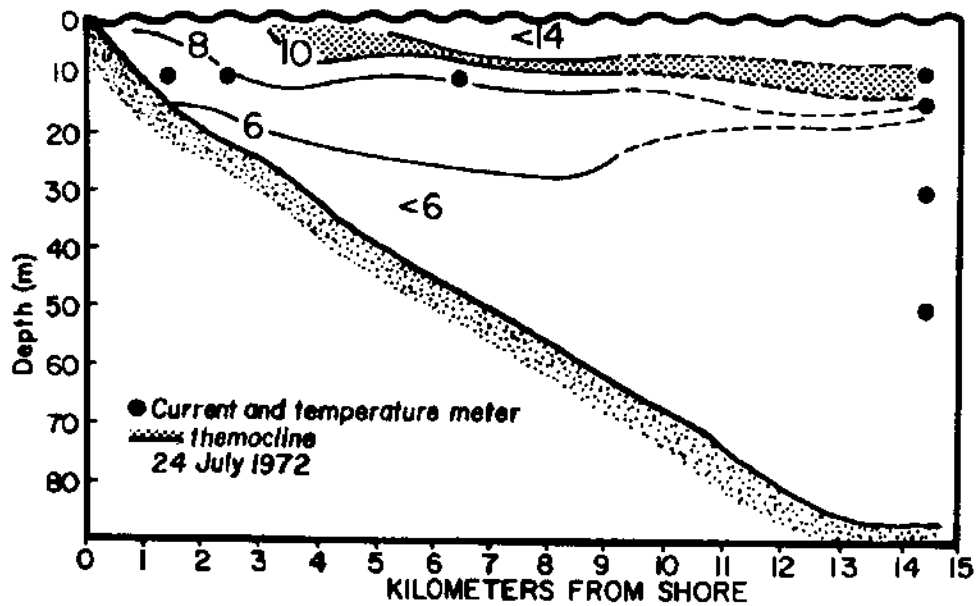
accompanied by an upwelling of cold water into the coastal zone (Figure 3a). The alongshore (eastward) currents were accompanied by components offshore near the surface and onshore near bottom. Surface effluents are likely carried away from the coast. After the alongshore current reversed (30 July), the thermocline downwelled (Figure 3b) and the direction of the onshore-offshore currents reversed. Surface effluents can be transported shoreward during downwelling where they can contaminate a local area until the situation changes. The degree of severity of such situations depends on many factors. Unless the speeds and associated turbulent fluctuations of the currents are high, the situation is basically unfavorable.

Shifting Currents. The transition between periods of shore-parallel currents is usually accompanied by complete reversal of the direction of currents. As discussed, we can expect a corresponding change of thermal structure from upwelling and downwelling and *vice versa* (Blanton, 1975). Five reversals may be seen in Figure 2. During times when currents are reversing or accelerating and decelerating, large differences in shore parallel currents can occur over 1 km distance. This is illustrated by large values of lateral shear from $0.5 \times 10^{-4} s^{-1}$ to greater than $10^{-4} s^{-1}$. The slope of the bottom is thought to be an important parameter in creating these large differences. Blanton and Murthy (1974) compared the lateral shear and turbulence values between steady currents and shifting irregular currents. The results are repeated in Table 1 for the alongshore current. The current meter data contain turbulent and wave-like oscillations about the smoothed curves in Figure 2. These are denoted as $\overline{v'^2}$. The smoothed oscillations of current around the mean speed for an episode is denoted $\overline{V'^2}$. The major result in Table 1 is the large increase in $\overline{V'^2}$ compared to $\overline{v'^2}$ under stormy conditions. The lateral shear increased by more than one order of magnitude.

The mixing and dispersing of effluents during shifting and reversing currents are very efficient (Csanady, 1970; Murthy, 1972). Figure 4 shows a comparison of dye concentration across the same plume before and after a current shift. The well-defined concentration peak present before the shift has been skewed off center, and the dye has been dispersed more uniformly across the mixing zone.

CONCLUSIONS

Each particular coastal area experiences a complex system of coastal currents whose effectiveness in mixing and diluting pollutants to acceptable levels is highly time-dependent. Major changes in effectiveness occur from day-to-day at a single location. Since the processes that govern circulation vary not only from hour-to-hour but season-to-season, fixed-point current measurements over long time periods are required to assess the dilution potential of water receiving effluents. Three basic current regimes can usually be identified from long records at a given location. The frequency of occurrence of each regime is important knowledge in environmental assessment.



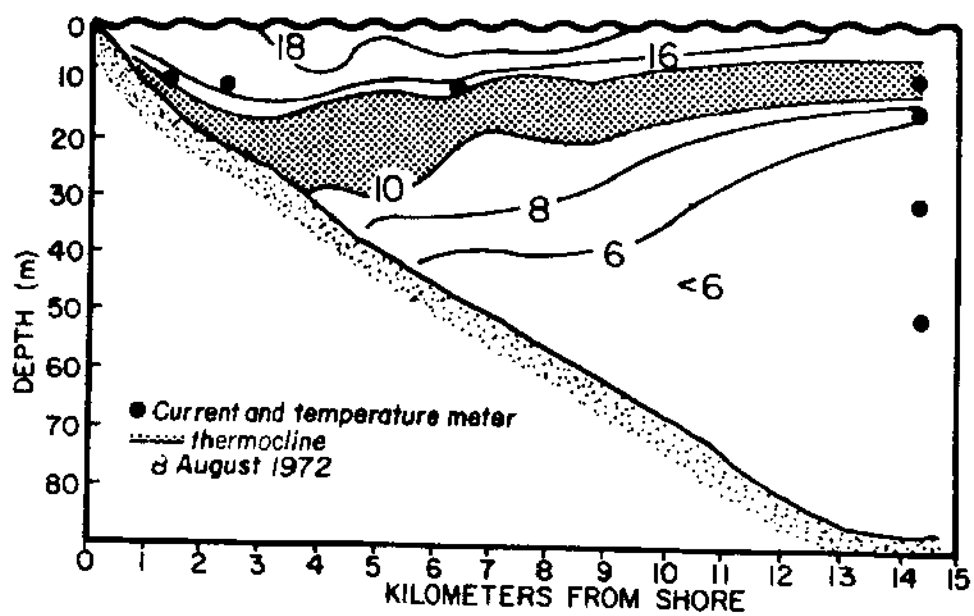


Figure 3. A vertical representation of temperature structure along the north shore of Lake Ontario from data obtained in 1972 by the University of Waterloo's Coastal Chain Project. The two dots (o) closest to shore mark the locations from which came the corresponding current meter data in Figure 2. (a) upwelling, 24 July; (b) downwelling, 8 August. (From Blanton, 1975).

Table 1. Turbulence parameters compared with lateral shear averaged over the duration of the episodes marked in Figure 2. Steady winds (3-4 m/s) were characteristic of the 25-27 July episode. Stormy winds (< 6 m/s) were characteristic of the period 9-12 August. Parameters for the currents are tabulated using units of cm/s at 1.5 and 2.5 km offshore (from Blanton and Murthy, 1974).

	Steady winds (3-4 m/s)		Stormy winds (< 6 m/s)	
	1.5 km	2.5 km	1.5 km	2.5 km
Mean alongshore (east)	+2.1	+2.4	+2.5	+10.2
Mean offshore	-1.0	-2.7	-0.2	- 1.5
Mean speed	4.2	4.8	6.9	14.0
$\overline{v'^2}$	2.4	4.5	8.0	21.4
$\overline{V'^2}$	5.3	3.7	37.2	108.4
$\partial V/\partial x$ $(10^{-4}s^{-1})$	-0.045		+0.75	

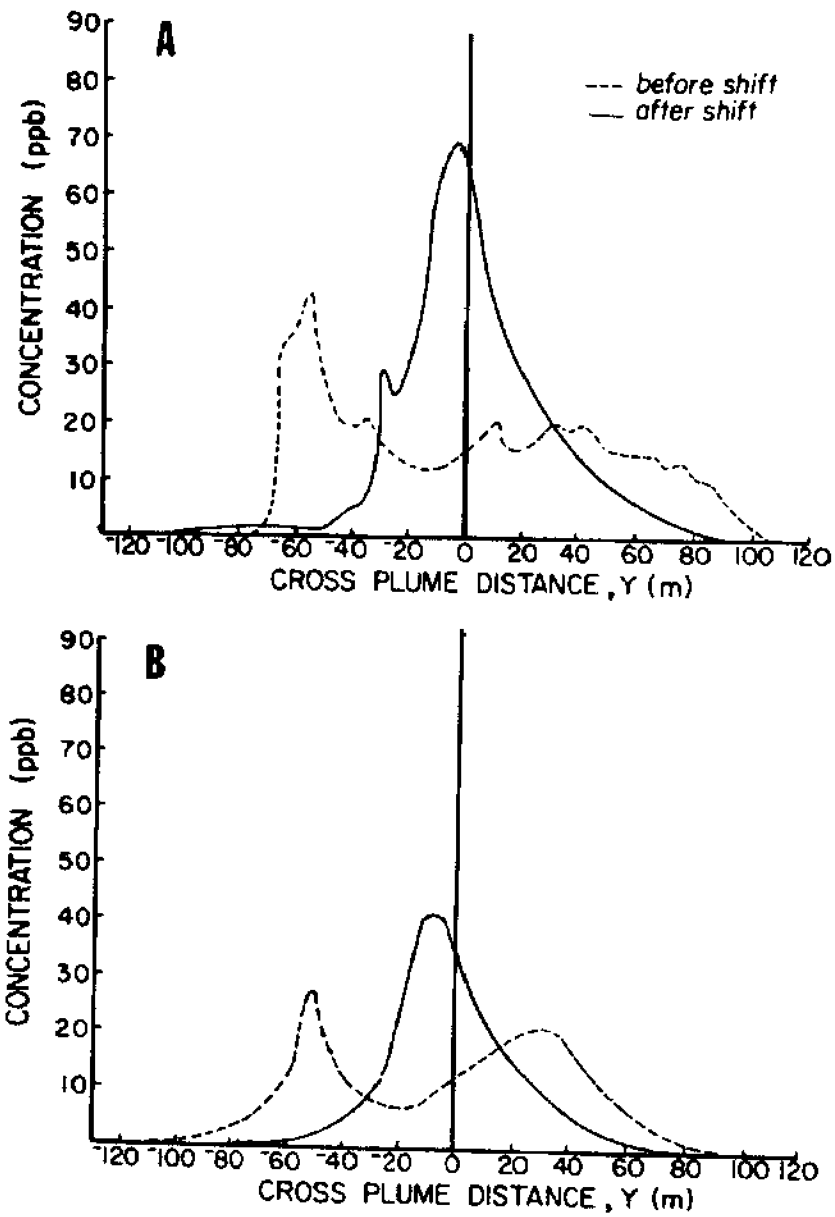


Figure 4. Concentration profile across a dye plume before and after a shift in currents. (From Murthy, 1972). (a) depth = 1.5 m; (b) depth = 2.5 m.

Current monitoring systems are required that are less expensive yet more reliable than presently available. The present systems are expensive to service and operate. Most do not perform adequately in the shallow, wave-contaminated environment. The amount of equipment a project can afford to buy and maintain is limited. Most systems capable of measuring currents in water less than 20-30 m deep are virtually homemade. The situation is not likely to improve before a well-conceived system approach is initiated. The team should be concerned not only with the current measuring instrument itself, but also with the mooring platform, the data logging devices and antifouling. One goal for such a team should be to design a system which is simple to use, easy to maintain, and which can attract large numbers of users to drive the cost per system down to a more manageable level.

ACKNOWLEDGMENTS

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CURRENT MEASUREMENTS FOR THE OCEAN THERMAL ENERGY CONVERSION PROGRAM

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ABSTRACT

The Ocean Thermal Energy Conversion (OTEC) Program of the Department of Energy is directed toward obtaining electrical power from a heat engine driven by the temperature differential between warm surface and colder subsurface waters. Preliminary design concepts envision a large surface plant, moored and/or actively propelled, attached to a long (order of 100 m's) cold water pipe. Water is pumped into the plant at the surface and bottom of the pipe, and discharged at some mid-depth. The designer of an OTEC plant must consider currents in order to minimize the effect of the plant on the environment and the effect of the environment on the plant. For instance, current data are required to evaluate the effect of the plant effluent on the environment. Also, the dynamic loading on the plant caused by ambient currents must be computed to design a suitable mooring or propulsion system. Current data are necessary to design a cold water pipe which will neither collapse nor bend. The observational programs developed for obtaining current velocity data at potential OTEC sites are presented.

WORKING CONFERENCE ON CURRENT MEASUREMENTS, JANUARY 1978. SPONSORED BY THE NOAA OFFICE OF OCEAN ENGINEERING AND THE DELAWARE SEA GRANT COLLEGE PROGRAM.

INTRODUCTION

The Ocean Thermal Energy Conversion (OTEC) Program is an alternative solar energy program of the Department of Energy. The program's ultimate goal is to extract energy from the sea in order to generate electrical power. The current measurement needs of this program are discussed in the following presentation.

Information on some initial plant design configurations is presented first to provide background for the remainder of the report. The requirements for ocean current data in the design process and the types of data which can satisfy these requirements will be discussed. Possible efficient methods for obtaining these data are identified. Finally, a brief discussior of the limitations in this method is given.

BACKGROUND

The OTEC power plant can be considered simply as a heat engine driven by the temperature differential between the warm surface waters and the colder subsurface waters. The immediate output of the plant is the production of electrical energy, the use of which is frequently discussed in terms of two concepts. One concept calls for the electrical output of a moored or grazing plant to be hard-wired to a land-based power grid (Trimble et al., 1975; Douglas, 1975; and Goss et al., 1975, for example). The other calls for using the electrical output of a grazing plant to power, at sea, an energy-intensive manufacturing process, such as ammonia production (Dugger et al., 1975). However, in both cases, many of the design features of the plants are similar.

Tables 1 and 2 summarize some of the preliminary proposals relating to OTEC platform and power plant design. Some of these design concepts are no longer under consideration, but all are presented for completeness. Also, the data in these tables may not represent the latest thinking of the proponents.

The design concepts, although diverse, have important similarities. All include a large, near-surface vessel to house the power plant, which will be attached to a long cold-water pipe. The warm water intakes are within 150 ft (50 m) of the surface, and the cold-water intakes range from 1100 feet to 4000 feet (370 m to 1300 m). All power plants require large amounts of warm and cold water to operate. The vertical temperature gradients driving the plants also are similar.

Figure 1 presents a portion of a milestone chart for the OTEC program. OTEC-1 and OTEC-5 are test platforms to be used to verify heat exchanger concepts and other OTEC systems. The Demonstration Plant is nominally a 100 megawatt output system for which the design criteria in Tables 1 and 2 have been developed. Several regions, shown on Figures 2 and 4, have been proposed as potential sites for moored OTEC plants.

Table 1: Preliminary Plant Design Specifications

Proponent	Hull Geometry, Dimensions, Material	Cold Water Pipe Design, Material	Mooring or Positioning	Manning	Life Expectancy	Depth Warm/ Cold Water Intake	Depth Warm/ Cold Water Discharge
Carnegie Mellon University	Cylindrical Spar, 2000' long x 50' wide, reinforced concrete	Lower part of spar	Guy wires	Unmanned	40 years	?/2000'	?/?
University of Massachusetts	Submerged twin-hull catamaran, hulls-870' x 100' reinforced concrete	Cylinder, 66' diameter, concrete	Single point mooring	Manned	40 years	45'/1120'	?/465'
Sea-Solar Power Incorporated	Rectangular surface vessel, 380' x 650', steel and aluminum	Stockade cylinder, 38' diameter, steel	Dynamic positioning	Manned	25 years	Surface/ 2000'	290'/150'
Applied Physics Laboratory Johns Hopkins University	Surface vessel, 275' x 225' x 175' deep, aluminum	Cylinder, 45' diameter	Grazing	Manned	?	Surface/ 2000'	Surface/ 175'
TRW	Cylindrical surface vessel, 340' diameter, 170' deep, concrete	Cylinder, 50' diameter, reinforced plastic	Positioning by water exhaust	Manned	25 years	100'/200'	400'/1500'
Lockheed	Submerged spar, 432' diameter 410' deep, concrete	Telescoping cylinder, 129' maximum diameter, concrete	Single point mooring	Manned	25 years	100'/200'	400'/1500'

Table 2: Preliminary Power Plant Specifications

Proponent	Net/Gross Power (MWe)	Heat Exchanger Type/Material	Enhancement	Heat Transfer Coefficient (BTU/hr-°F-ft^2)	Condenser or Evaporator area 10^6 ft^2)	Working Fluid	Vertical ΔT Required °F/°C	Warm/Cold Water Supply 10^6gpm	Warm/Cold Water ΔT °F	Remarks
CMU	100-140	shell & tube aluminum	tubes fluted on NH_3-side	1000	2-6	ammonia	40/22	8.5/ 8.1	3.6/ 3.6	Designed for optimum heat ex-change
U Mass	400/500	plate & fin 90-10 copper nickel	fins on NH_3 side	200-400	10-40	propane	32/18	7.6/ 8.1	1.9/ 5.0	Designed to minimize biofouling corrosion
SSPI	100/125	plate & fin aluminum	thin walls	200	3-10	R-12/31	36/20	10.0/ 4.9	3.0/ 6.0	Designed to minimize cost
APL-JHU	?	aluminum				ammonia	36/20		3.6/ 3.6	
TRW	100/122-138	shell & tube titanium		400	4	ammonia	38/21	~10.0/ ~7.8	4.1/ 4.1	Designed to use state-of-the-art technology
Lockheed	160/240	shell & tube		500	3	ammonia	33/18	6.3 8.1	2.2/ 1.7	Designed to use state-of-the-art technology
DSS Engi-neers, Inc.		plate & fin plastic		271		ammonia				

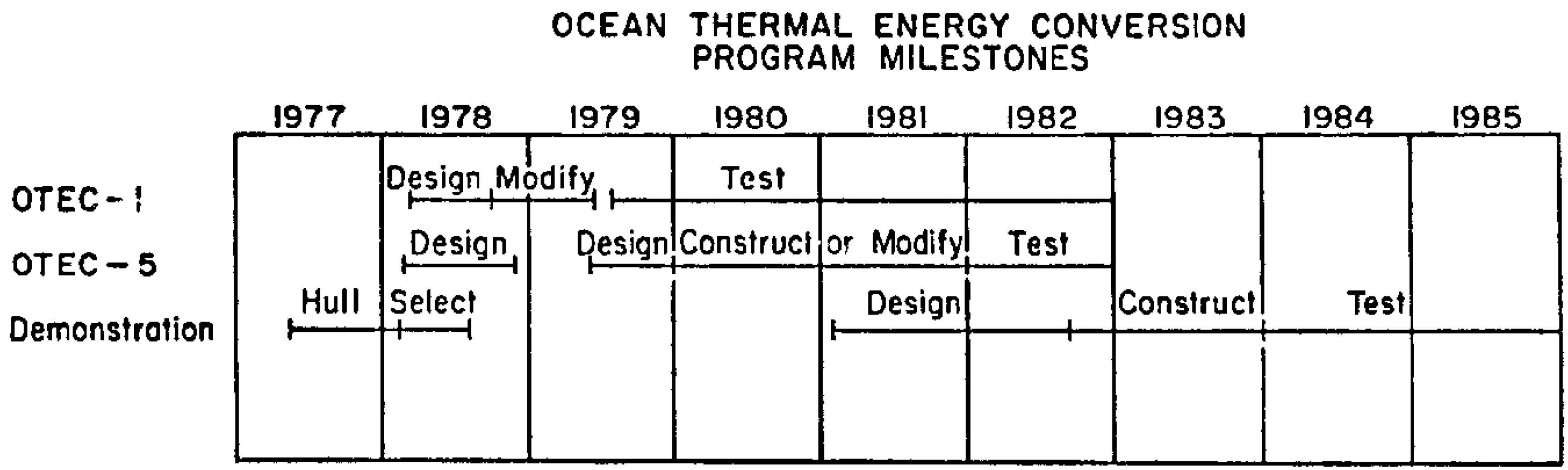
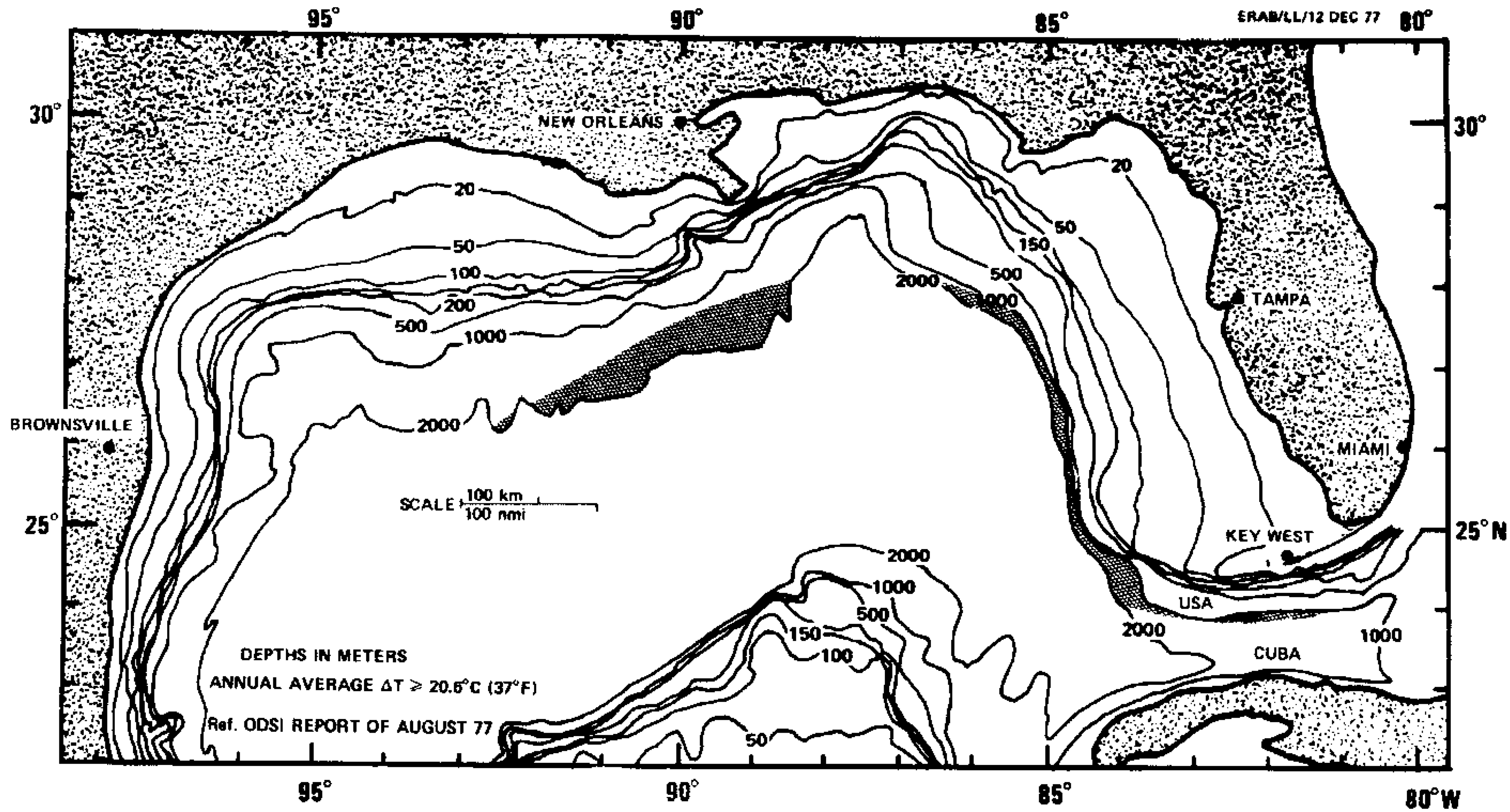


Figure 1. Project milestone chart for several OTEC components (ERDA, 1977).



OTEC RESOURCE REGION - GULF OF MEXICO

Figure 2. Potential OTEC sites (shaded areas) in the Gulf of Mexico.

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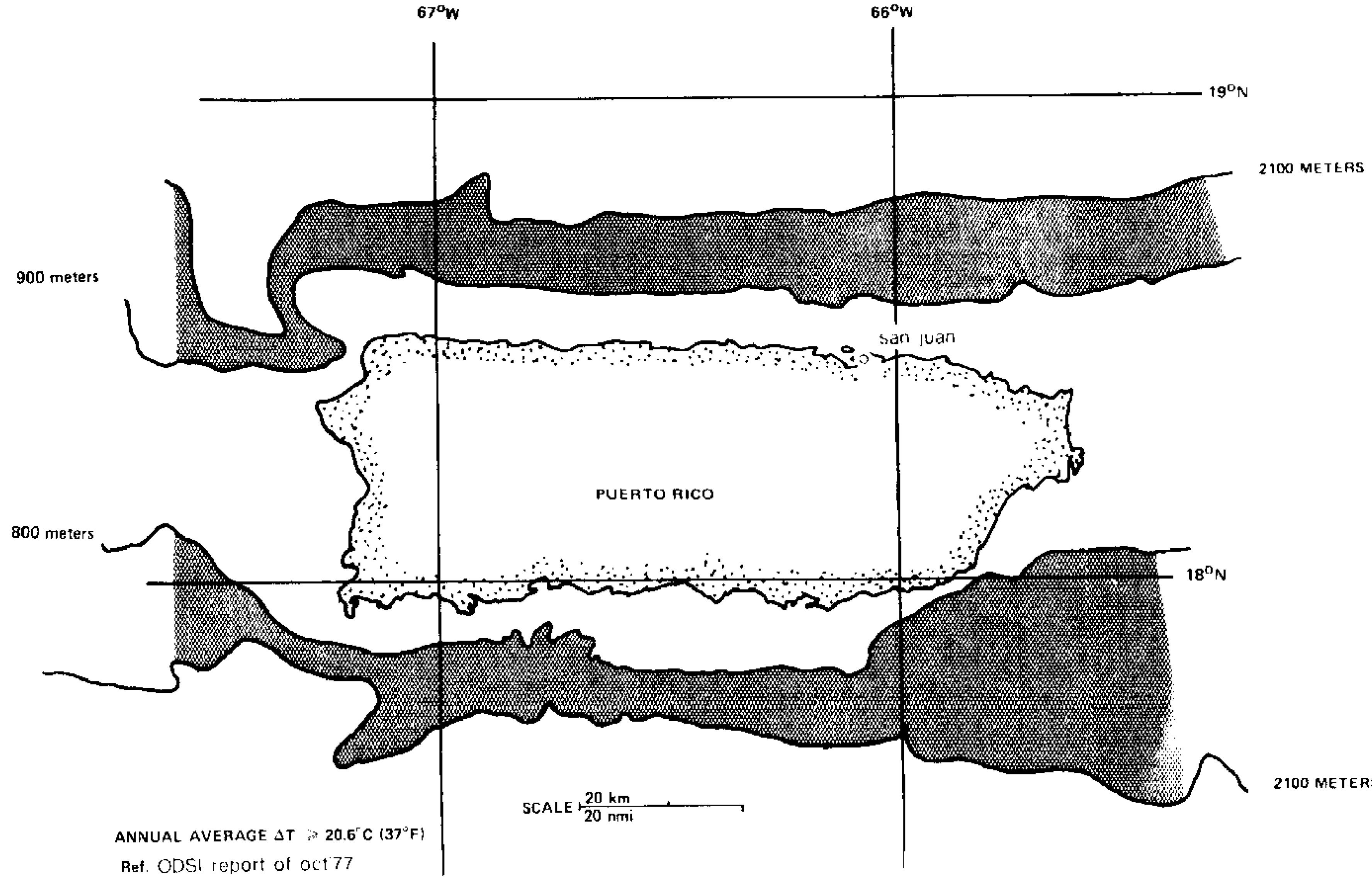
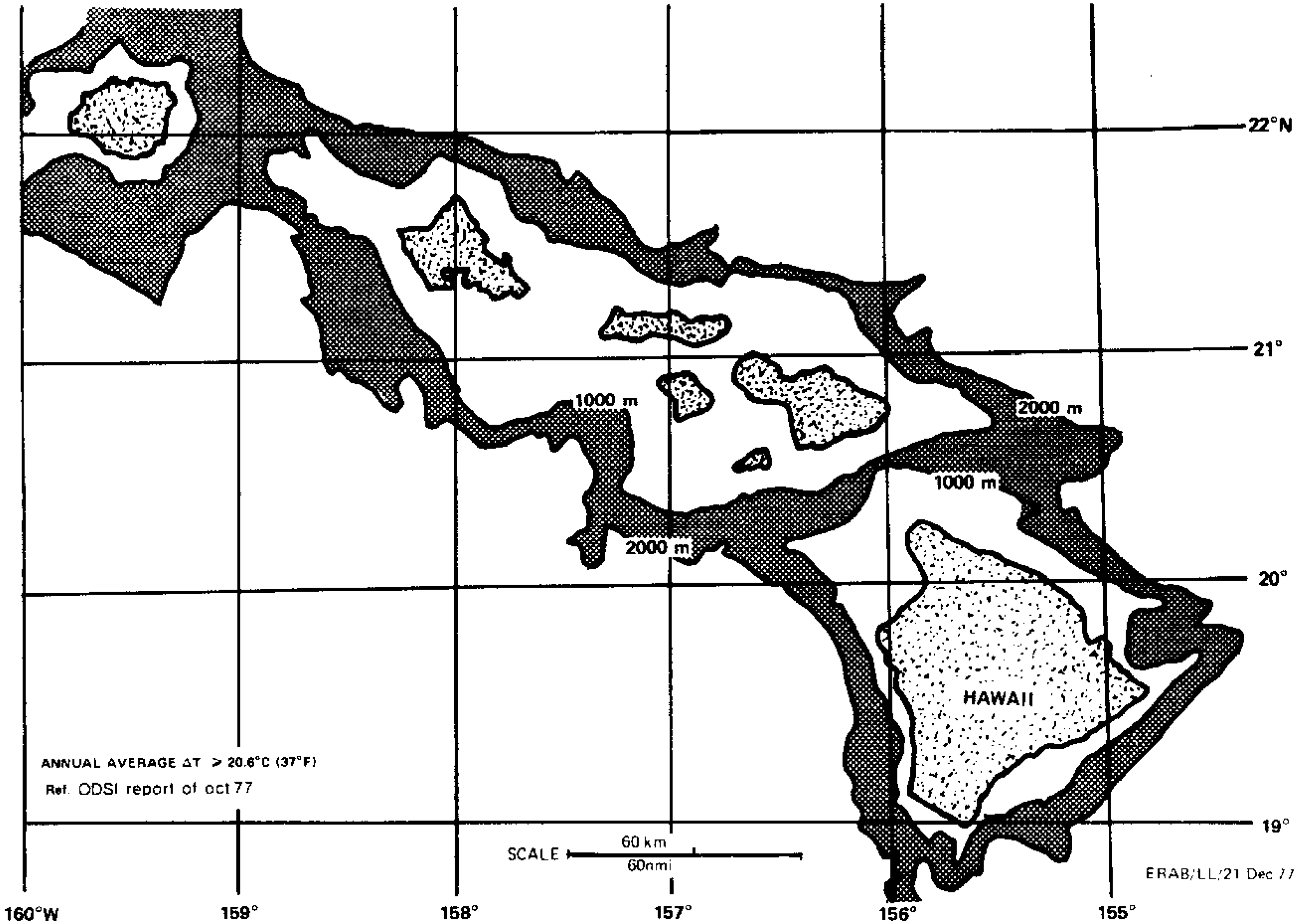


OTEC RESOURCE REGION - PUERTO RICO

Figure 3. Potential OTEC sites (shaded areas) in the region off Puerto Rico.



OTEC RESOURCE REGION - THE HAWAIIAN ISLANDS

Figure 4. Potential OTEC sites (shaded areas) in the region of Hawaii.

The South Atlantic off Brazil (Figure 5) has been considered as one potential site for a grazing plant. Current measurements are required at these sites for all stages of the program leading to the eventual commercialization of OTEC.

If it is assumed that the final design of the demonstration plant will be some variation of the concepts given in Tables 1 and 2, rather than a totally different design, then the common properties of these proposals allow for a generic specification for current data requirements. These requirements should be valid for the most important design similarities and are discussed next.

REQUIREMENTS FOR CURRENT DATA IN DESIGN AND IMPACT STUDIES

Current data are required in the design process and for impact studies to minimize:

(1) the detrimental effect of the plant on the environment;
(2) the detrimental effect of the environment on the plant;
(3) the cost of plant construction; and
(4) the cost of daily plant operation.

The final design of an OTEC plant will require accurate site-specific data. However, even at this early stage in plant development, the design requirements for current data should address these four items.

Ocean velocity fields will have an impact on many aspects of the OTEC design process. Examples of these impacts are presented in Table 3. Recirculation refers to the possibility of water discharged from the plant returning to the intake port and thereby degrading the thermal resource. A mixed discharge is one wherein cold and warm water are mixed internally in the plant before discharge, or in the near field of the plant upon discharge.

Before a sufficient data-set can be developed to address the impacts given in Table 3, the mechanisms by which the data are actually input into the design process are required. The American Petroleum Institute (API, 1977), for example, gives a recommended practice for the design of fixed offshore platforms, in which various data-dependent expressions are presented to evaluate the effect of the environment on the platform. A similar format will be followed for the OTEC ocean velocity data. However, in contrast to the API report, the relations presented here are merely examples of where ocean data are needed in the design effort. They are not guidelines for use in design.

Surface Vessel

Velocity Profiles. Vertical profiles of the horizontal velocity are necessary to compute the current loading on the plant. Current

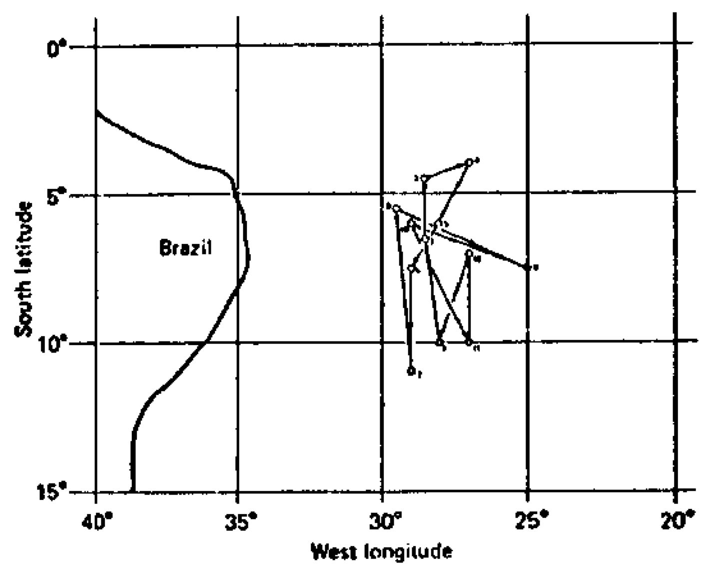


Figure 5. Possible trackline for a grazing OTEC plant in the South Atlantic (Francis and Seelinger, 1977).

Table 3: Impacts of Current Velocity on Design Process

1. Surface Vessel
    a. Drag computations
    b. Plant motions
    c. Streamlining requirements
2. Cold Water Pipe
    a. Drag computations
    b. Pipe buckling
    c. Bending moments
    d. Vibrations
3. Positioning Method
    a. Dynamic positioning propulsion requirements
    b. Static mooring requirements
        i. Strength of mooring
        ii. Scouring around anchor
4. Recirculation
    a. Potential for recirculation
    b. Type and position of discharge - mixed or separate
5. Environmental Impact
    a. Advection of harmful plant discharges

loading can be separated into two components, drag and lift (API, 1977). The drag component is caused by the frictional stress on the object, and the lift component is due to the unsteady forces linked to vortex shedding. Both forces are proportional to the current speed squared. Because of this dependence, the total plant loading is very sensitive to the velocity profile used. Streamlining to reduce coupling between the plant and medium may be required if the lift and drag forces are too large.

Near-surface current data also are necessary to determine the potential for motion of a particular plant design. Plant motion is a factor in evaluating worker safety and comfort.

Cold-Water Pipe Design

Velocity Profiles. Ocean current velocity data are required to compute the drag and lift forces, as described above, on the cold-water pipe (CWP). In addition, current velocity data are used to determine the minimum wall thickness of a CWP to avoid pipe collapse due to nonuniform external pressures generated by ocean currents. The minimum wall thickness required to prevent collapse is proportional to the ocean velocity raised to the two-thirds power (Wu, 1976). The minimum wall thickness required for a CWP to be free from local buckling is proportional to the ocean current speed.

Current Accelerations. Acceleration data are required to determine the possibility of CWP fatigue failure. Fatigue failure can occur if significant internal wave energy exists at the shorter periods (order of tens of minutes).

Positioning Requirements

Velocity Profiles. Current data are required to compute the total drag on the plant, CWP, and mooring line system, and thus determine mooring line and anchor requirements. If a drifting plant is used, current data are needed to compute propulsion requirements, since the propulsion power is proportional to the plant velocity cubed (Olsen and Pandolfini, 1975).

Bottom Currents. Data on bottom currents, particularly during extreme events such as hurricanes, are necessary to determine the potential for scour around an anchor.

Recirculation

Velocity Profiles. Sundaram et al. (1977) find that the percent recirculation is a function of several nondimensional parameters, one of which is Q/d^2u, where Q is the discharge flow rate, d is the separation between intake and discharge, and u is the current speed. Jirka et al. (1977) find that recirculation potential is inversely proportional to current speed. Therefore, site-specific current profiles are needed to evaluate recirculation potentials.

Distribution of Horizontal Currents. The identification of eddy structures at an OTEC site is important because of their possible role in increasing recirculation. Eddies (circular current structures) with spatial scales ranging from 10's to 100's of kilometers have been observed in the ocean, and the smaller ones in particular could quickly advect parcels of discharged water back to the plant. Small ambient currents (non-eddying) can be useful in advecting away plant discharges.

Environmental Impact

Small-Scale Current Variability. Local turbulence data are required to evaluate the effect of the momentum discharge of a plant on the local ambient current field (ERDA, 1977a).

Regional Current Fields. The advective field in the vicinity of an OTEC site determines the trajectories of harmful material which may be discharged from the plant.

OCEAN DATA TO MEET DESIGN REQUIREMENTS

Table 4 lists the current velocity data requirements to address the design issues discussed previously. Horizontal current distributions are listed as requirements for several reasons in addition to those described above. They are necessary to determine the validity of extrapolating data from a point to the surrounding region, since even a moored plant will experience some excursion around the mooring. The structure of current features also will determine the most efficient trajectory of a grazing plant.

Two types of data are necessary, those which address operational conditions and those which address extreme conditions. Operational conditions are those which occur regularly, following a seasonal cycle. This cycle could be induced by the seasonal march of atmospheric variables. The seasonal cycle can vary from year-to-year due to yearly differences in seasonal heating or cooling, for instance.

Extreme conditions occur at irregular time intervals and impose severe stresses on the plant. In addition to determining their frequency of occurrence and persistence at a site, it is important to be able to determine precisely when an event will occur. Only then can appropriate action be taken on the plant or ashore to reduce the impact of the event.

An extensive historical data-set is required to compute the variables given in Table 4. The operational current velocity data are available only from long-term, site-specific current meter arrays. Extreme conditions can be extrapolated to the site from data collected in regions with similar ocean conditions. The operational horizontal current distribution can be estimated from geostrophic computations. These data can be used in environmental impact studies and in determining power requirements for

Table 4: Current Data for Design

Current Variable	Vertical Spatial Resolution	Horizontal Spatial Resolution	Temporal Resolution	Additional Requirements
1. Velocity profiles a. Operational	0, 30m, 100m, 200m, 300m, 600m, 1000m	Site-specific	Tidal (i.e. diurnal)	Additional vertical resolution at subsurface maxima, countercurrents, etc. Variability about tidal cycle.
b. Extreme	0, 30m, 100m, 200m, 300m	Site-specific	Event time-scale	Frequency of occurrence, persistence of event, predictability
2. Distribution of horizontal currents a. Operational	Sea surface, discharge depths	25 km	Monthly	Variability about monthly mean
b. Extreme	Event-dependent	10 km	Event time-scale	Frequency of occurrence, persistence of event, predictability

drifting plants. The extremes in horizontal velocity shears, which are probably related to events such as hurricanes, can only be determined from closely spaced current measurements. These measurements can be Eulerian, such as by current meter, or Lagrangian, such as by drifting buoy.

The designer of an OTEC plant must consider the survival environmental state caused by a nonlinear combination of extreme wind and wave, as well as current velocity events at a particular site. One method of specifying an extreme condition is to determine the magnitude of the individual conditions, independent of their direction, and add them linearly. A second approach is to determine statistically the joint probability distribution of these events, considering both magnitude and direction. The second approach is likely to provide a more realistic estimate of the survival state and reduce the initial cost of the plant.

None of the sites proposed to date has sufficient data to meet the requirements stated above (Atwood, 1976; Bathen, 1975; and Molinari and Festa, 1977). Therefore, a data acquisition effort is required to ensure a data-set for input to the design and impact process.

All available data and literature should be reviewed to design an efficient measurement program. The data and literature should be examined for those conditions which could have significant impact on the OTEC operation at a particular site. For instance, hurricanes have been observed at the Puerto Rico and Gulf of Mexico sites (Atwood, 1976; Molinari and Festa, 1977), while Loop Current eddies have been observed at the Gulf of Mexico site (Molinari and Festa, 1977).

However, if no or minimal data exist, a reconnaissance survey is necessary to establish the background for a more detailed survey. Table 5 lists the requirements for such an effort. Requirements for temperature data are also listed, since these data can be obtained concurrently to evaluate the thermal resource. Many of these specifications are transferable to the detailed study.

A number of current meters exist which can meet the specifications in Table 5. Therefore, particular current meter types are not specified. It is important that the mooring be properly designed. The procedure for designing a mooring given by Walden and Silva (1976) is one means of ensuring that a mooring will survive environmental conditions.

Present state-of-the-art current meter design and mooring technology prohibit the inexpensive collection of in situ current data at depths less than 100 m. Therefore, this information must be approximated with current profile data from a ship servicing the deeper current meter moorings, or from Lagrangian techniques.

These data needs will be updated as the plant design becomes more refined. For instance, once the shape and draft of the platform are known, it will be possible to rearrange the vertical placement of the

Table 5: Site-Specific Reconnaissance Survey for Design

Ocean Variable	Instrument	Vertical Resolution	Horizontal Resolution	Temporal Resolution	Accuracy	Duration	Remarks
1. Temperature (vertical structure)	Thermister (thermister string)	0-300 m, every 50 m 300-1500 m every 200 m	on-site	hourly	±0.5°C	1 year	
2. Current (vertical structure)	Current meters on same mooring as above	1 mooring, meter placement 0-300 m, every 100 m, 300-1000 m, every 350 m	on-site	hourly	Direction: ±15° Magnitude: 10% of speed (minimum ±5 cm/sec)	1 year	Present state-of-the-art mooring technology makes surface measurements unreliable. If resources are limited, a minimum of 4 meters would be sufficient.
3. Temperature (horizontal structure)	STD or XBT	Continuous to 1500 m	25 km station spacing in a box around the site	every two months	0.02°C	1 year	Accomplished during servicing of meters. In addition a 3 day serial station on-site taking temperature and current profiles.
4. Current (horizontal structure)	Profiler	Continuous to 500 m	same as 3 above	same as 3 above	Direction: ±10° Magnitude: ±5° cm/sec	1 year	Same as 3.

current meters to sample more efficiently. When the depth and type of discharges are determined, more detailed current data can be obtained to evaluate recirculation potential.

LIMITATIONS IN PRESENT TECHNOLOGY IN REGARD TO OTEC

State-of-the-art current meter and mooring technology limit the usefulness of near-surface measurement techniques for OTEC. Inexpensive methods are required because of the need for measurements at many sites for long periods of time to ensure that severe events are sampled. This requirement for current measurements at depths shallower than 100 m, particularly during extreme events, eliminates most systems presently used.

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CURRENT METER MEASUREMENTS FOR ENVIRONMENTAL STUDIES

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ABSTRACT

Environmental impact studies differ from scientific or engineering studies in the uses to which the data are put, and because they may become the object of legal proceedings. This imposes unique requirements on the type and accuracy of current sensors. An environmental study must be done by any company wishing to build a major facility. Data and impact analyses are turned over to regulatory agencies, who in turn review or enlarge the analyses and issue their own Environmental Impact Statement. Typical analyses for coastal facilities are concerned with dispersion of thermal or effluent plumes; probability of advection of effluent to inhabited or otherwise critical areas; determination of mean velocities, tidal velocities, and other "climatological" parameters; and establishment of predictive modeling capability, for use in hindcast studies and for extrapolation to extreme conditions. Issuance of construction permits follows public hearings, at which opponents may attack the conclusions indirectly, by attacking the accuracy or adequacy of the data itself. Major current meter considerations thus are: (1) There is a need to accurately measure low velocities, which are important in dispersion studies; (2) There is a need for commercially available Lagrangian sensors, for direct measurement of probability of advective impact; and (3) There is a need for traceability in current meter calibrations, to avoid needless exposure of data to unwarranted criticism. On a higher plane, there is also a need for a methodology for current measurements in environmental studies, to establish achievable goals and assure credible results.

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My company is a consulting firm which has done work for large utility companies trying to obtain permits to build power plants in the coastal zone. I'm going to talk from the point-of-view of someone who has to collect and analyze oceanographic data for environmental impact assessment studies. I'm going to point out, in a very broad way, the distinction between these studies and scientific or engineering studies, and the consequent requirements for future current meter development.

The unique features of environmental assessment studies lie in the uses to which the data are put, and the possibility of involvement in legal proceedings. By way of background, we first note that any company wishing to do anything in the ocean that might affect the environment, must get permits to do so. This usually requires an environmental study, and the company would generally hire a consulting company, which specializes in such studies, to do the work. The data and the analyses produced by the consultants then go to the regulatory agencies in the form of an "Environmental Report." For a nuclear power plant, the Nuclear Regulatory Commission is the principal agency; in other cases, EPA may be. The regulatory agency may have guidelines for such studies; but for studies involving physical oceanography there are, to my knowledge, no such guidelines.

The regulatory agency reviews the data, adds its own analyses, and summarizes it all in the Environmental Impact Statement (EIS), which attempts to state whether or not the proposed facility would, on balance, be beneficial to society. But before the permit can be granted, public hearings are held, and at these hearings, the basis of the environmental impact assessment can be questioned in a quasi-legal forum. Opponents of a project might try to shake the EIS conclusions by attacking the accuracy or adequacy of the data themselves; this possibility poses some special requirements for current meter data.

So we must ask: What is current meter data used for, and what kind of instruments would we really like to have?

1. The first thing you want to construct in an environmental study is a general description of the environment -- a "climatological" summary. This might consist of mean velocity, tidal velocity amplitude, range or variability, etc. A climatology is not particularly valuable in itself, but if it covers a long enough time span, it can be valuable in determining the representativeness of events or of short data segments, and for assessing the significance of changes.

The need for a lot of data for a useful climatology suggests a need for an inexpensive current meter that can be deployed for long periods (say three months at a time) to keep the costs down. Absolute accuracy is a secondary consideration, provided the instrument is capable of resolving significant changes in major current constituents.

2. The second major type of analysis concerns dispersion. Where thermal or effluent plumes are present, it is necessary to predict the shape and concentrations of the plume. Numerical and/or physical models are often used, but these are typically local models which require the ambient current to be specified as an external input. Or, larger questions of radiological or pollution hazard to the population may require estimates of dispersion in an entire coastal region.

For such analyses, a key requirement for the ideal current meter is the ability to reliably measure low current speeds. This is very different from the requirements of the engineers, who are mainly interested in high speeds. But for environmental impact studies, the worst-case buildup of heat or effluents is a major concern, and this requires good data under low flow conditions. This suggests a need for current meters with low threshold speeds and good direction accuracy at low speeds. Unfortunately, these measurements must often be made in very shallow water, say 10 meters or so, and this means that the current meter must measure low mean speeds in the presence of wave velocities that may be one or two orders of magnitude higher than the mean. This requires a current meter with a wide dynamic range and good linearity. Avoidance of "rectification" effects and systematic direction bias errors is particularly important.

The problem of direction errors is one that is often neglected. But direction errors can be crucial, especially in open coastal locations, where the currents are strongly polarized into the shore-parallel direction. Small direction errors in the presence of strong longshore flows can cause relatively large errors in the measured on-offshore component. For example, suppose we have a 20 cm/sec longshore current, which is a typical speed. A direction-sensing error of 20° will effectively inject a spurious 2 cm/sec velocity into the on-offshore component; but 2 cm/sec is the typical magnitude of on-offshore velocity near the coast, so the 20° error will result in 100% relative error in the on-offshore component. The on-offshore component, of course, may actually be the most important component for the analysis of shore impact.

Biaxial current meters, such as electromagnetic types (EMCMs) don't sense direction *per se*. But the zero stability of EMCMs is important in determining current direction, especially for net velocity over long periods. Errors caused by zero offsets do accumulate, and this is one of the main objections to the use of EMCMs for environmental impact studies.

3. A third application for current data is for estimation of the probability that an effluent will be advected to populous or otherwise critical areas. For example, if you want to build an offshore facility, what is the likelihood that the effluent will wind up in an ecologically sensitive marsh on the coast? If current measurements can show that this event would be unlikely, then that would be a strongly positive statement for an environmental impact analysis, and this could avoid controversy later.

The question of recirculation also involves a similar analysis. In trying to assess the impact of a discharge, the maximum effluent concentration in the receiving water must be estimated, and this usually occurs when some fraction of the discharge is recirculated into the intake. However, recirculation can occur only for certain current speeds and directions, and therefore you want to estimate how frequently this type of undesired advection can occur.

Estimating the probability of advective transport is a problem that practically cries out for Lagrangian current sensors. What is needed are expendable drogues that can follow near-surface currents, and can be tracked from automated equipment on the shore over ranges of perhaps 50 km or less, with an accuracy of roughly 1 km at 10-km range, and most important, that are cheap enough to be used in large numbers. Only with large numbers can a statistically valid estimate of the probability of advection be built up. For example, a reasonable experiment might be to release about ten drogues around the site of a proposed facility once a week for a year, and track them continuously until they come ashore or go beyond some pre-established range. This would be an expensive program, but I feel confident that if a credible Lagrangian current measuring system were available, it would be in demand for major environmental studies because of its ability to demonstrate, directly and graphically, water transport patterns.

4. The fourth major type of analysis is the establishment of predictive modeling capability. This analysis is the closest to the kinds of scientific research problems that were discussed at yesterday's session of this conference, and the instrument requirements are generally similar. The principal use for predictive modeling capability for currents is in hindcast studies of extreme currents, and for design-basis studies of extreme conditions. These are not strictly environmental impact analyses, but generally it is the oceanographer doing the environmental study who must construct (or at least verify) the models using the measured current data. The main requirement for the current meters is that they neither overestimate nor underestimate current speeds during storm conditions, because if they do, the models may be wrong. Incidentally, this is why I'm appalled to see some people using Aanderaa-type instruments in very shallow water for these purposes, because the sizable speed overestimation that these instruments produce is by now well known.

Those are the most common applications of current data in environmental impact analyses. The next question is what happens after the environmental study is done and the Environmental Impact Statement is written. Here we get into the problem of defending the data from attacks during the hearing process, or worse yet, during court proceedings.

There are two main weak spots. One is the traceability of current meter calibrations, or rather the lack thereof. If a client wants a temperature sensor that's traceable to the National Bureau of Standards, that's easy because either the manufacturer or the user can provide transfer standards against which the field instruments can be calibrated. But just try approaching an oceanographer about traceable current meter calibrations. He'd fall out of his chair laughing. It's almost unheard of. Oceanographers count themselves lucky if the manufacturer provides a usable calibration of the sensor type. Recalibrations are rarely done during the life of an instrument because of the expense of the necessary tow tanks, etc. Also, we really don't have an acceptable transfer standard for water velocity, nor a standard calibration methodology. Provision by manufacturers of easier electronic readout and simulated-current inputs would help greatly. The establishment of a user-oriented national current meter calibration facility would be the real solution.

The second weakness is the customary lack of diagnostic data to back up the current measurement. Tilt, direction variability, maximum current speed, variance, and other parameters would be very useful.

Now, we all know that from a scientific point-of-view, the exact calibration of current sensors in tow tanks is a red herring. Errors due to waves or mooring tilts can greatly exceed the uncertainty inherent in tow-tank calibrations, for example; and the analyses that are done on the data are really very crude in themselves. However, when you're on the witness stand trying to defend your measurements, and you don't have even a basic calibration report to show, it's too easy for the opposition to destroy the credibility of the data, needlessly so. The existence of traceable calibrations, plus auxiliary information, would allow us to get beyond these trivial concerns and elevate the discussions during these hearings onto a more scientific plane.

It's obvious from this discussion that no single type of moored current meter is ever likely to meet all the requirements. Thus, different current meters are going to be needed for different phases of the study -- cheap ones that measure only current for the climatological phase of the study, fully instrumented ones for shorter-length intensive studies upon which major analyses can be based. This diversity shouldn't be in conflict with the concept of a systems approach to current measurement; in fact, a "building-block" systems approach is probably the only feasible way to provide such diversity within reasonable acquisition and operating cost limits.

I hope we can work some of these special requirements into the recommendations of this conference for future current meter development.

OPERATIONAL SURVEYS

Session Chairman: Robert Peloquin
U. S. Naval Oceanographic Office

U.S. NAVY OCEAN CURRENT SURVEY REQUIREMENTS

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ABSTRACT

Navy requirements for ocean current data extend over all depths in both deep and shallow water. These requirements are global because of the great range of applications, from ocean engineering to operational problems. The time scales of interest typically range from hours to months, and horizontal scales are on the order of several kilometers to hundreds of kilometers, and vertical scales are as small as a meter. The Navy's current measurement capability has recently been enhanced by improved measurement accuracy and data quality, and by increased record lengths. The Navy has an interest in the improvement of current measurement technology, particularly that which reduces costs and facilitates the handling of equipment.

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INTRODUCTION

The Naval Oceanographic Office compiles surface current data, measures ocean currents at all depths, and analyzes current patterns. In 1842, Lt. F. Maury initiated the preparation of surface current charts for the Navy, using information obtained from ship's navigation logs. This data set has grown to 4.3 million observations worldwide, and it continues to grow at the rate of 15,000 observations per year. The data are presently being compiled in the form of atlas-type graphical displays by season and by month in the format of Figure 1. The observation of surface currents is expected to remain an integral part of the Navy program, which we hope will receive additional impetus through the development of a two-axis, towed EM log.

In recent years, the emphasis has changed to the measurement of subsurface currents. In the mid 1950s, a program to measure currents in relatively shallow ocean depths was initiated. The locations of the measurements (which continue and have been extended into deeper water) are shown in Figure 2. Navy requirements now demand that a broader perspective be taken. Accordingly, currents are being measured at all water depths and with record durations of one year or more. Through the assistance of other naval laboratories and facilities as well as ONR contractors, we are in the process of establishing a sizable capability for Eulerian measurements using mooring arrays. With the shift in emphasis of our current measurements to deeper water, we have adopted the mooring design that is the outcome of the Deep Ocean Current Measurement System (DOCMS) Study, conducted by Woods Hole Oceanographic Institution through the support of the Naval Facilities Engineering Command. Fixed bottom-mounted platforms are frequently used for shallow water measurements. ONR has recently funded developmental work (Winget, 1977) for this purpose. A program to measure vertical shear has been initiated. The instrument used is the Profiling Current Meter (PCM), based on developments made at the University of Miami. Future measurements will include the use of unattended (moored) profilers and free-fall instruments. We also need Lagrangian descriptions of ocean circulation in limited areas. For this, we have cooperated with other groups in the use of neutrally buoyant floats to track eddies. The equipment demands for such measurements can be quite extensive.

MEASUREMENT REQUIREMENTS

The current measurement requirements for Navy applications are generally satisfied by accuracies of ±5 cm/sec (0.1 knot) in speed and ±8° in direction. In many cases (particularly the near surface measurements), these accuracies are not attainable because of the influence of surface waves on the sensor or on the mooring. The improvement of subsurface moorings by the DOCMS design effort is discussed briefly.

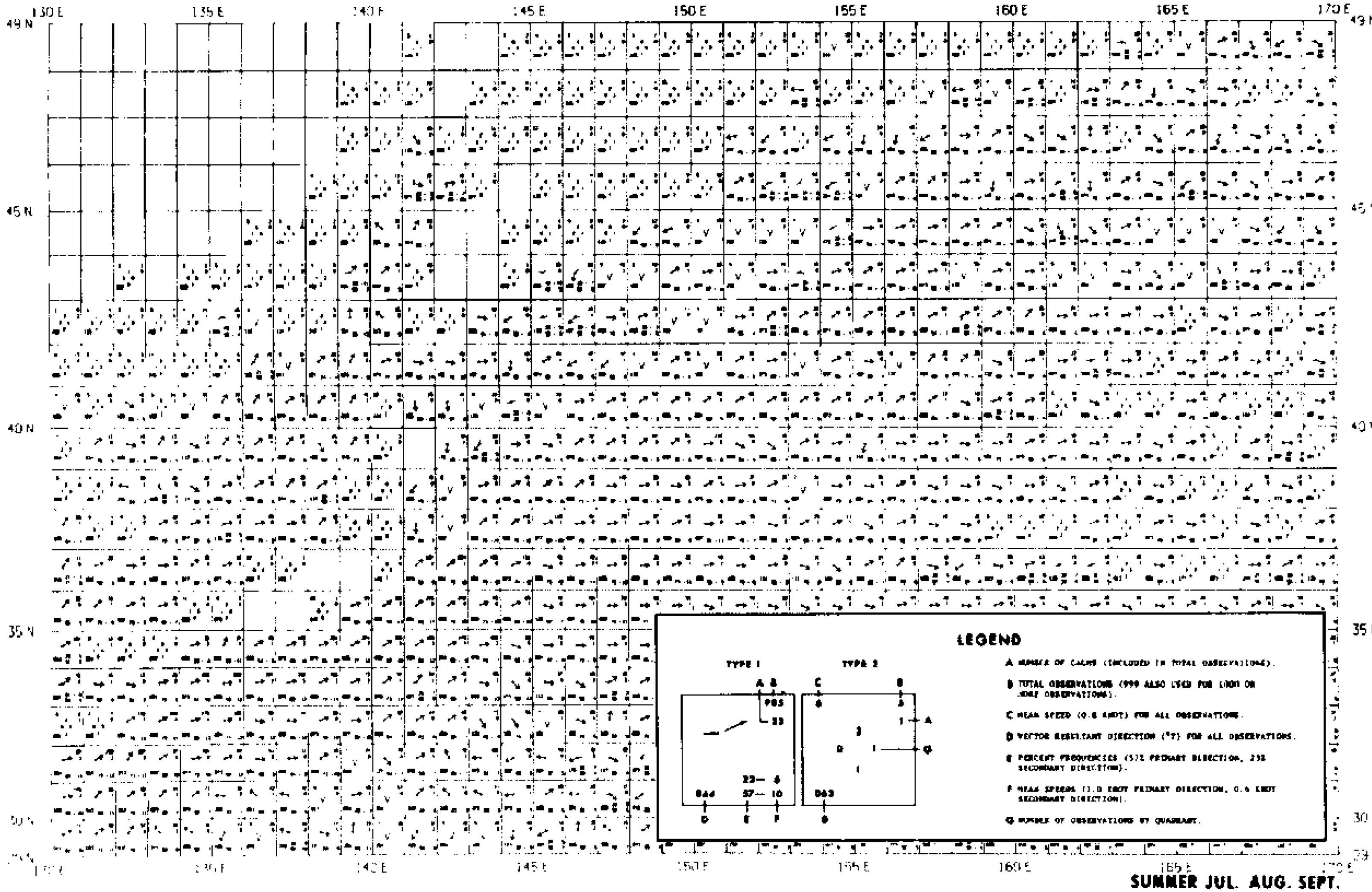

Figure 1. Compilation of surface currents in the North Pacific from ship set and drift observations.

DISTRIBUTION OF SUBSURFACE CURRENT DATA
By 10 Degree Squares (764 Records)

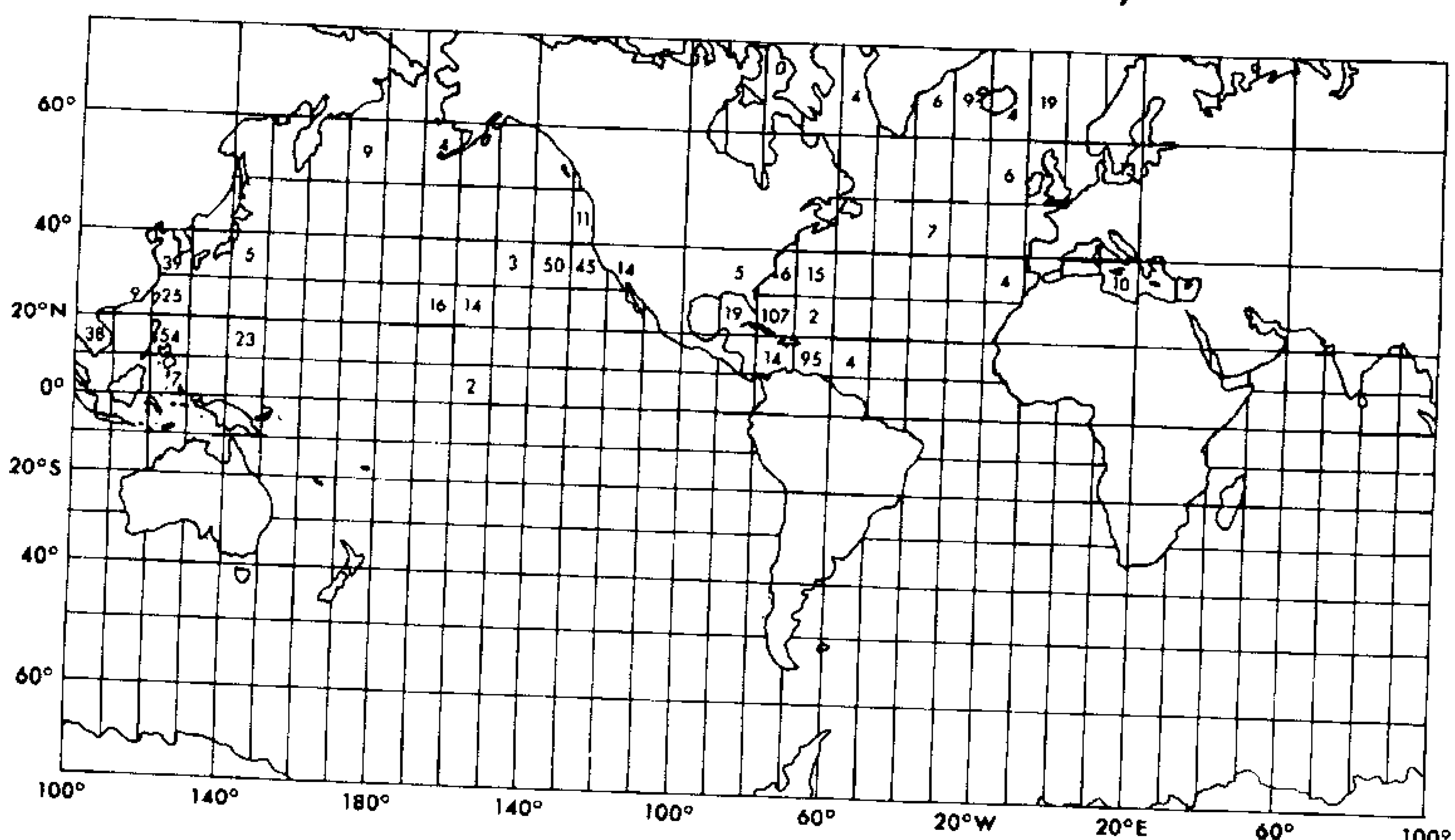

Figure 2.

DOCMS ARRAY DESIGN

The DOCMS uses an array consisting of a large subsurface buoy that provides the main buoyancy (at least 2000 pounds) and associated glass spheres which provide distributed tension throughout the mooring line. It represents a combination of mooring technology (single large subsurface buoy) previously used by the Oceanographic Office and the distributed buoyancy used by Woods Hole. The result is the Hybrid DOCMS Array, which reduces mooring motion by as much as a factor of three. Design details are provided by Walden (1975). A typical deep water current array is shown in Figure 3. The line tension in this type of array, however, may be increased considerably to reduce motion, as is the case in Figure 4, where the maximum tension of 3200 pounds is limited only by the breaking strength of the mooring line (the design tension is not allowed to exceed 50% of breaking strength). The computed horizontal excursion of the top of the array is, in this case, 10.3 meters, and the vertical excursion is 0.6 meters. The array design model is of the finite element type and accepts individual components and their characteristics (weight, length, drag coefficients, area, etc.). The current profile used for the design is a constant speed of 12.5 cm/sec from 100 to 1500 m depth. If, as an extreme case, we assume that deep water currents exhibit rotary motions at semidiurnal tidal frequencies, the speed of the uppermost meter through the water would not exceed 1.5 cm/sec.

MEASUREMENT ERRORS

Most of our current measurements are made using subsurface current arrays to avoid surface-induced errors. While a measurement accuracy of ±0.1 knot is sought, it is not known that this value is attained in all cases. On the basis of the development work performed at Woods Hole, we are confident that our measurements using subsurface moored arrays are close to this value. It appears that array motions are reasonably well predicted using existing array design models. The relatively long-period, pendular motions can be controlled through judicious use of buoyancy elements, while minimizing total drag on the array. Although this usually is a trial and error procedure, the design task is greatly facilitated by the use of computers. Errors induced by cable or current meter oscillations do not appear to be significant. The DOCMS study explored both the possibility of occurrence of resonant excitations in the cable and current meter motion resulting from vortex shedding. The first possibility was eliminated as a potential problem since the cable lengths required to support such motions are very much greater than the length of our longest mooring. The second possibility occurs when the Strouhal frequency Ws(V) equals the natural frequency Wn(K) (see Figure 5) of oscillation of the meter. Schott (1976) estimates that for a typical DOCMS mooring (array stiffness coefficient K of 1.0), the two frequencies are equal at a current speed of 5 cm/sec. At this speed,

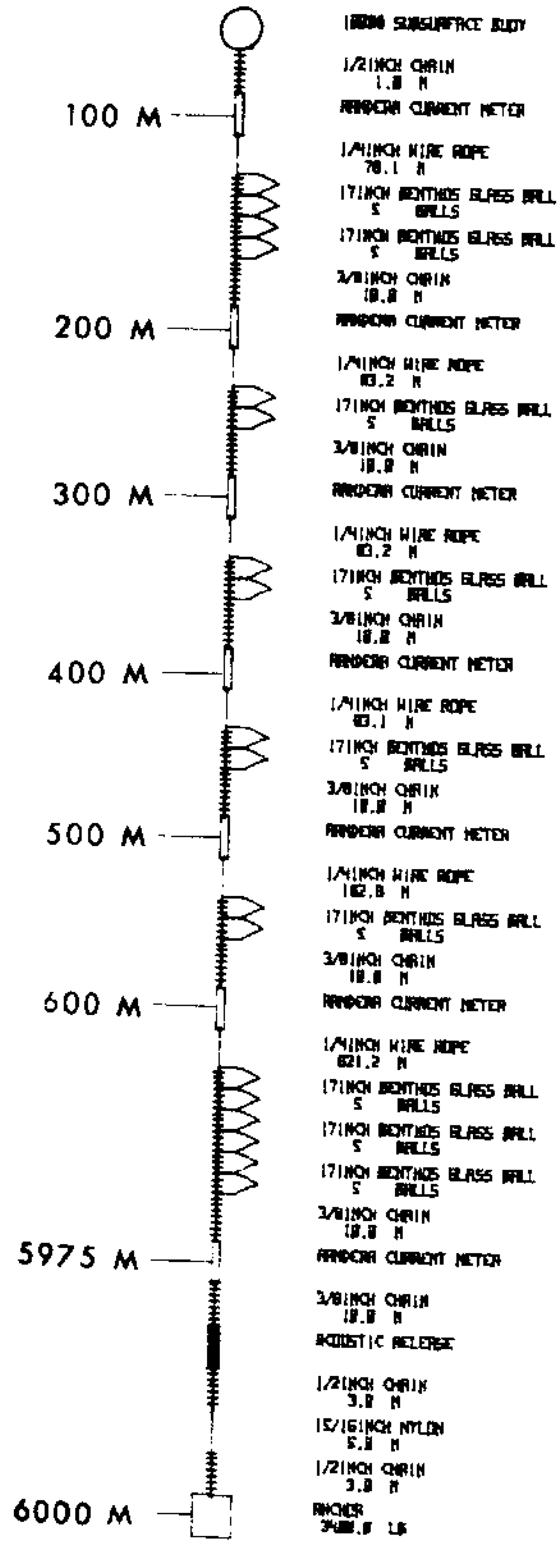

Figure 3. DOCMS current array.

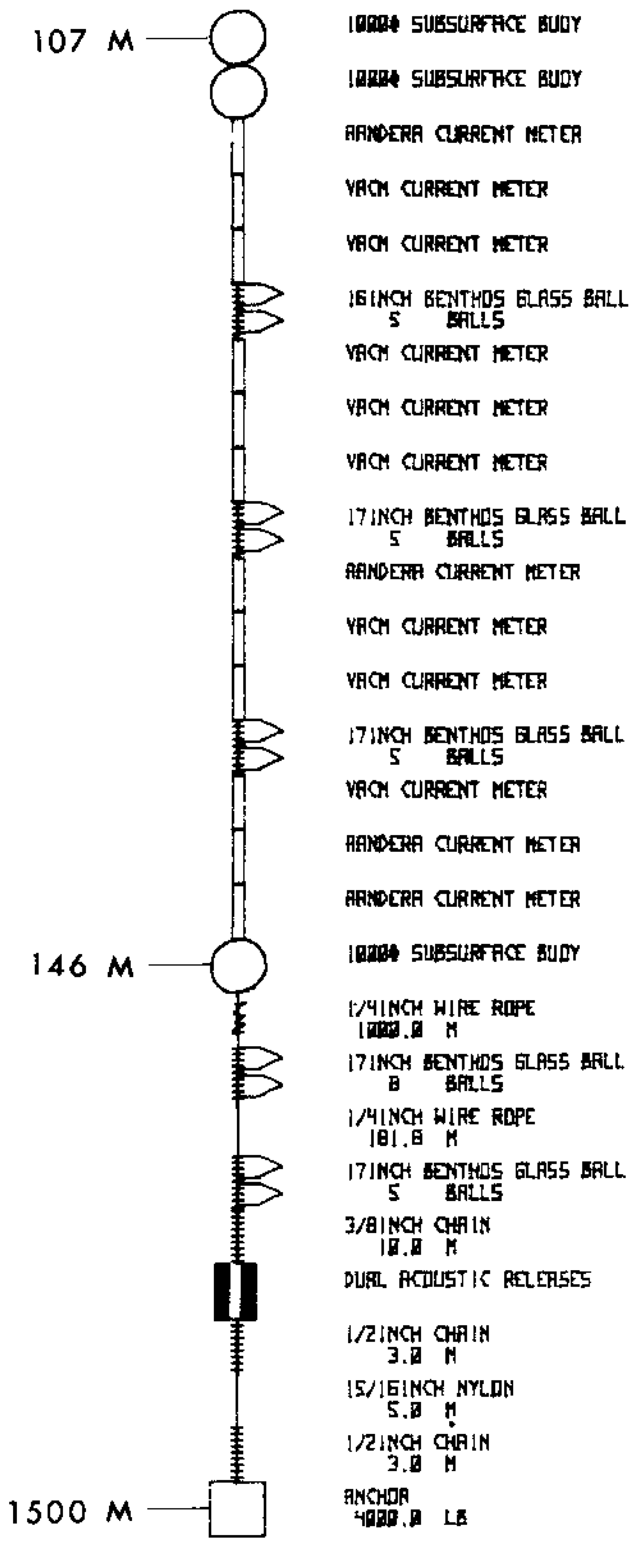

Figure 4. DOCMS array modified for current measurement in the thermocline.

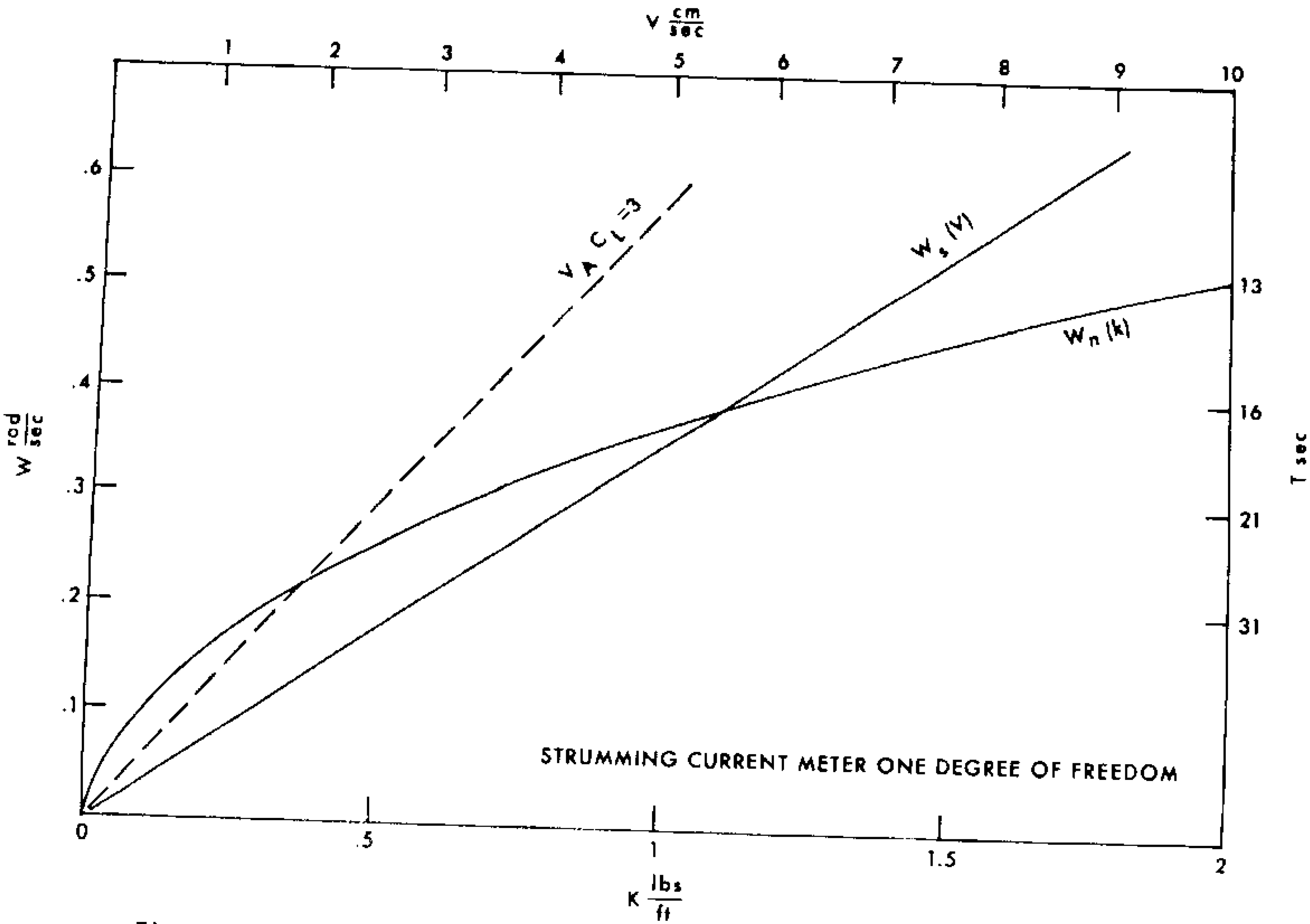

Figure 5. Natural frequency of oscillation Wn of a current meter vs. stiffness coefficient K and Strouhal frequency Ws vs. current speed (from Schott 1976)

current measurements conducted with Savonius rotor sensors would read 20% higher than the actual current. A 1 cm/sec error at a measured speed of 5 cm/sec is not of great significance from an applications point-of-view.

Although the DOCMS work was performed for the AMF VACM current meter, the many intercomparisons of other Savonius-type current meters using subsurface moors have not revealed significant differences. We therefore conclude that the DOCMS design is also appropriate for the Aanderaa and Geodyne current meters.

BOTTOM CURRENTS

The Navy needs nearbottom current information, particularly for test ranges and sites. Normally, bottom-mounted current meters have been used. Different types of arrangements have been used for this purpose. The tripod has been a favorite when the mount is to be lowered from a ship. The measurement of bottom currents requires at least two meters positioned within the bottom boundary layer to establish the velocity profile. We have yet to determine whether or not our meters are adequate for this purpose. Conceivably, our measurement requirements will have to be modified, and new instruments will be required.

SHALLOW WATER AND NEARSURFACE MEASUREMENTS

A scaled version of the DOCMS array is being used to conduct current measurements in shallow water. This restricts the measurements to depths greater than 10 to 15 m and requires the use of rapid response direction sensors, such as the VACM current meter. A mooring system is needed. The spar buoy used in recent years holds promise, but mooring motion studies have not yet been made. It is therefore difficult to assess the quality of the measurements.

Shallow water surveys are often conducted aboard small ships having limited deck facilities and weight handling equipment. The use of small, lightweight equipment is often mandatory. The instruments, as well as the buoyancy components, anchors, acoustic releases, etc., must be small. An array that can be easily handled by two men during deployment and recovery is desired.

DATA ANALYSIS

The type of analyses performed on our measurements varies depending on the application. For example, measurements were conducted in approximately 400 m of water east of Iceland from 10 June to 8 October 1975. The east-west components of two measurements made at 138 and 238 m depths are shown in Figure 6. The spectral analyses of these components

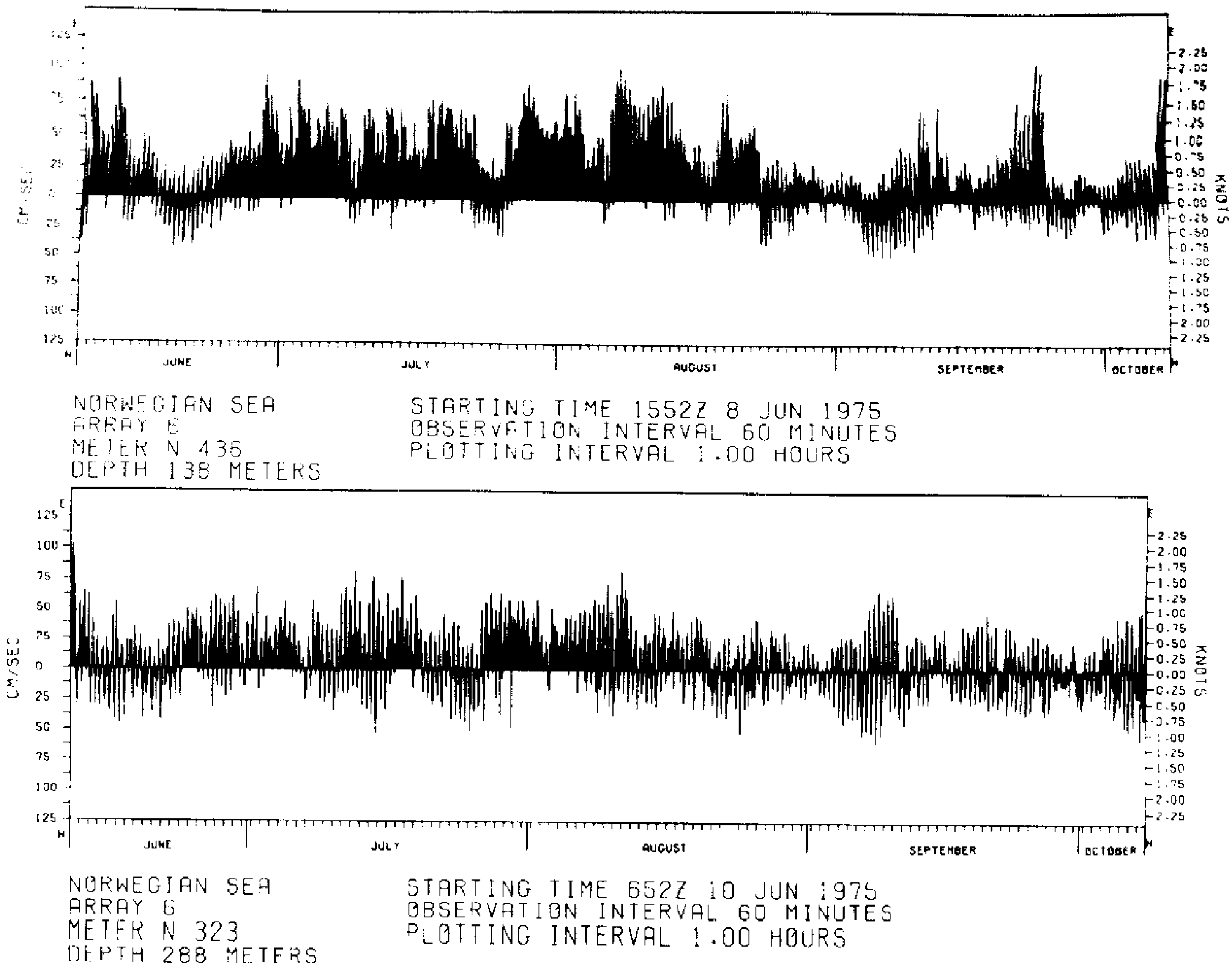

Figure 6. East-West components of current measurements conducted east of Iceland.

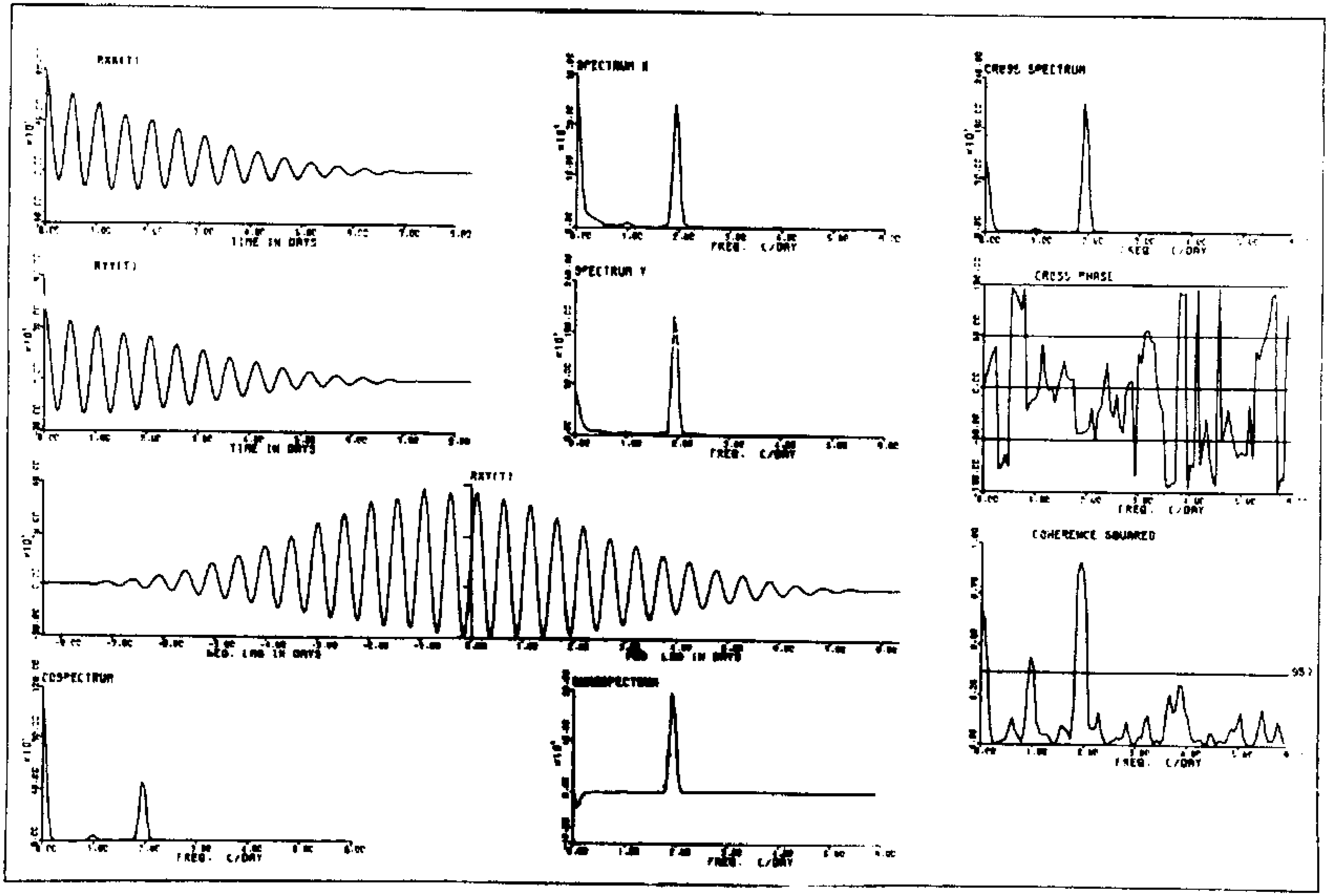

Figure 7. Spectral analysis of east-west components of current measurements conducted at depths of 138 and 288 meters to the east of Iceland. (RXX(T), RYY(T) signifies auto- and cross-correlations).

(Figure 7) show strong, high coherent tidal signals that are 90° out of phase. Harmonic analyses are being performed on the tidal components, and the results will be published.

SUMMARY AND RECOMMENDATIONS

The subsurface array designs now being used for shipboard deployment of current meters are adequate for survey purposes. We can restrict horizontal array motions to surprisingly small values by increasing total buoyancy. The use of properly designed arrays allows us to meet our accuracy requirements with mechanical sensors, such as those used on the VACM and Aanderaa current meters. We continue, however, to be faced with the problem of accurately measuring current within 10 m of the surface. Spar buoys are potential survey tools for this purpose, but they need to be optimized for this application.

As mentioned earlier, there is a requirement to measure vertical current shear. The instrumentation must accurately resolve velocity gradients over vertical scales of 1 m. There has been some development work but more is required. The moored, unattended profiler (such as the instrument developed at the University of Miami) is attractive because it does not tie up ship time.

The cost of current measurements needs to be reduced. Our most recent estimates are about $8,000 per current meter per deployment, including all costs (equipment, maintenance, data processing, personnel and ship time, etc.). To reduce costs, smaller equipment which requires less maintenance and preparation is needed. Design of such systems for aircraft deployment could reduce costs.

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CURRENT MEASUREMENT PROBLEMS IN A CIRCULATION SURVEY

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ABSTRACT

"Operational" or "circulation" surveys are carried out year-round by the National Ocean Survey on both coasts of the United States, including Alaska. Each survey completely covers a specific area, usually an estuary, for a period ranging from two months to several years, obtaining current measurements along with simultaneous tide, salinity, temperature, and weather data. These measurements are made at selected locations and depths in order to obtain a reasonably complete three-dimensional description of the dynamic properties of the body of water, that can be used for environmental purposes as well as for navigation. Analysis results of these data are also included in the Tide and Tidal Current Tables and Tidal Current Charts published by NOS.

Formerly the Coast and Geodetic Survey, the National Ocean Survey has been taking current measurements on a regular basis since 1844 and has used a number of current measuring devices, from the early current pole to the present Aanderaa and TICUS current meters now being used on the West and East Coasts, respectively. NOS is presently reviewing available and prototype current sensors in preparation for an upgrading of its current measurement systems in the near future.

In addition to the usual current measurement problems that affect all users (e.g., the effects of noise, mooring motion and drag, uncertain dynamic response characteristics of the sensors, accuracy, etc.), NOS must also cope with instrument errors that interrupt the processing scheme setup for the handling by technicians of the huge quantity of data it receives year-round. For example, in the past if a current sensor was not equipped with an independent interval counter or hour marker, the loss of one or more data points in a current record would create additional hours of work in order to accurately assign time to the data series. Time determination is critical for NOS since accurate tidal current predictions must be made based on these data. Also, frequent errors in the recorded data values, due to bit drop or other electronic or mechanical causes, though correctable using computerized statistical editing techniques, require considerable computer time to do so and occasionally hand editing as well.

These problems and others, as well as NOS's on-board and in-house processing schemes, are described.

WORKING CONFERENCE ON CURRENT MEASUREMENTS, JANUARY 1978. SPONSORED BY THE NOAA OFFICE OF OCEAN ENGINEERING AND THE DELAWARE SEA GRANT COLLEGE PROGRAM.

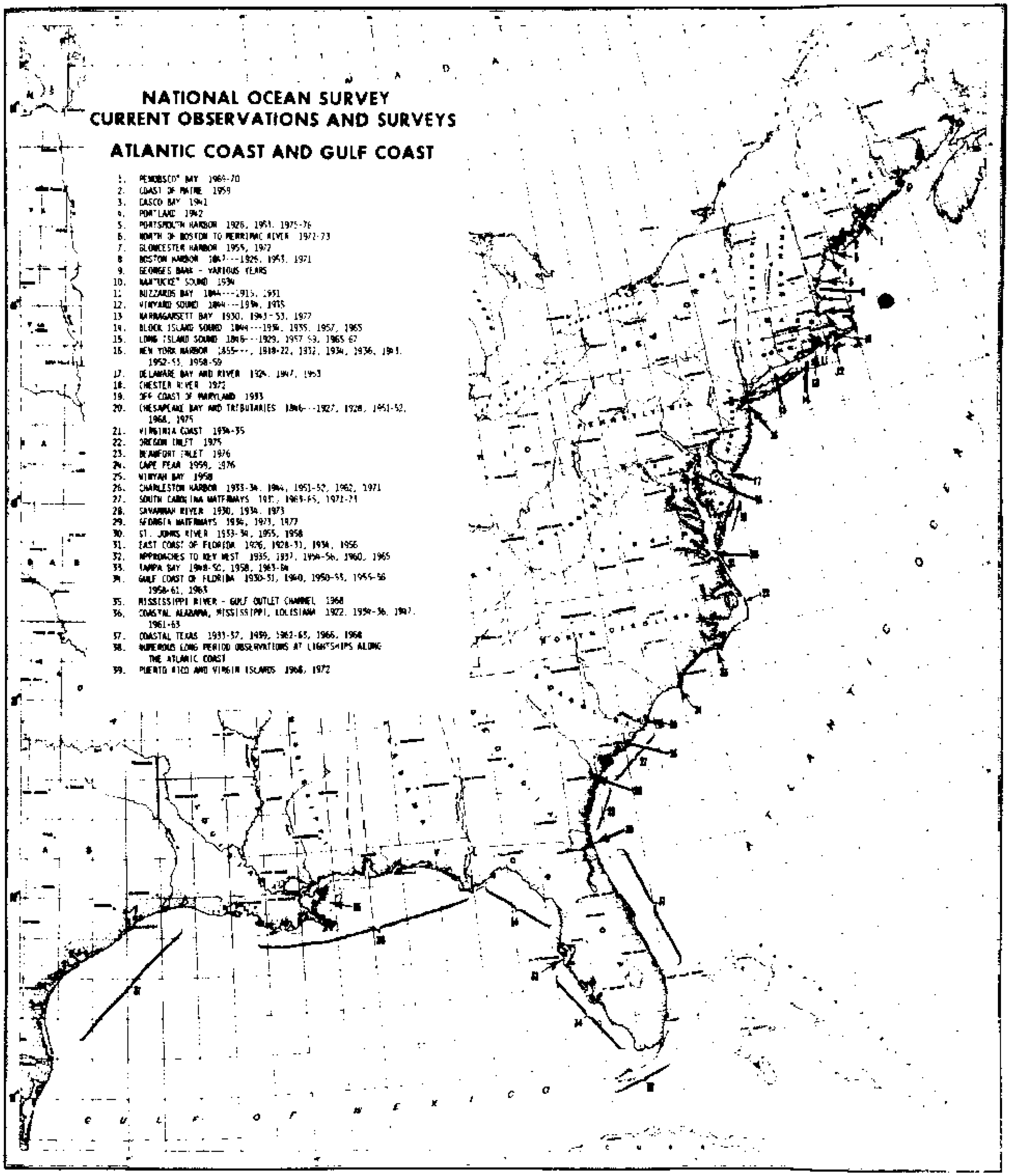
The National Ocean Survey (NOS), formerly the U.S. Coast and Geodetic Survey, has been making current measurements on a regular basis since 1844. The charts in Figures 1 through 3 show the locations along both coasts of the continental United States and Alaska, for which NOS has acquired current observations since that time. These current measurements have been made using a wide variety of devices, beginning with the early current pole and log line. More recently, NOS has used a number of current meters, including the Ekman, the Petterson, the Price, the Roberts Radio Current Meter, various Richardson-types, and the present Aanderaa and TICUS current meters now being used on the West and East Coasts, respectively. NOS is now reviewing available and prototype current sensors in preparation for upgrading its current measurement systems.

The NOS is one of the largest collectors and processors of current data in the United States today; over 500 meter-months of current data were processed in 1977. Because of the large-scale nature of its operation, NOS must cope with a few special current measurement problems in addition to those faced by all users. These problems will be discussed later in this paper. We will preface that discussion with some background remarks about the nature of NOS' circulation surveys, the type of data obtained, and the purposes for which it is used.

Some of the locations in Figures 1 through 3 are areas where the current data may have been taken one or two stations at a time over the years by NOAA "ships of opportunity." Most locations, however, represent complete surveys with numerous current stations. Now, NOS obtains current data exclusively from circulation surveys carried out year-round on both coasts of the United States, including Alaska. Each survey completely covers a specific area, usually an estuary, for a period ranging from two months to several years.

A "circulation" or "operational" survey consists of the acquisition of various physical oceanographic and meteorologic data, from which an accurate description of water movement can be deduced, along with a theoretical appreciation of its causes. More specifically, it includes the measurement of currents, tides, the temperature and salinity of the water, and various atmospheric parameters such as wind speed and direction, sea level pressure, and air temperature. These measurements are made at numerous selected locations and depths in order to obtain a reasonably complete, three-dimensional description of these dynamic properties. The resulting description of the water movement can then be used to help solve or prevent environmental problems, as an aid to navigation, in research, and in coastal zone management and engineering.

Most of NOS' recent circulation surveys have come about because of the concern over existing or potential environmental problems. For example, the completion of the Alaskan pipeline was responsible for NOS carrying out two such surveys, one in Prince William Sound, where the pipeline ends, and one in the Strait of Juan de Fúca - Puget Sound area, which has a number of refineries to which the oil will be brought by


NATIONAL OCEAN SURVEY
CURRENT OBSERVATIONS AND SURVEYS
ATLANTIC COAST AND GULF COAST
1. PENOBSCOT BAY 1969-70
2. COAST OF MAINE 1959
3. CASCO BAY 1941
4. PORTLAND 1942
5. PORTSMOUTH HARBOR 1926, 1951, 1975-76
6. NORTH OF BOSTON TO MERRIMAC RIVER 1972-73
7. GLOUCESTER HARBOR 1955, 1977
8. BOSTON HARBOR 1847---1925, 1953, 1971
9. GEORGES BANK - VARIOUS YEARS
10. NANTUCKET SOUND 1934
11. BUZZARDS BAY 1844---1915, 1951
12. VINEYARD SOUND 1844---1934, 1935
13. NARRAGANSETT BAY 1930, 1943-53, 1977
14. BLOCK ISLAND SOUND 1844---1934, 1935, 1957, 1965
15. LONG ISLAND SOUND 1846---1929, 1957-59, 1965-67
16. NEW YORK HARBOR 1855---, 1918-22, 1932, 1934, 1936, 1943, 1952-53, 1958-59
17. DELAWARE BAY AND RIVER 1924, 1947, 1953
18. CHESTER RIVER 1972
19. OFF COAST OF MARYLAND 1933
20. CHESAPEAKE BAY AND TRIBUTARIES 1846---1927, 1928, 1951-52, 1968, 1975
21. VIRGINIA COAST 1934-35
22. OREGON INLET 1975
23. BEAUFORT INLET 1976
24. CAPE FEAR 1959, 1976
25. WINYAH BAY 1958
26. CHARLESTON HARBOR 1933-34, 1944, 1951-52, 1962, 1971
27. SOUTH CAROLINA WATERWAYS 1937, 1963-65, 1971-73
28. SAVANNAH RIVER 1930, 1934, 1973
29. GEORGIA WATERWAYS 1934, 1973, 1977
30. ST. JOHNS RIVER 1933-34, 1955, 1958
31. EAST COAST OF FLORIDA 1926, 1928-31, 1934, 1956
32. APPROACHES TO KEY WEST 1935, 1937, 1954-56, 1960, 1965
33. TAMPA BAY 1948-50, 1958, 1963-64
34. GULF COAST OF FLORIDA 1930-31, 1940, 1950-55, 1955-56 1958-61, 1963
35. MISSISSIPPI RIVER - GULF OUTLET CHANNEL 1968
36. COASTAL ALABAMA, MISSISSIPPI, LOUISIANA 1922, 1934-36, 1947, 1961-63
37. COASTAL TEXAS 1933-37, 1939, 1962-65, 1966, 1968
38. NUMEROUS LONG PERIOD OBSERVATIONS AT LIGHTSHIPS ALONG THE ATLANTIC COAST
39. PUERTO RICO AND VIRGIN ISLANDS 1966, 1972
G U L F O F M E X I C O

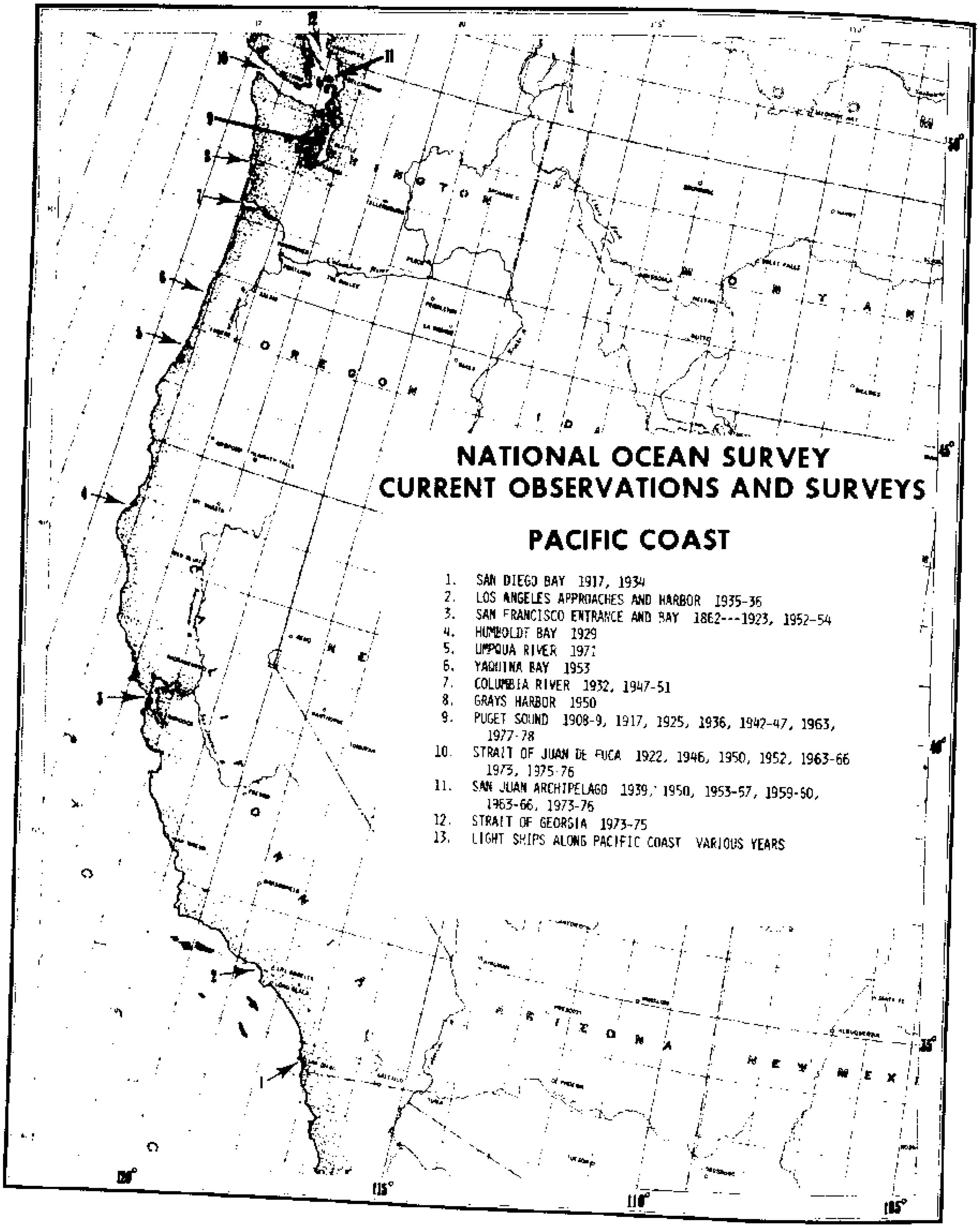


Figure 2. National Ocean Survey current observations and surveys on the Pacific Coast.

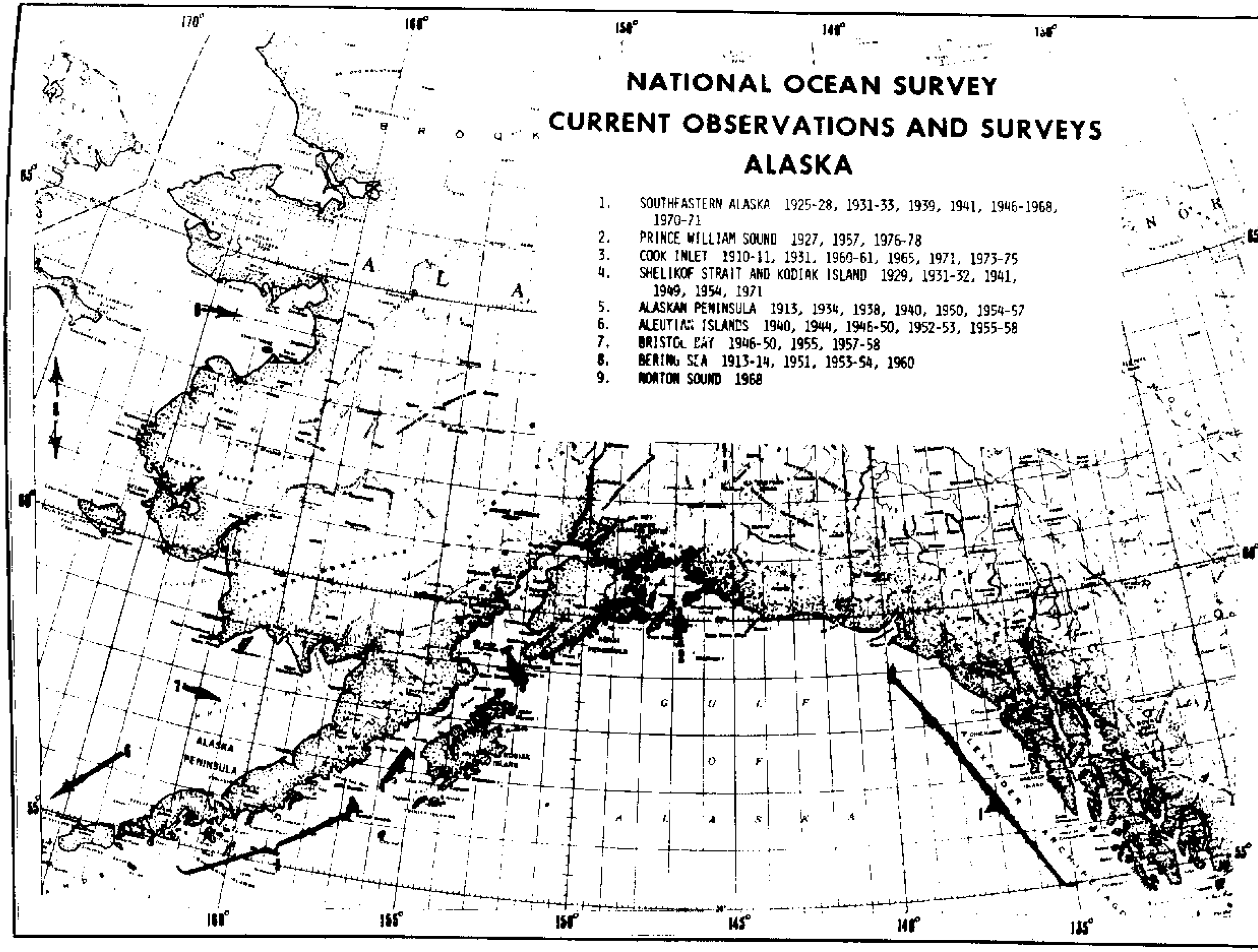


Figure 3. National Ocean Survey current observations and surveys in Alaska.

tanker. The chart in Figure 4 shows the current meter station locations occupied in the Strait of Juan de Fuca - Strait of Georgia. This survey began with a one-month preliminary survey in October 1973, and was followed by six phases, done three months at a time in the spring and fall of 1974-1976. Phases 7 through 9 (not shown in this figure) were conducted south of this area in Puget Sound. At the end of phase 9, a total of 188 current meter stations will have been occupied, along with about 100 tide stations and 200 STD stations (including transects and time-series).

Each coast has a NOAA ship dedicated to circulation surveys. On the West Coast, it is the NOAA ship McARTHUR, a 175-foot long, 995-ton Class III vessel, with a draft of 11 feet and a personnel complement of 40. In the summer, she has generally worked in Alaska (presently Prince William Sound, and previously Cook Inlet). In the spring and fall, she stays south, which since 1973 has meant the Puget Sound area. On the East Coast, surveys are carried out by the NOAA ship FERREL, a 133-foot long, 360-ton Class IV ship that has a personnel complement of 20. The FERREL has a draft of only 5 feet of water, enabling her to work in the many shallow estuaries on the East Coast. She also works north in the summer (e.g., Narragansett Bay, Boston Harbor, Penobscot Bay) and south in the spring (e.g., in the salt marsh estuaries of South Carolina and Georgia).

On the West Coast and in Alaska, NOS uses Aanderaa RCM4 current meters suspended from taut wire moorings (Figure 5). The Aanderaa converts a one-minute Savonius rotor count into current speed and takes one instantaneous direction reading, at the end of the rotor count, using a compass and large vane. All meters also measure temperature and many have conductivity and pressure sensors. Sampling is usually set at six samples per hour. The data are stored internally (using a mechanical encoder) on a three-inch reel of half mil, quarter-inch-wide magnetic tape, which can hold 60 days of data, if necessary. This tape is retrieved and copied to a five-inch reel of 1.5-mil magnetic tape, which is then sent to Rockville, Maryland for processing.

The data on the five-inch reel are transcribed onto a seven-track computer-compatible tape, and then a three-phase data processing scheme is carried out using software written for a CDC 6600 computer. This processing scheme accomplishes the following: (1) it takes care of extra or missing Aanderaa words (there should be six words per data point); (2) it converts Aanderaa units into engineering units, using calibration results obtained annually from the Northwest Regional Calibration Center in Vellevue, Washington; (3) it assigns correct times to the data points of the time series, after a careful time-checking procedure is carried out; and (4) it does a computerized statistical editing to eliminate erroneous data values caused by mechanical or electronic malfunctions.

On the East Coast, NOS uses the Tidal Current Survey (TICUS) current measuring system. This system was designed in-house and uses Richardson-type cylinders with Savonius rotors and small vanes. The

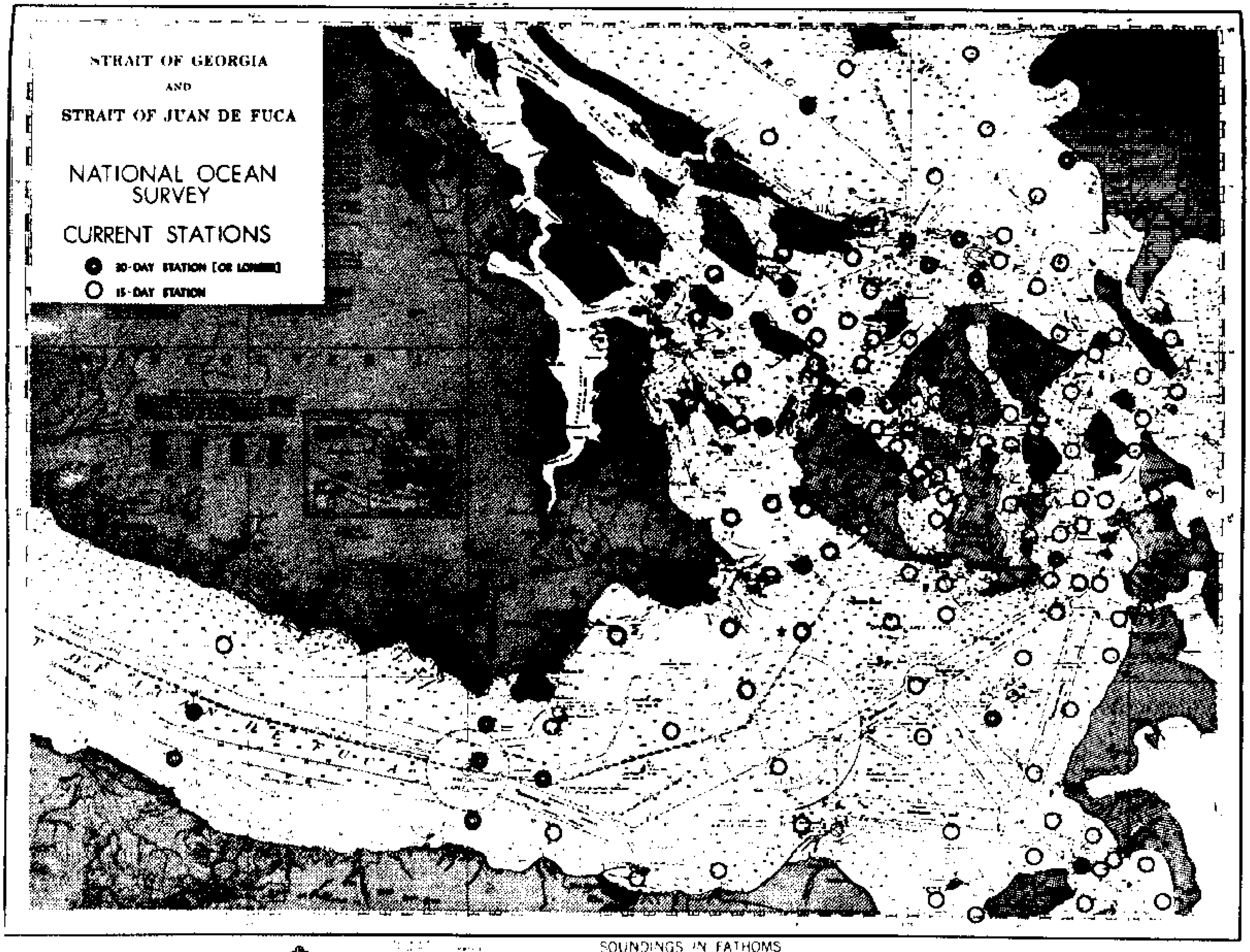


Figure 4. Current stations occupied by the National Ocean Survey in the Strait of Juan de Fuca--Strait of Georgia in a recent cirulation survey.

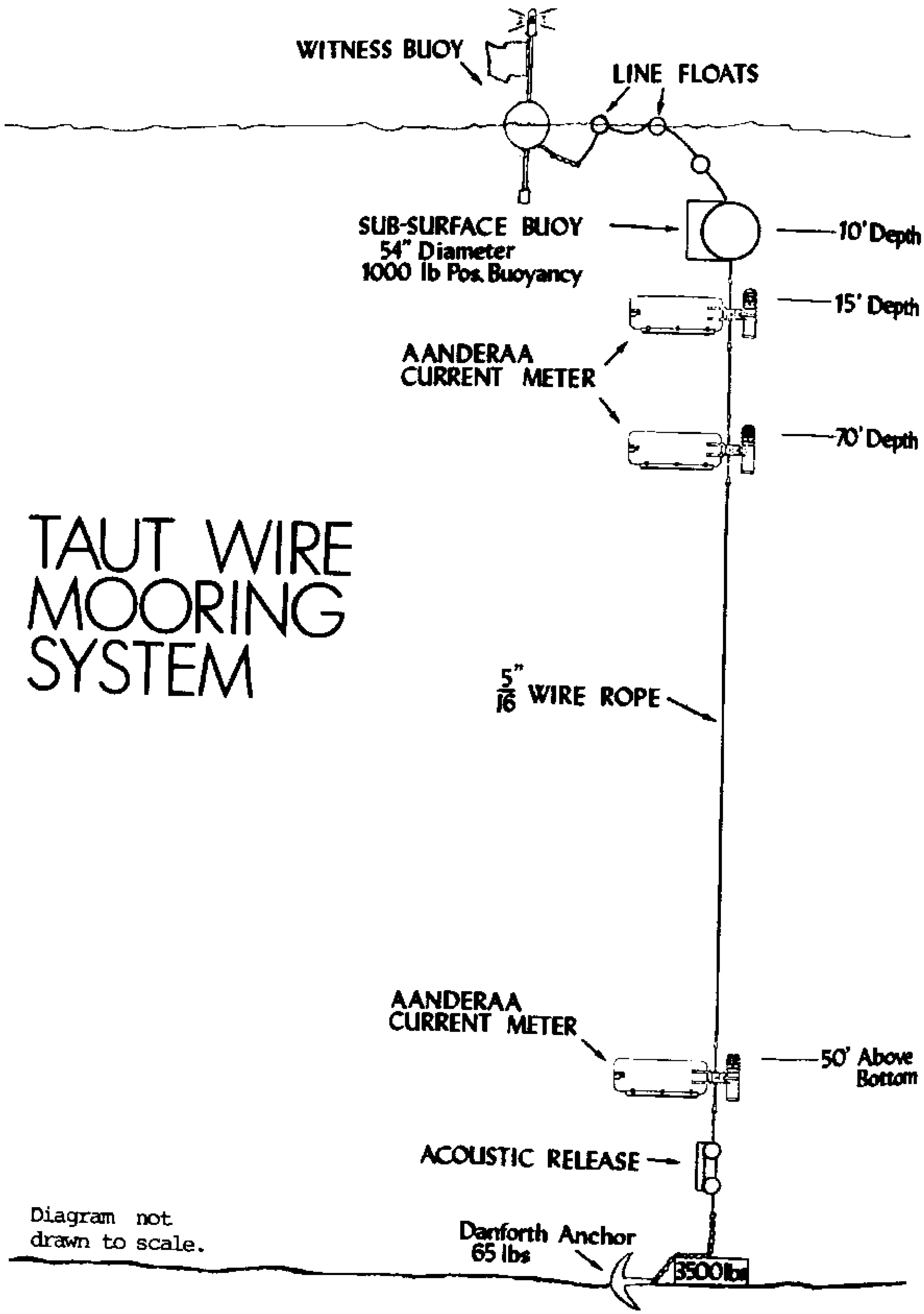


Figure 5. Taut wire mooring system used on the West Coast and in Alaska with Aanderaa current meters.

meters are suspended from special boat-type buoys that have three tubs (Figure 6). The data from all current meters suspended from a buoy are sent up cables and stored on a large cartridge of magnetic tape contained in one of the tubs. These data are also telemetered to the ship via a radio transmitter in a second tub. The power supply is in the third tub. Each current station can be regularly interrogated by the ship via telemetry or can be set on an independent recording mode. The telemetering capability is especially useful for checking for meter malfunctions or excessive tilt (the meters have inclinometers), or simply for the real-time study of currents.

Sampling is usually set at five samples per hour, each sample consisting of five sets of rotor counts, directions, and tilts taken within a 37.5 second period. Each rotor count lasts 5.8 seconds; 0.85 second after the rotor count ends, an instantaneous direction is taken and an instantaneous tilt reading is made. The five sets of values, plus station number and times, are recorded.

As much data processing as possible is carried out onboard the ship using a PDP8 mini-computer and peripheral equipment. The five pairs of speeds and directions are averaged to obtain one pair of hourly values, and a "weight" value is calculated and assigned as an indication of the amount of noise contained in these values. Erroneous times are also corrected on the ship, and the Julian day and the year for each data point are added to the processed tape. Time series from different tape cartridges for the same station are pieced together and missing data points are flagged. The data recorded on the buoy cartridges are generally used for the processing, but the data telemetered to and stored on the ship are also available as a backup if for some reason a buoy cartridge malfunctions. The processed data are then sent to Rockville, where they are checked, headings are added, some statistical editing is done, if necessary, and they are stored more compactly.

Historically, the main reason for NOS obtaining current data has been for use as an aid to navigation. NOS has been publishing tidal current predictions since 1890. These predictions, which in 1923 became of such quantity to warrant two separate publications, Current Tables, Atlantic Coast and Current Tables, Pacific Coast, have been used by both the commercial and recreational boating communities. NOS also publishes Tidal Current Charts for important bays and estuaries in the U.S. These usually consist of 12 charts showing the mean current speed and direction for each hour of the tidal cycle, for numerous locations in the area covered. Instructions are also provided for obtaining daily predictions at each location using the Current Tables.

In recent years, environmental concerns have played the major role in determining where NOS carried out its surveys. We have already mentioned the surveys that came about as a result of the completion of the Alaskan pipeline. Most other surveys have also been in response to the need for detailed water movement information in a polluted or

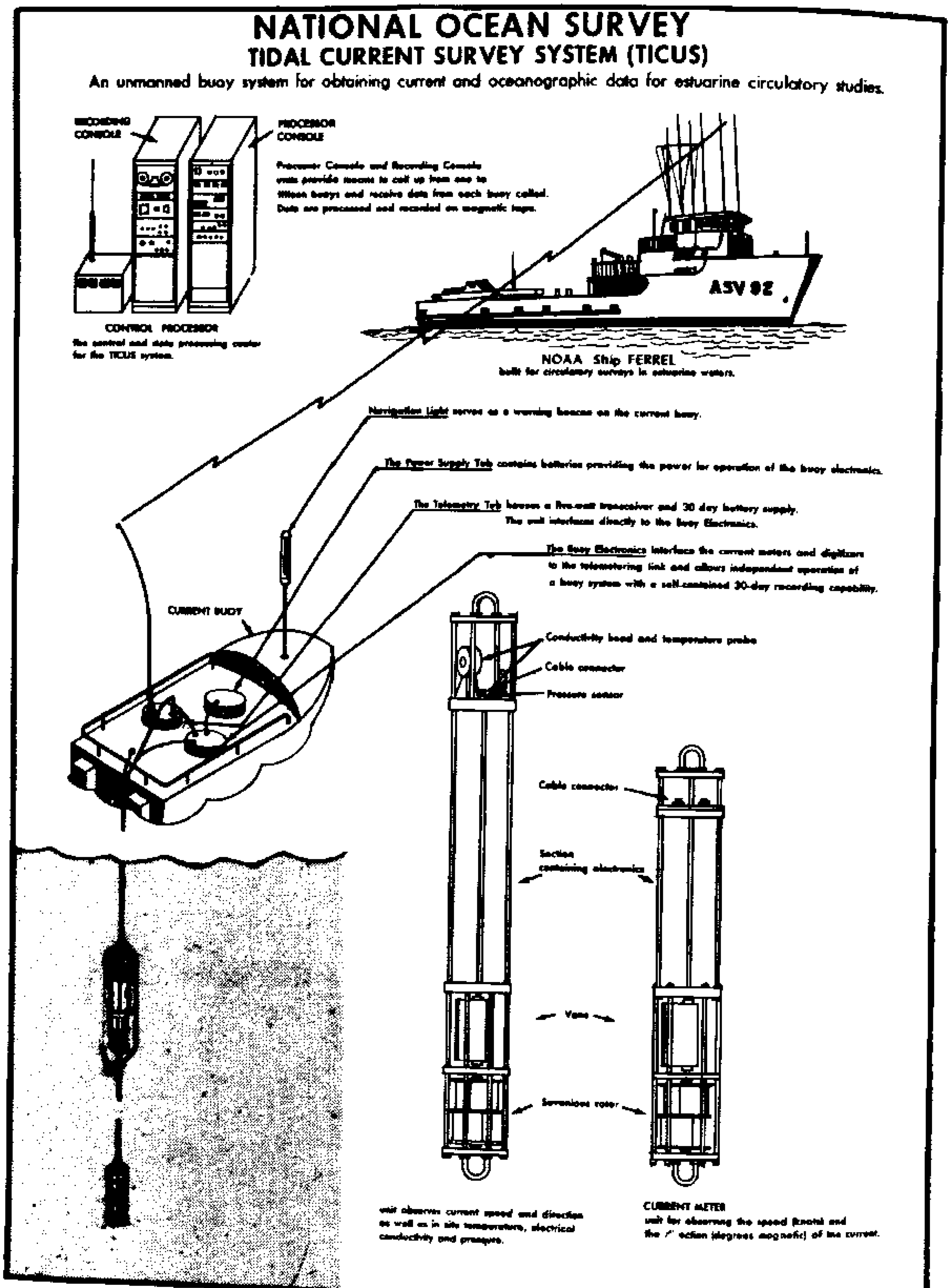


Figure 6. TICUS current meter system and mooring.

potentially polluted area. Thus, NOS surveys are planned in great detail, and include the measurement of sea level, salinity and temperature, and various atmospheric parameters, in addition to the measurement of currents, in order to obtain a full hydrodynamic documentation of the area in question. The results from such a survey lend themselves to oceanographic research, coastal zone management and engineering, as well as to navigation. The analysis results from such a survey are still used in the Current Tables and Tidal Current Charts, but they also appear in more research-oriented reports and papers and are sent to numerous users at universities, private firms, and other government agencies, as are the actual data.

NOS has mainly surveyed inshore areas; i.e., estuaries, and thus its current data have generally been characterized by a strong tidal signal (and a high signal-to-noise ratio). There have been some recent exceptions. Prince William Sound in Alaska, for example, can be considered inshore, but it is so deep (up to 2,600 feet) that the tidal currents are extremely weak over most of the area. NOS' increased involvement with offshore surveys, such as the MESA New York Bight project and the upcoming Department of Energy Louisiana coastal project, are increasing the amount of low signal-to-noise data it must contend with.

Even with the increase in the amount of low signal-to-noise data collected, NOS' main concern must still be considered the tidal signal (including the higher harmonics). NOS is, however, also interested in energy at the inertial frequency and in other lower frequency phenomena (that can be correlated to wind, atmospheric pressure, river runoff, etc.). NOS' interest in higher frequency phenomena, such as waves, is limited to an interest in how such high frequency phenomena contaminate NOS' measured current data. In the past, this may not have been such a concern, but with NOS surveying more low signal-to-noise areas, it will be an important consideration in choosing new current measuring systems.

A typical NOS survey, though routine by now, is still a rather involved project whose planning begins as much as a year before its start. Once the current station locations have been selected (as well as the locations for tide stations and STD casts), detailed project instructions are written and sent through official channels to the ship for comments and suggestions regarding potential problems from an operations point-of-view (e.g., current stations in heavy traffic lanes or in fishing areas). Advanced notice is also given to the local residents of the survey area, especially fishermen, to avoid possible conflicts.

The selection of current station locations is always affected by time and equipment (buoy and meter) restraints. There is always a trade-off made between obtaining full area coverage and obtaining long time series. Long time series are needed to obtain more accurate harmonic constants from the data, and thus to produce more accurate tidal current predictions. A long time series also enables one to better study low frequency and seasonal effects. On the other hand, full coverage of an area with current stations enables one to collect data in all places of navigational and environmental importance, as well as at key cross-sections, for making transport calculations, and at other points of interest for hydrodynamic research.

Generally, a compromise is made. A few key locations may be occupied for the entire field season. Other important areas may be occupied for a month, while less important stations may be occupied for only 15 days (or only 7 on the East Coast). Key groups of stations are occupied simultaneously, if possible. A minimum of 29 days of data is required for a harmonic analysis that calculates the five most important constituents, M_2, S_2, N_2, O_1, and K_1. Fifteen days of data can also be used, but then N_2 must be inferred. Data series from short stations are analyzed using a nonharmonic comparison method that relates these data to the data (or predictions) from a nearby long period station. A minimum of 15 days is used in this analysis for West Coast stations because of the diurnal inequality. Various spectrum and correlation analyses are also performed on the data.

Generally, three current meters are installed at a current station if the water depth is great enough. Occasionally, a fourth meter is also installed if the water column structure seems to warrant it. But then one must cope with the added drag and the resulting excursion and tilt-problems. On the West Coast, where tautline moorings are used, the standard depths are generally 20 feet below the surface at the mean lower low water (MLLW), 70 feet below MLLW, and 50 feet above the bottom. On the East Coast, the survey areas have generally shallower depths. The meters are usually suspended at 10 and 20 feet below the boat buoy, with additional meters if the water depth allows and the currents are not great enough to create drag problems.

Tide gages are also installed at key locations from a hydrodynamic point-of-view, as well as at historical sites in order to redefine tidal datums for land movement and shoreline boundary determinations. Between installing and checking on the current and tide stations, the ship also makes a number of STD casts (transects, time series stations, and all-season stations) in order to describe the density structure.

A certain degree of onboard processing is carried out on both ships, as mentioned before. When the data reach NOS headquarters in Rockville, they are rapidly processed and checked so that any station with poor data results can be reoccupied. Regular maintenance of the current meters is carried out on the ships. FAILOGS are also completed to record any instrument malfunctions.

NOS, of course, has the same problems in measuring currents that other users have, and the same uncertainties as to how the data quality has been affected by such things as noise, mooring problems, and the lack of information on the true response of the current meter under field conditions. Until recently, however, the study areas surveyed by NOS have had high signal-to-noise ratios due to the strong tidal signal, so perhaps some of these problems have not been quite as serious for NOS. In addition, NOS has a few special problems caused by the size and nature of its operation.

The large quantities of current data sent year-round to Rockville for processing and analysis require a fast, efficient data processing scheme. Any instrument malfunction that interrupts this smooth processing scheme will cost NOS time and money. Ordinarily, technicians perform all data processing functions. The computer software used is designed for simple operation and as little manual intervention as possible. Processing is carried out in stages with double checking after each stage. Instrument malfunctions, however, may necessitate the intervention of an oceanographer to solve special problems. Such malfunctions also require additional programming so the software can handle as many problems as possible.

The kind of problems we confront are current meter malfunctions that cause problems in the data that are solvable and do not greatly affect the quality of the data if handled correctly, but they are problems that require valuable extra time to handle in the special way required. This extra processing time becomes quite an expense if additional man-hours are required. We try to minimize the expense by programming around the problems whenever possible. It sometimes seems that we are forever modifying our software to try to handle special errors caused by current meter hardware problems--hardware problems which we hope will not occur in the current meter models now being developed. A few examples will help to clarify.

As mentioned earlier, NOS' major concern has always been the tidal signal, and one of the results of our current data acquisition, processing, and analysis is the accurate forecast of tidal currents. This means that time determination, i.e. the assigning of an accurate time to each data point, is crucial. NOS has never had a current meter system that did not occasionally lose (or sometimes even add) data points. This can be caused by sticking mechanical encoders, faulty tape drives, electronic problems, or temporary power failures due to temperature effects on the batteries. Such omissions or additions are found through a careful time-checking procedure that uses "start and stop times" and "into and out-of water times" to determine how many data intervals should be on the tape.

If data points are lost or added and we do not know where in the data series this happened, erroneous times will be assigned to the rest of the data points following this occurrence. This, in turn, will lead to erroneous analysis results. Predictions made from the harmonic constants obtained from these data will be in error. The harmonic constants, both amplitudes and epochs, can be seriously affected by a time shift inside the data series at some unknown point. There are enough local effects that can affect tidal current harmonic constants, in a way which most models cannot account for, without having to worry about what effect a time shift in the data may have had. NOS supplies current data to many users, and if perhaps a few erroneous values were left in the data series, the user could spot them fairly easily. But a user would have no way of knowing, or checking to see if all the times were correct.

The obvious solution to this problem of missing or extra data points is to have as part of the current meter electronics some type of hour marker or interval counter, independent of the tape writing mechanism and the sampling impulse, and independent of anything else that might cause an interval loss, short of a complete power failure. Unfortunately, NOS until very recently has had Aanderaa current meters without hour markers. When one of these meters lost, for example, five data intervals, our only hope was that all five intervals were lost at one place in the data series, so that we might be able to locate it by studying tidal progressions. Such a procedure is obviously quite time-consuming. If it is unsuccessful, we cannot use the data.

Another problem common to all our current meter experience has been "glitches" in the data caused by some meter malfunction; i.e., obvious erroneous data values that could not be reasonably considered to have resulted from normal physical processes. Even with the regular maintenance our meters receive in the field and between surveys, this has always been a problem. In the Aanderaa, it seems that the mechanical encoder may be primarily responsible for such problems. When such glitches appear in the data series from a particular meter, it is frequently found that most erroneous values differ from the expected values by an amount equivalent to a particular binary bit, as though one encoder pin occasionally sticks. But similar problems have occurred in other kinds of current meters and may also be due to tape drive problems or electronic malfunctions.

It is hoped that such problems will be less frequent in the newest current meters taking advantage of the latest solid state circuitry and non-mechanical encoders. In the meantime, NOS uses computerized statistical editing to find and correct erroneous values caused by meter malfunction. These corrected values are flagged so the user of these data will know which data points are estimated.

Computerized statistical editing saves a tremendous amount of human effort and standardizes the correction procedure. This procedure should not be confused with smoothing or filtering. NOS uses a Wiener-type predictor. The computer program is based on the original ERROR subroutine of Zetler and Groves (1964), but the matrix solution has been modified to take less computer time. Even with this modification, however, this editing program still uses a good deal of computer time, a fact that becomes important when one processes a huge amount of data. Thus, a significant expense will be eliminated if the problem of data glitches is solved in the newest current meters.

Other current meter problems, such as lack of durability in harsh conditions, susceptibility to fouling, or limited data storage capability, can also add cost and man-hours, since a current meter must often be replaced every couple of weeks because of them. This means that the time series from each current meter that occupied a particular station-depth must be pieced together after the usual processing. Then there is also the possibility that these current meters were inadvertently set to sample at different times after the hour, thus leading to problems with all analyses requiring continuous data with constant time intervals.

As mentioned earlier, NOS must also cope with the same current measurement problems that other users have--problems that directly affect the quality of the data. (Of course, the problems just discussed can affect data quality if they are not handled correctly.) These problems have been discussed to some extent by others at the Conference, so they will merely be summarized here.

Probably the major concern of every user is the contamination of a current data series with noise. By noise, we usually mean the unwanted high frequency energy due to waves. Noise contamination has become much more of a problem for NOS since we began surveying such low signal-to-noise areas as Prince William Sound and New York Bight. To truly eliminate noise contamination, one must essentially be able to measure continuous, instantaneous speeds and directions, so that the high-frequency energy will vectorially average out over the sampling duration. The equivalent of this, and a more realistic approach, is to measure the flow along each orthogonal component. There is, of course, some disagreement about the best method for accomplishing this.

In cases where one must use a current meter not meant for a noisy environment, it seems that a tethered spar buoy, such as the EDL/MESA tethered spar buoy mentioned in the talk by Beardsley, Boicourt, Scott, and Huff, can minimize the problem. It is essentially a wave follower, and it does seem to reduce wave noise. However, it is only usable near the surface, and there is often a good deal of noise deeper than we could probably use the spar. This has been apparent in the MESA New York Bight Project where current meters attached to a tethered spar buoy have shown lower speeds and more distinct minimums (due to rotary tidal currents) than deeper meters on a tautline mooring.

This brings us to mooring problems in general. We know that the mooring itself can add noise to the data, but rarely can we accurately describe it. We have used tautline moorings to get away from the noise of the surface layer. Although this may be preferable to an ordinary surface buoy, there can still be quite a lot of noise at these greater depths. Using a tautline mooring, however, will also put in doubt any correlations we try to make between our measured currents and simultaneous wind measurements, since the rise and fall of the tide will change the position of the current meter relative to the surface.

There is also the serious problem of mooring drag, especially in deep areas with strong currents (e.g., in Haro Strait). Whether a current meter is suspended from a surface buoy or attached to a tautline mooring, the drag from the mooring will cause the meter to change depth according to current speed. This can also cause the meter to tilt (depending on how much play the gimbals may allow), which will affect the measured values recorded by the meter.

To minimize mooring drag problems, EDL has supplied our survey ships with "haired" Kevlar fairing (1/4-inch line with 3-inch-long nylon tufts, 20 hairs per tuft, every 3/4-inch). The nylon tufts, by reducing vortex shedding, reduce the drag and thus reduce the vertical excursion of the current meter (Taylor, 1977). (Another method for reducing current meter excursion might be to use three-point tautline moorings, but these would be difficult to deploy.) It is also obvious that some current meters, by the nature of their shape, make the drag problem much worse.

Another problem still facing most current meter users is the uncertain dynamic response characteristics in the field. Tests in flow tanks may not accurately cover all conditions possible in the field. Also, the accuracy of some current meters is still a problem. Fouling was mentioned earlier. In some areas, unless a meter is changed frequently, fouling can obviously affect the measured current values.

The problems just discussed are outlined in Table 1. It does seem that many of these problems are in the process of being solved, and one would hope that the Conference will in some way accelerate these solutions.

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Taylor, Bob J. (1977). "Ocean Current Measurement System, Mooring Subsystem Field Test," Engineering Development Lab, Office of Marine Technology, National Ocean Survey (in-house report).

Zetler and Groves (1964). "A Program for Detecting and Correcting Errors in Long Series of Tidal Heights," International Hydrographic Review, Vol. 41, pp. 103-107.

Table 1. Current Measurement Problems

I. Problems that slow up processing of current data, but do not seriously affect data quality if handled correctly.

   A. Loss or addition of data intervals (if current meter has no independent hour marker or interval counter).

   B. Bit failure problems, which create erroneous values (requires computerized statistical editing).

   C. Durability and/or fouling (if cannot leave one current meter in water for a long period, then must piece together time series from different meters in-house).

II. Problems that affect the quality of data.

   D. The problems in Section I if not handled correctly.

   E. Effects of noise (especially in low signal-to-noise areas, with current meters not having solid state instantaneous vector averaging).

   F. Mooring problems

      1. Adding noise to signal
      2. Drag in stronger currents (especially in great water depths) causing a great change in the depth of the meter and tilting the meter in some cases.

   G. Uncertain dynamic response characteristics of the current meters (especially under field conditions).

   H. Accuracy of the current meters.

COMPARISON OF A FEW RECORDING CURRENT METERS IN SAN FRANCISCO BAY, CALIFORNIA

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ABSTRACT

A team of research scientists in the U.S. Geological Survey uses San Francisco Bay, California, as an outdoor laboratory to study complicated interactions of physical, chemical, and biological processes which take place in an estuarine environment. A current meter comparison study was conceived because of the need to select a suitable current meter to meet field requirements for current measurements in the Bay. The study took place in south San Francisco Bay, California, in the spring of 1977.

An instrument tower which was designed to support instruments free from the conventional mooring line motions was constructed and emplaced in south San Francisco Bay. During a period of two months, four types of recording current meters have been used in the tests. The four types were: (1) Aanderaa, (2) tethered shroud-impeller, (3) drag-inclinometer, and (4) electromagnetic current meters. With the exception of the electromagnetic current meter, one of each type was mounted on the instrument tower, and one of each type was deployed on moorings near the instrument tower. In addition, a wind anemometer and a recording tide gauge were also installed on the tower.

This paper discusses the characteristics of each instrument and the accuracy that each instrument can provide when used in an estuarine environment. We pay special attention to our experiences in the field operation with respect to handling of the instruments and to our experiences working up the raw data in the post-deployment data analysis.

WORKING CONFERENCE ON CURRENT MEASUREMENTS, JANUARY 1978. SPONSORED BY THE NOAA OFFICE OF OCEAN ENGINEERING AND THE DELAWARE SEA GRANT COLLEGE PROGRAM.

INTRODUCTION

San Francisco Bay, California, serves as an outdoor laboratory for research scientists in the U.S. Geological Survey to study complicated interactions between physical, chemical, and biological processes which take place in an estuarine environment. We consider various aspects of solute transport and establish methods of analyzing and predicting temporal and spatial changes in solute concentrations. To improve our understanding of the interactive processes, mathematical models are being developed and used to assist quantification of the relative importance of delta outflow, winds, tides, and other dynamic forces which act on the estuary system.

Nearly monthly surveys of hydrographic properties (temperature, salinity, nutrients, oxygen, carbon, chlorophyll, suspended particles) in the main channels have pointed to the need for better understanding of the water-circulation patterns and mixing characteristics of the San Francisco Bay. This system consists of mostly shallow basins (<10 m) with relict river channels lying in their central parts. Large, exposed surface areas are susceptible to diurnal winds which generate wind-fetched waves up to 1 m amplitude, and the average tidal range is about 2 m.

A current-measurement program has been initiated to define both short- and long-term circulation patterns, and we envision a systematic, bay-wide current-measurement program using a sizable number of *in situ* recording current meters. A comparison of current meters was conceived as the first step of our measurement program. The goals of this study were to gain field experience working with *in situ* recording current meters and to select a suitable current meter to meet the specific field requirements for the Bay. No prior studies are known to have been conducted in a similar estuarine environment.

This report represents an extended summary of the comparison of current meters in San Francisco Bay. A brief description of our experiments will be given, followed by discussion of samples of current-meter data from which the main conclusions are drawn.

FIELD EXPERIMENTS

The decision was made at the outset of the field experiment that for future measurements, this research team will use the most suitable and presently available current meters (that is, off-the-shelf instruments); thus, we discounted several types of instruments which, though very appealing, are considered in their final phase of development. Important factors are accuracy for measurement of long-period mean current, ease of handling in the field, with preference for instruments which can be deployed using a small boat (5 to 6 m), and the procedures required for post-deployment data processing.

One common difficulty of wave zone current measurement which is particularly pertinent to our applications is the contamination of data by wave motions and mooring line motions. To delineate various motions in the current records, an instrument tower was designed to support instruments free from the conventional mooring line motions. The instrument tower consisted of a large tripod which supported a mast (11.6 m), and at the top of the mast were three instrument arms. A cable, pulley, and winch assembly was installed on each arm. When an instrument was mounted on the cable, the cable was under tension and the instrument could be positioned at a selected depth.

The instrument tower was emplaced near the geometric center of South San Francisco Bay (37°39.5'N; 122°18.7'L), where mean water depth was about 8 m. During a period of two months, early February to early April 1977, four types of recording current meters were used in the tests. The four types were: (1) Aanderaa, (2) tethered shroud impeller, (3) drag inclinometer, and (4) electromagnetic current meter. With the exception of the electromagnetic current meter, one of each type was mounted on the instrument tower, and one of each type was deployed or subsurface mooring near the instrument tower. Initially, all the current meters were set at a depth of 5 m from the basin bed. In addition, a wind anemometer and a recording tide gage were also installed on the tower. Figure 1 depicts the relative position of each instrument (not to scale); those instruments on moorings were anchored not more than 30 m from the tower. Table 1 summarizes the general characteristics of each instrument, its working principle, basic and additional sensors, and the data-recording medium used by each.

SUMMARY OF RESULTS

Handling. Most of the field work was accomplished using a 17-foot Boston Whaler with a manual winch built on the bow. Because of the working space on this boat and on other vessels suitable for use in this work, occasional rough handling of the instruments sets a requirement standard for the instruments. The preferred instrument, with respect to handling, should be small and lightweight, and have no mechanical sensors. Among the current meters used in this test (Table 1), GO-6011 is smallest in overall dimension and lightest. It has no mechanical moving parts. Rotating mechanical sensors are used by both Endeco and Aanderaa current meters. The Aanderaa current meter is the heaviest and bulkiest among all the meters used in this study.

Data Processing. Table 1 is a good example of the fact that there is no industry standard of data-recording media for the current meters. At the present time, we have no capability for raw data translation (that is, for translating the raw data tapes to a computer-readable form). After the raw data tapes were recovered, they were sent back to the respective instrument manufacturers for translation. Our experience in working with each current-meter manufacturer showed that the data

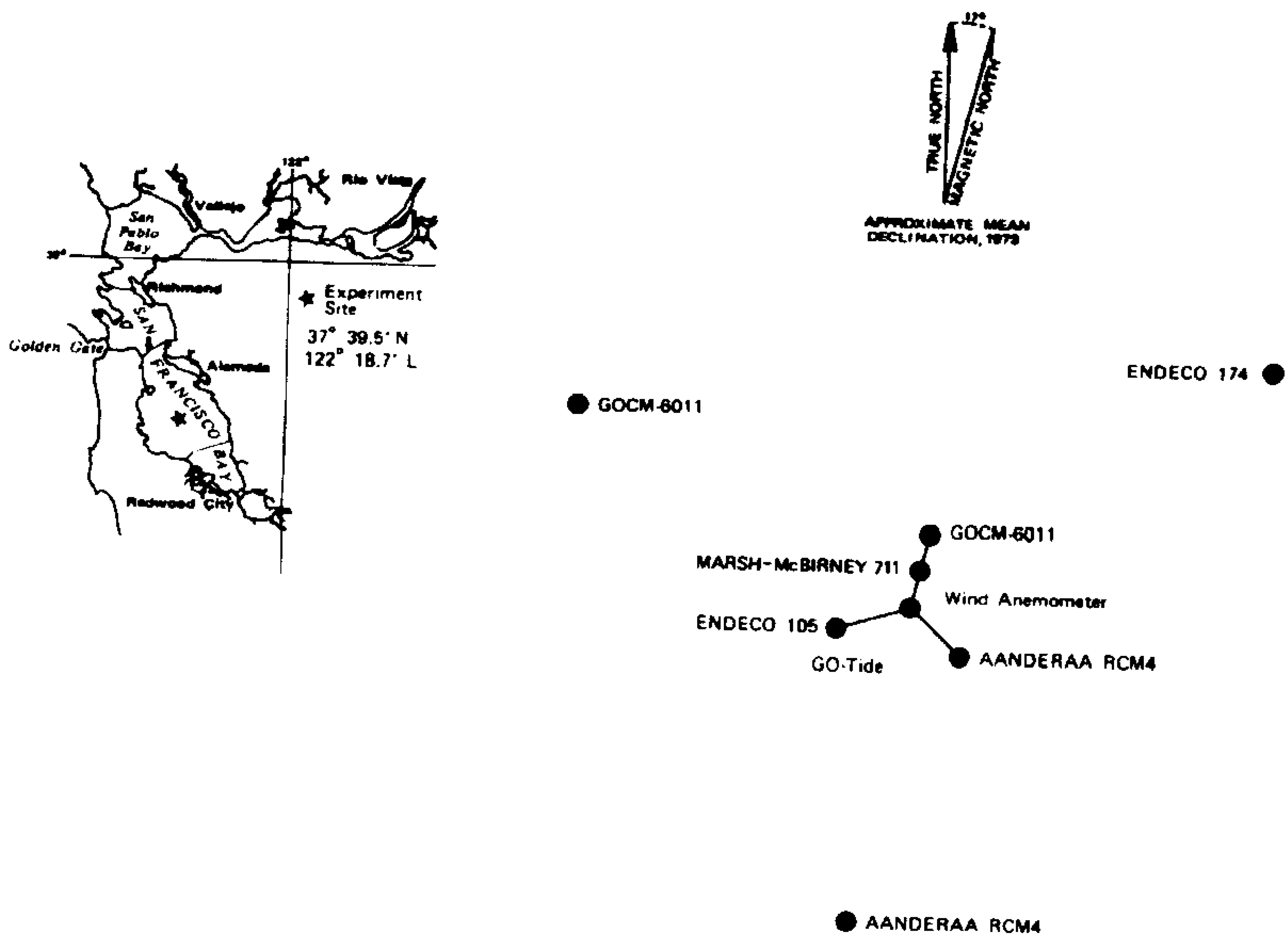

Figure 1. Schematic diagram of the relative position of each current meter. Meters are identified in Table 1.

TABLE 1

CURRENT METER CHARACTERISTICS

CURRENT METER[1]	WORKING PRINCIPLE	PARAMETERS MEASURED	RECORDING MEDIA	REMARKS
GENERAL OCEANICS 6011	INCLINO-METER (DRAG)	SPEED[2] DIRECTION TEMPERATURE[3]	PHILIPS CASSETTE	SOLID-STATE, MEASURES EARTH'S MAGNETIC FIELD; INTERFACE UNIT GO-6000
ENDECO 105	DUCTED IMPELLER	SPEED DIRECTION	16-MM MOVIE FILM CARTRIDGE	DATA USUALLY PROCESSED BY MANUFACTURER
ENDECO 174	DUCTED IMPELLER	SPEED DIRECTION TEMPERATURE[3] CONDUCTIVITY[3]	¼" MAGNETIC TAPE CARTRIDGE	INSTRUMENT FUNCTION PINGER AND TRANSLATION UNIT AVAILABLE
AANDERAA RCM4	ROTOR	SPEED DIRECTION TEMPERATURE[3] CONDUCTIVITY[3] PRESSURE[3]	¼" MAGNETIC TAPE, REEL TO REEL	HYDROPHONE; TRANSLATION UNIT AVAILABLE
MARSH-MCBIRNEY 711	ELECTRO-MAGNETIC	SPEED DIRECTION	STRIP CHART RECORDER	EVALUATION INCOMPLETE

[1]MENTION OF A COMMERCIAL COMPANY OR PRODUCT DOES NOT CONSTITUTE AN ENDORSEMENT BY THE AUTHOR OR BY THE U.S. GEOLOGICAL SURVEY.

[2]ALL METERS MEASURE HORIZONTAL VELOCITY COMPONENTS.

[3]OPTIONAL SENSORS AVAILABLE.

translation services vary widely in sophistication. We requested that the raw data be translated from the original recording medium to half-inch computer tapes, and that the characteristics of the raw data be preserved on computer tapes. Only Aanderaa current-meter data are in a format that includes information concerning the possibility of erroneous data code. From these raw data, we proceeded to the next step of data reduction.

Because there is no industry standard on data format, and because each instrument works on a different principle, the parameters recorded on raw data tapes and subsequently translated to computer tapes were coded in different word lengths and formats. Before further processing, a set of new data tapes was produced; data on these tapes were edited whenever possible and written in a standard format compatible with our computing facility. These steps were followed so that the remaining data processing could share a standard computer program.

In working up the current-meter data on hand, we encountered some difficulties with each type of instrument. I have gone to great length explaining the detailed steps of data processing only to stress that one should not underestimate the data processing aspects of current measurements.

Accuracy. After field experiments, we evaluated these instruments in the U.S. Geological Survey towing facility at the Gulf Coast Hydro-science Center in Bay St. Louis, Miss. Each instrument was towed in a speed range of 0 to 120 cm/s; in most cases, the instruments were towed after two months of field deployment without extensive servicing. The towing rating of the Aanderaa current meter was in excellent agreement with manufacturer's recommendation. The Endeco 174 current meter was towed twice: first, the old impeller bearings were used, then a pair of new bearings was installed and the instrument was towed again. The two rating results were consistent, but they both gave a reading 10 percent lower than the manufacturer's own rating.

Testing of the General Oceanics 6011 current meter reflected its nonlinear nature. The S-shaped rating curve which related the tilt angles of the current meter to speed readings had a very steep slope in the speed range of 25 to 55 cm/s, whereas the rating curve became very flat for speeds exceeding 70 cm/s. The former gave a long response time in that speed range, and the latter gave low sensitivity at high current speed. Though the rating curve was a direct result of the wing design, the general features would probably remain for other wing designs.

DATA SUMMARY

By mid-February 1977, when the weather was extremely calm, all the current meters were deployed; soon thereafter, the San Francisco Bay region experienced a storm which lasted about a week. The current-meter records from the beginning of the test to the end of February 1977 thus covered a period when extreme weather conditions that one could expect occurred in the Bay. We will not show all the results here, but give a summary of the voluminous data.

During the calm period, the three current-meter pairs (the same instrument on the tower and on mooring) gave consistent readings. The electromagnetic current meter gave intermittent readings which could be attributed to the strumming motions of the instrument cable. Inclusion of this current meter in the test was decided after the instrument tower was built; actual evaluation of this current meter was deemed incomplete. The current pattern at the experiment site was strongly bidirectional, with prevailing flow directions approximately 330° and 150° from magnetic north, and speeds ranging from slack up to 75 to 80 cm/s. Existence of a slack period provided an excellent opportunity to evaluate the performance of each instrument with specific regard to possible contamination of records due to mooring line motions. During this period, the Endeco current meters and Aanderaa current meters recorded slack water and were generally in good agreement with each other for other phases of the tides. Current readings during slack were typically 5 to 10 cm/s or less (30-minute averaged), and slightly higher speeds were shown on records of current meters on moorings. The General Oceanics current meters recorded slack water accurately, but the directional readings were in apparent error. When the speed was in the range of 60 cm/s and above, the General Oceanics current meter lost its sensitivity and recorded much higher speeds than the other instruments.

Current meter data obtained during the stormy period, when winds were up to 30 knots and waves approximately 1 m, were most interesting and revealing. Substantial differences were recorded between the three current-meter pairs; the current meters on the mooring all showed much higher energy (speed squared). The Aanderaa current meter on mooring failed to show slack periods over the tidal cycles, and instead recorded 30-minute averaged speeds up to 20 to 30 cm/s. On the other hand, the measurements made by current meters on the tower did record slack water, and the mean energy during slack was only slightly higher than the energy level at slack when the weather was calm. This result was most surprising, particularly for instruments using the rotor and large directional fin. Figure 2 depicts the current-meter data obtained by Aanderaa RCM on the tower and on mooring for the same period of the 55th through 58th Julian days. Clearly, the current meter on mooring showed a much higher energy level, which is believed to be due to mooring-line motions driven by surface waves. Data obtained by the pair of Endeco current meters showed similar behavior, though the difference between the two current meter records is not nearly as substantial. The GO current meter pair gave close agreement between themselves. It is encouraging that the GO current meter on the mooring recorded slack water during the storm, but unfortunately, this meter also gave erroneous direction readings and low sensitivity of speed in the high speed range.

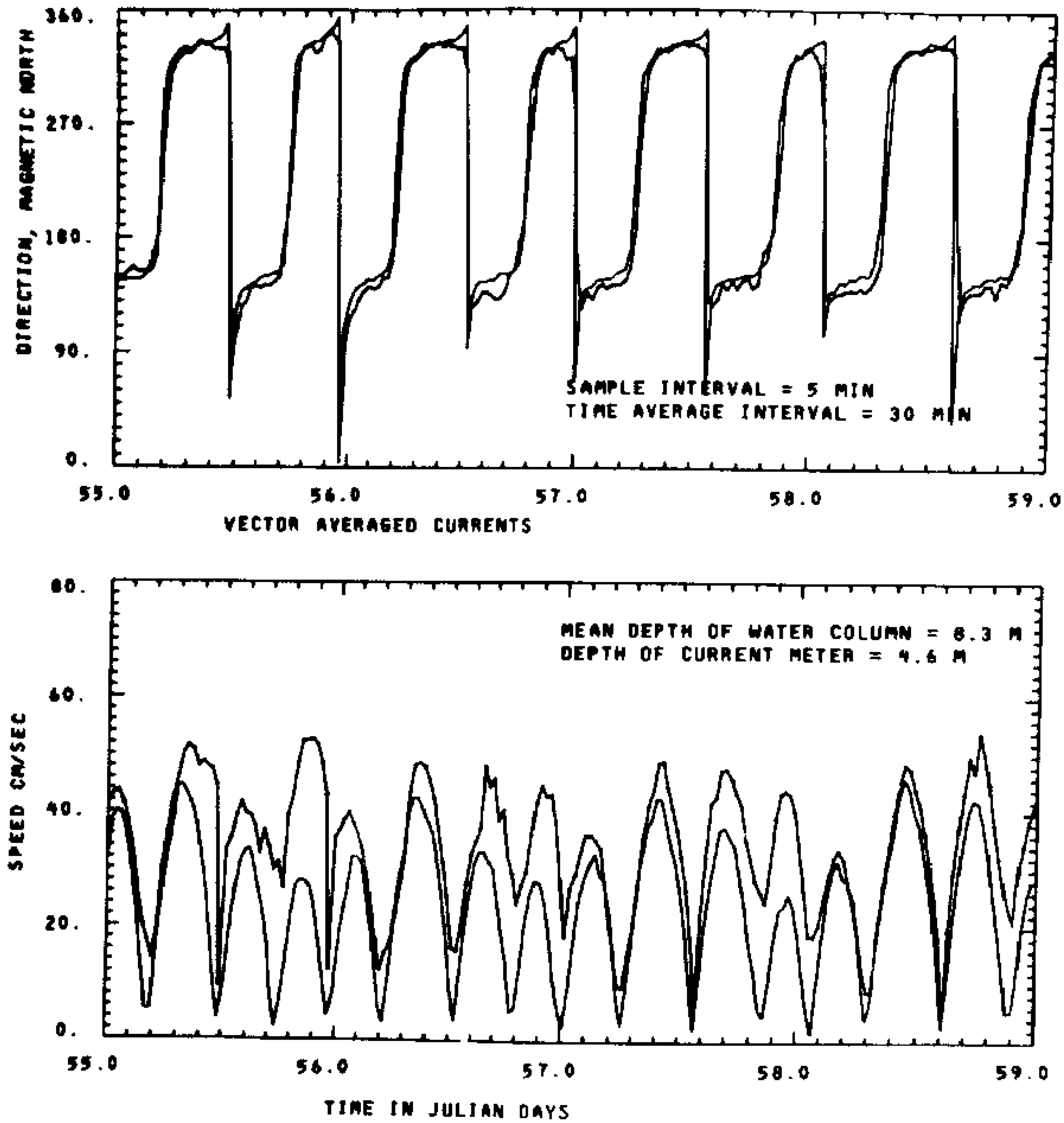

Figure 2. Comparison of the current-meter data obtained by two Aanderaa current meters; the solid lines are data measured by an Aanderaa current meter mounted on the tower, and the solid lines with dots are data measured by an Aanderaa current meter mounted on a subsurface mooring.

DISCUSSION

Through two months of field operations of several recording current meters, we gained valuable field experience which is indispensable for our planned program of current measurements in San Francisco Bay. Use of an instrument tower has successfully separated mooring line motions from the actual movements of water parcels. The current meter data indicated that the types of current meters tested are, to some degree, susceptible to mooring line motions. Since the waves in the Bay system are wind-fetched short-period waves, the orbital motions due to waves do not have substantial influence over current meter records. These results suggest that none of the tested instruments is completely satisfactory on a conventional subsurface mooring. When rigid instrument supports are used, both the Endeco and Aanderaa current meters can provide accurate current readings in the San Francisco Bay system.

W O R K I N G   S E S S I O N

<u>Panel Members</u>:

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INTRODUCTION

Although the original intent of the conference working session was to focus on preselected questions, some additional, important current measurement technology issues emerged during the conference and assumed the highest priority for discussion. The following were identified as needs during the discussion:

A. A handbook or compendium that would assemble basic current measurement technology information;

B. Community-sanctioned, standardized testing methods and procedures;

C. Government-sponsored facilities and services for test, evaluation and calibration of current measurement systems;

D. Hardware and software standards:
   - Laboratory measurement standard or class of standards
   - *In situ* hardware standard(s) and/or calibration facility
   - Data recording standards: both technique and format;

E. An *ad hoc* committee to address the issue of current measurement standards;

F. A reference library or "reading room" at which all pertinent current measurement literature would be available;

G. Resolution of the question whether government or industry should underwrite the cost of technical development.

DISCUSSION

A. A handbook or compendium which would assemble basic current measurement technology information.

The suggestion for a summary handbook stems from the need for the current measurement community to understand the operational capabilities, performance characteristics and recommended applications of available technology. Although some of this information exists, it may not be easily available and tends to be non-standard in methods of data presentation. The Testing and Evaluation Laboratory of NOAA/NOS has recently prepared a current sensor technology matrix*. In general, the matrix contains manufacturer-supplied information on the operational characteristics of commercially available current measurement subsystems and is intended to be an aid in assessing the state-of-the-art of this technology. A handbook could be created by expanding this matrix to include results of performance evaluations independent of the manufacturer and to include subjective, yet credible, opinions from users based on experience with particular system applications. The objective would be an easily modified document that would assist the user in making decisions about which technology to use and its appropriate application.

B. Community-sanctioned, standardized testing methods and procedures.

Again, the need of the community for technology performance information motivates the request for some standardized testing methods and procedures. In general, there are many useful procedures for testing specific aspects of certain current measurement devices being implemented throughout the community. Because these procedures invariably differ among investigators, or at the very least are not well documented, a comparison of test results on different (or even the same) instruments can be difficult or even meaningless. Even more important, however, these existing procedures are not complete enough to define the total performance of the instrument.

Understanding the total performance implies having a testing capability that can subject the instrument to a full range of anticipated natural variations and platform-induced motions, and determine its response to them. The testing procedures and facilities needed do not exist. Thus, the testing procedure problem involves two things: (1) standardizing procedures that now exist and (2) performing the testing research needed to develop a full testing capability that can ultimately be standardized. The overall objective would be to establish a procedure or sets of procedures for testing various classes of current measuring instruments. A vital consideration in developing "standard" procedures is that they be generated from within and sanctioned by the current measurement community.

C. Government-sponsored facilities and services for test, evaluation and calibration of current measurement systems.

The expense of building and operating the testing facilities required to determine the response characteristics and overall performance capabilities of a current measurement instrument is a basic problem contributing to our lack of knowledge of how well we can measure currents. The current measurement instrument market is

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*Available from G. F. Appell, NOAA/NOS/T&EL, C651, Bldg. 160, WNY, Rockville, Maryland 20852 relatively small, yet it is supported by as many as 15 or 20 commercial instrument manufacturers. By necessity, these companies tend to be small and operate with a low overhead to remain competitive. This has precluded capital investment by the manufacturers in large testing facilities. Also, because no urgency for a "certified" qualification of instrument performance before purchase has been communicated by the user community, a minimum of "personalized" testing has generally sufficed.

Because the community's awareness of the difficulties of current measurement is increasing, the need to document instrument performance is greater. Accordingly, the burden for instrument qualification is greater and should naturally fall to the manufacturer. But the manufacturer still has the small sales volume and low overhead problems. Increasing the instrument cost to reflect additional testing may not compromise his competitive position, but this presumes that a test facility and test procedures are available.

Willingness by the user community to pay higher initial instrument costs to reflect increased testing may solve part of the problem. But the very large capital investment for the facilities needed to perform the tests would still be a problem. At least in the near future the manufacturing community will not be able to afford that cost. Besides, the manufacturers have similar testing needs and a single manufacturer may not be able to keep a test facility fully utilized.

The size of the market and the facility expense problems suggest that some type of centralized testing capability would be a cost-effective way to determine the response characteristics of current measurement instruments. Because the federal dollar is directly or indirectly associated with the purchase of the majority of current measurement instruments, and because it is recognized that the manufacturers do not have the resources for the facilities, it would be appropriate for the government to support a centralized testing capability. This central capability would ultimately save the taxpayers money by assuring that good quality instruments are used to support current measurement programs.

The suggestion is, therefore, that the best way for the instrument user to pay for the costs of tests that will ensure quality instruments is as a taxpayer. Access to these test facilities during the current measurement development phase will reduce ultimate current measurement costs to all parties concerned.

D. *Hardware and software standards: laboratory measurement standard or class of standards, in situ hardware standard(s) and/or calibration facility, data recording standards: both technique and format.*

A consensus evolved on the need for standards applicable to the measurement of water current. It was apparent that the word standard is interpreted differently and some definition is needed. A general discussion of the concept relative to the measurement of current is included in the appendix and specific standards requirements are presented below.

For laboratory measurements, there is a need for some type of current measurement device of known accuracy capable of measuring the relative water motion past an instrument undergoing tests. Because laboratory testing includes both steady and non-steady conditions, this device or combination of devices must be responsive over a broad range of temporal and spatial scales. The resulting hardware with this capability could be considered a current measurement laboratory standard or class of standards.

Present techniques for field testing current meters allow for only relative comparison of instrument capability and not absolute determination of performance. Thus, there is a need for a field device of known accuracy, or perhaps a calibrated flow field, for the determination of absolute performance.

Another standards issue that was discussed vigorously throughout the Conference was the problem of the lack of recording format and technique standards for current meter data. The discussion centered around magnetic tape recording techniques and pointed out the costly and unnecessary duplicate magnetic tape processing facilities required because of the myriad of recording methods available in existing current measurement instrumentation. The problem, it was agreed, is not a simple one, but certainly one that is solvable because standards now exist which could be adopted through appropriate community action.

A most important consideration relative to all of the above discussion is that the current measurement field is one that is continually evolving. There are many different classes of instruments available. As a result, it may not be technically feasible or correct to develop a standard that would be applicable to all classes. Perhaps a class of evolving standards would be appropriate. In the case of the field standard, because of the variety of deployment and mooring systems, classes of standard systems rather than a standard current meter might be most appropriate.

E. An ad hoc committee to address the issue of current measurement standards.

Because of the general agreement regarding the need for standards as discussed above in B, C, and D, it was proposed at the working session that an ad hoc committee be formed at the Conference to be the initial community mechanism responsible for addressing the issue of current measurement standards. Formation of the committee was agreed upon and it was decided that the committee membership would be two elected members from each segment of the community--scientific research, ocean engineering, operational surveys, environmental impact assessment, and testing--under the guidance of a single elected chairman. Because representation of the manufacturing community by two individuals was impossible at that time (i.e., until further industry rapport developed), it was agreed that the manufacturers would have no direct representation but would be invited to all meetings as observers and have their ideas and opinions solicited on all issues raised by the committee. The committee is to have a lifetime of one year and during that time will pursue creating a permanent committee to be affiliated with one or more professional societies (such as, MTS, AGU, IEEE, etc.).

Among the list of charges drafted for action, it was decided to have the committee focus on the development of standardized testing methods and procedures. A report of progress is planned for the September 1978 MTS/IEEE Oceans 78 Conference. The committee has thus been named, The Ad Hoc Committee on Current Measurement System Test Procedures and Standards. The elected members are:

Chairman:	William E. Woodward, NOAA/Office of Ocean Engineering
Scientific Research:	James McCullough, Woods Hole Oceanographic Institution Dr. J. D. Smith, Univ. of Washington
Ocean Engineering:	Dr. George Forristall, Shell Development Co. Dr. Robert Stacy, Mobil R&D Corp.
Operational Surveys:	Robert Peloquin, U.S. Naval Oceanographic Office Lewis Walker, NOAA/National Ocean Survey
Environmental Impact Assessment:	Dr. Richard Scarlet, EG&G, Environmental Consultants Dr. Harold Palmer, Dames & Moore, Inc.
Testing:	Gerald F. Appell, NOAA/National Ocean Survey Dr. Lloyd Huff, NOAA/National Ocean Survey

F. A reference library or "reading room" at which all pertinent current measurement literature would be available.

Because much of the information related to current measurement technology is in the form of institutional reports (or is never published in a report form), a library, "reading" room or rooms (perhaps regional) would be useful. The library would have the charge to follow the daily activities of the current measurement community and be constantly on the lookout for published or unpublished information or data pertinent to current measurement technology. The material would then be available for reference at one place and reduce the need for individual library research. The library could be an adjunct to or at least patterned after the National Oceanographic Data Center.

G. Resolution of the question whether government or industry should underwrite the cost of technical development.

The question of whether government or industry should underwrite the cost for research and development of new current measurement technology was raised and discussed briefly. In private enterprise, if a manufacturer has a concept that, based on a market analysis, could be transformed with some R&D activity, into a product which could be sold in quantity and a profit realized, then the money required for R&D

product engineering could profitably be invested by the company. In a small volume market as with current meters, although the above principle is the same, the market is not well defined, which makes commitment of resources in the R&D phase more risky because of uncertain future profits. In general, most current meter manufacturers do provide their own R&D money, but because of the risky market try to keep the investment to a minimum. This procedure often leads to the current meter user bearing the brunt of development costs and delays during use.

The major issue is that if the R&D funding source is not consistent and the government does fund some R&D, then the government may be charged with supporting the development of technology that is in direct competition with existing technology, the development of which was funded by the manufacturers. This issue can be defused with use of appropriate management procedures. For example, if it can be demonstrated that existing technology cannot meet stated government specifications for a particular project, then R&D may be necessary and government funding on a competitive basis is appropriate. Following such a procedure would alleviate the fear of unwarranted government initiatives in the development of new current measurement technology.

In the case of current measurement technology, the demonstration of an instrument's ability to meet certain specifications may be difficult, if not impossible, because of the lack of testing methods and standards as discussed earlier. The lack of testing capability complicates the issue of R&D funding, making it difficult to judge the appropriateness of the government sponsored development.

RECOMMENDATIONS

1. Assemble existing basic current measurement technology information into a handbook or compendium.

2. Develop community-sanctioned standardized testing methods and procedures.

3. Develop a government-sponsored current measurement system test, evaluation and calibration capability (including both laboratory and field facilities and services).

4. Investigate the feasibility of developing current measurement hardware and software standards.

5. Create a library or "reading room" at which all pertinent current measurement literature, published or unpublished, would be available for reference.

6. Have the Ad Hoc Committee on Current Measurement System Test Procedures and Standards investigate creation of a permanent committee affiliated with one or more professional societies.

POSTER SESSION SUMMARIES

THE ARCTIC PROFILING SYSTEM

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INSTRUMENT

The Arctic Profiling System (APS) is a wire-lowered device used for making continuous vertical profiles of density and velocity. The sensor package shown in Figure 1, consists of three basic units: the Inertial Reference Unit (IRU), the CTD, and the Current Meter Triplet. The IRU is used to measure the orientation of the APS. It consists of a North-seeking gyro compass, a three axis accelerometer package, and a two axis rate gyro unit. The CTD is a standard Guildline model 8101A. The electronics pressure case is mounted just below the IRU and the conductivity and temperature sensors are mounted near the bottom of the electronics pressure case. The Current Meter Triplet is used to measure the complete velocity vector relative to the descending APS. It is mounted at the bottom of the APS and consists of three ducted rotor current meters in an orthogonal mount.

DEPLOYMENT AND DATA LOGGING

The Arctic Profiling System is cycled continuously to depths up to 140 m by an automatic winch at speeds from .5 m/sec to 2 m/sec. Data are recorded in digital form on magnetic tape using a Nova 1200 mini-computer.

PROCESSING VELOCITY DATA

The processing of the APS velocity data proceeds along the following lines. Current meter frequencies averaged over 1.2 sec are used to compute initial estimates, U_1, U_2, U_3, of velocity using "head on" calibration coefficients,

$$U_j = af_j + b \qquad a = 3.601 \text{ cm/pulse}, \quad b = 1.089 \text{ cm/sec}$$

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Figure 1. The Arctic Profiling System

The ratios U_2/U_1 and U_3/U_1 are used to calculate current meter angle of attack corrections G_1, G_2, and G_3. These corrections are given by a polynomial in U_2/U_1 and U_3/U_1. The polynomial has been derived as a curve fit to the result of iterative determinations of angle of attack corrections for a large ensemble of hypothetical data. Once G_1, G_2, and G_3 are determined, true velocities, $V_j = G_jU_j$ are calculated. Data from the compass and accelerometers and a knowledge of the triplet geometry are used to transform the velocity vector into a reference frame carried with the profiling device and oriented North, East, and down. Horizontal velocities measured during each down profile are plotted (see Figure 2) along with σ_t (as calculated from the CTD data) as a function of depth and recorded on tape for further analysis.

The measured horizontal velocity is relative to the profiling device, but comparison with fixed current meters indicates that under Arctic conditions (low currents), the profiling device is heavy enough to make any horizontal motions of the device negligible (see Figure 2). The measured velocity can thus be assumed equal to the water velocity relative to the ice. When used from an anchored ship, the ship motion is measured with a microwave ranging system and accounted for. Over a one hour period, horizontal motion of the profiler due to ship motion averages to a small value. Because the descending motion of the profiler keeps the current meters rotating continuously, the measurements of horizontal velocity have zero threshold. Groups of vertical profiles can be averaged together to obtain long time sequences of velocity profiles. Such sequences are shown for an Arctic experiment in Figure 3.

APPLICATIONS

The short cycle time (typically 5 minutes), high resolution with depth, and the ability to simultaneously measure velocity and density fields make the APS especially useful in studies of regions with strong stratification and velocity shear, such as oceanic mixed layers and estuaries.

The system has been used from an Arctic ice camp in the Beaufort Sea in a study of the Arctic mixed layer. It has also been used on-board a small research vessel in Knight Inlet, British Columbia, during a study of the dynamics of that fjord. Profiles have been made continuously for periods up to two weeks.

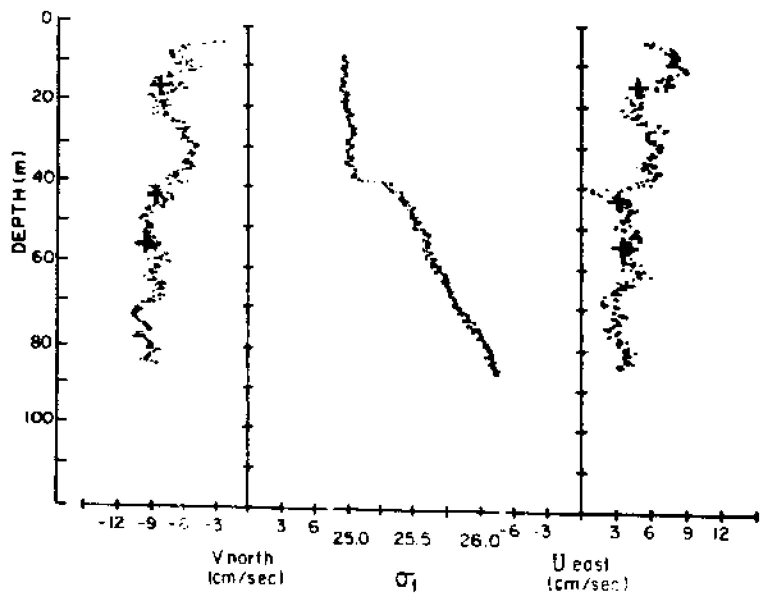

Figure 2. Velocity and σ_t profiles from a single down profile made during Arctic Experiments. + denotes data from fixed current meters.

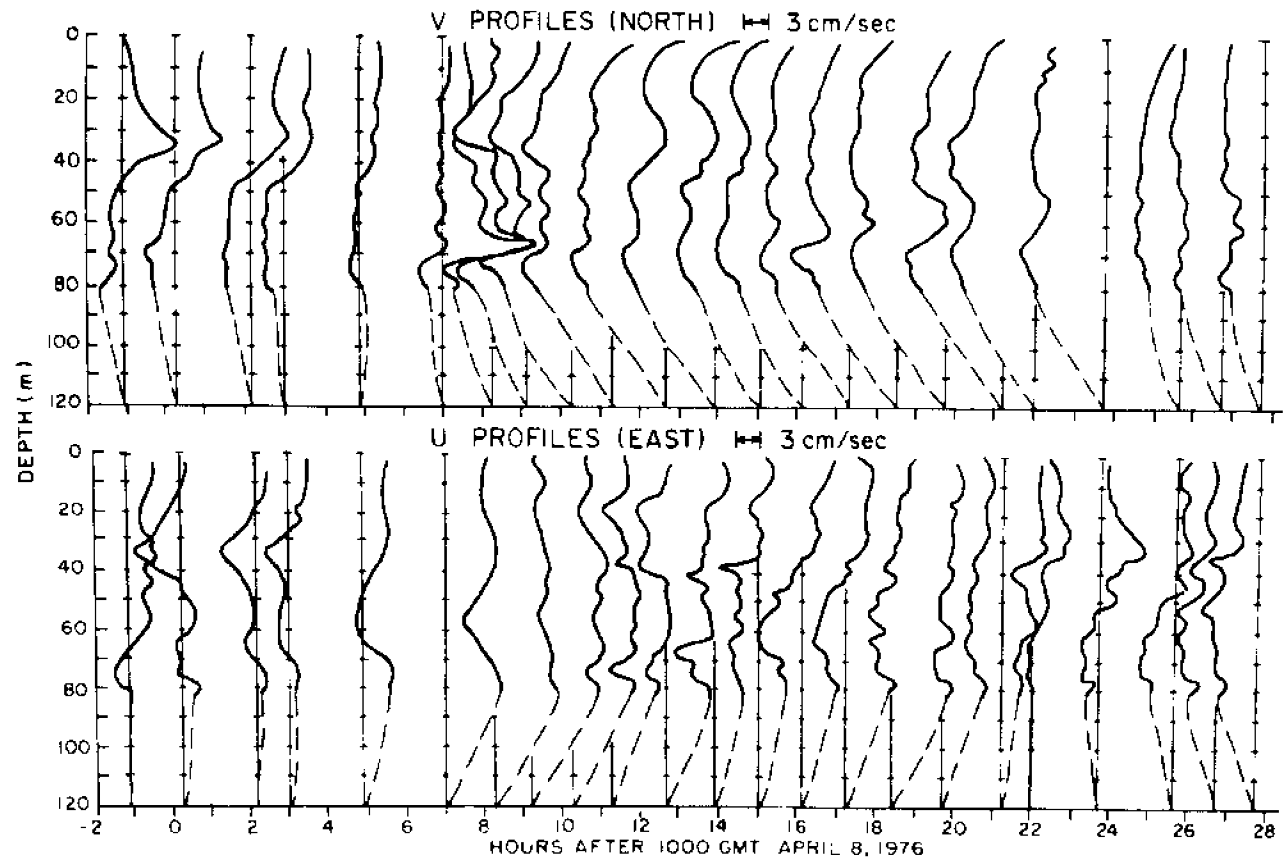

Figure 3. Sequence of 1 hour average (12 profiles) profiles of velocity made during the 1976 Arctic Mixed Layer Experiment.

CURRENT DATA FROM BREAKWATER HARBOR, SOUTHEASTERN DELAWARE BAY

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ABSTRACT

In a study of the present and past processes of the breakwater Harbor-Cape Henlopen area, currents were measured with a General Oceanics film recording current meter (Model 2010) in two locations within Breakwater Harbor. An accurate representation of trends and variabilities in the current regime of the harbor was produced.

The data are presented in a "rose diagram" with the radius of 20° sectors representing the percentage of the readings that were recorded flowing in the indicated direction. Different rose diagrams were drawn for velocity groups at 10 cm/sec increments. The data in each sector are divided according to whether the readings were recorded during times of predicted flood or predicted ebb tidal currents. The data indicate that the Harbor is strongly dominated by ebb tidal currents, both as a result of higher ebb currents and the longer duration of ebb tides.

Our system of deployment and retrieval of the current meter requires no buoy on the surface, no mechanical or electronic release mechanism, and no SCUBA diving. This makes it well suited for use in coastal and estuarine waters where accurate navigation is easy. These collection techniques and data presentation format are a reasonable solution to some of the problems of cost effective, reliable, and accurate current data collection and analysis.

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INTRODUCTION

As part of a larger study of the shoaling history and sedimentation patterns of the Breakwater Harbor-Cape Henlopen area (Demarest, 1978), currents were measured in two locations within Breakwater Harbor (Figure 1). These stations were selected to characterize the tidal current environments of the Harbor. Station 1 was located in the 12-meter-deep channel between Cape Henlopen and the inner breakwater. In both cases, the center of the current meter was about 40 cm above the bottom. The bottom sediment patterns are shown in Figure 2.

Breakwater Harbor, located in southeastern Delaware Bay, is funnel shaped with a wide opening to the west and a narrow opening to the east. Cape Henlopen deflects ebb tidal currents northward as the water rounds the eastern end of the inner breakwater. The Cape May-Lewes ferry terminal jetty, which extends northward from shore, south of the west end of the inner breakwater, constricts flow somewhat in the western entrance to the harbor (Figure 1). On the western side of the Cape, an extensive sandy tidal flat extends into Breakwater Harbor along the shore (Figure 3). Offshore of Cape Henlopen to the north, there is a 15-meter-deep channel between the tip of the Cape and the outer breakwater (not shown).

First, a low-cost current measurement setup for long-duration measurement will be described, including deployment and retrieval techniques. Second, the data acquired will be presented.

DESCRIPTION OF INSTRUMENTATION

A General Oceanics film-recording current meter (Model 2010) was used. This current meter was chosen because of its low cost ($800 in 1975) and self-contained, long-duration data recording mechanism. For the purpose of this study, these factors more than offset the imprecision of the instrument as compared to more sophisticated instruments.

One constraint was that the instrument had to be deployable and retrievable from a small boat. This greatly restricted the amount of weight that could be used in the tethering system. The instrument was, therefore, tethered to a cement block approximately 10x30x60 cm and weighing about 18 kgs, submerged (Figure 4). This also made it possible for any other (non-authorized) person to "retrieve" the instrument. Therefore, it was desirable to have no surface markers or floats attached to the instrument.

Danforth anchors, on the ends of 15 to 30 meter-long anchor lines, were used to prevent the current meter from dragging along the bottom. Plastic pipe was used to protect the anchor lines against chaffing on the cement block. A grappling hook was made for retrieval with 5/8-inch concrete reinforcing rods and lead weights (Figure 5). The location of the current meter was determined using a sextant for triangulation from shore points.

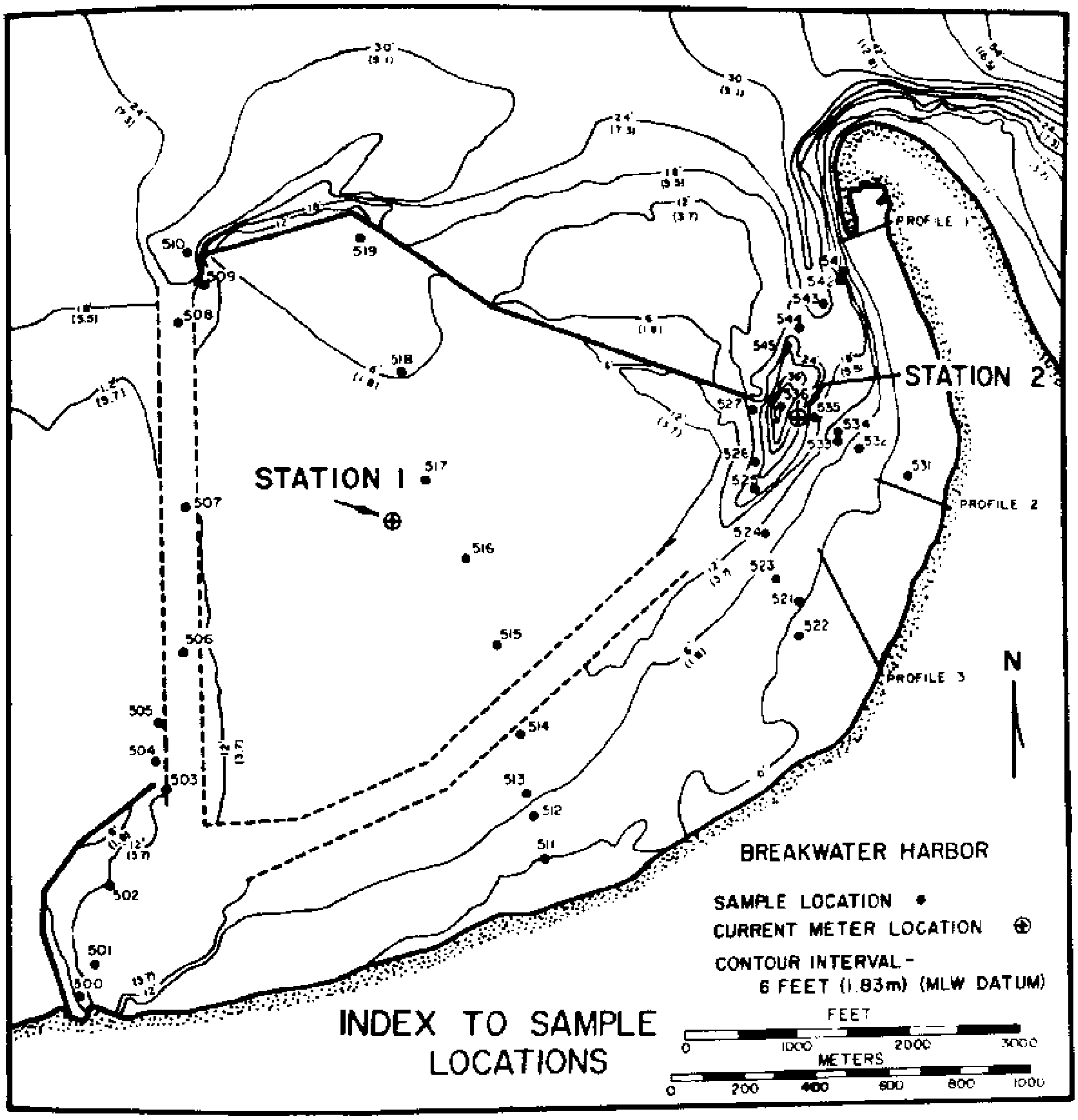


Figure 1. Index Map. Current meter stations are shown, Station 1 in center of harbor and Station 2 in eastern channel to harbor. The breakwater shown here is called the inner breakwater and was constructed in 1831. The jetty on the southern shore is the ferry terminal jetty and was constructed in 1964. An outer breakwater is present to the north of Cape Henlopen off this map.

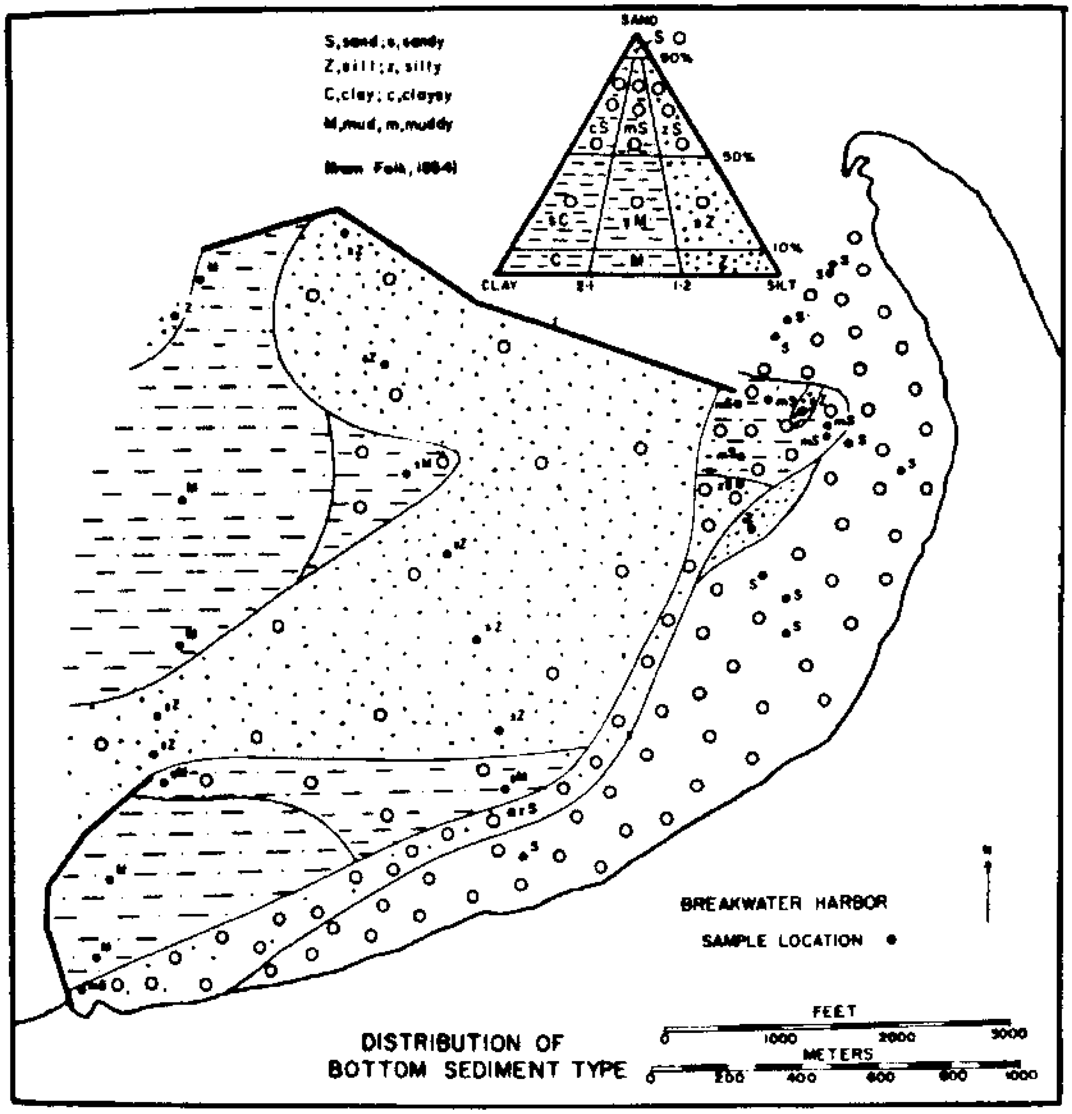


Figure 2. Bottom sediments in Breakwater Harbor. Sediments are classified according to Folk (1954). Note the sharp transition between the sandy sediment and the finer grained sediment in the southeastern part of the harbor.

Figure 3. Oblique aerial photograph from the northeast. Note the position of the sand ridges on the western side of the cape. This approximately defines the extent of the tidal flat.

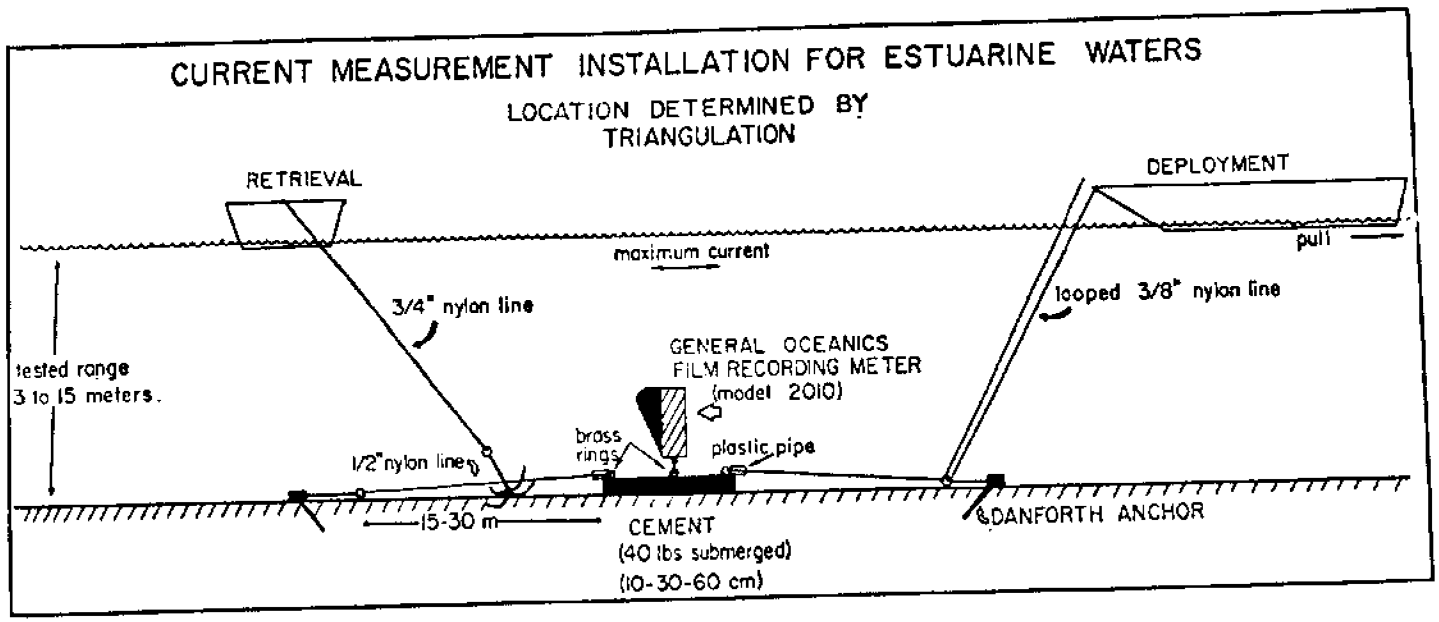
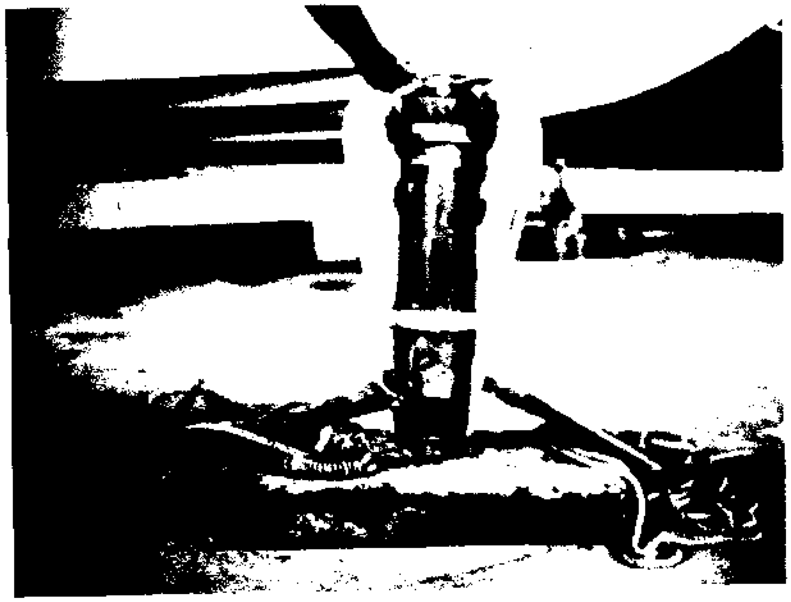


Figure 4. Schematic of current measurement apparatus, including deployment and retrieval techniques.



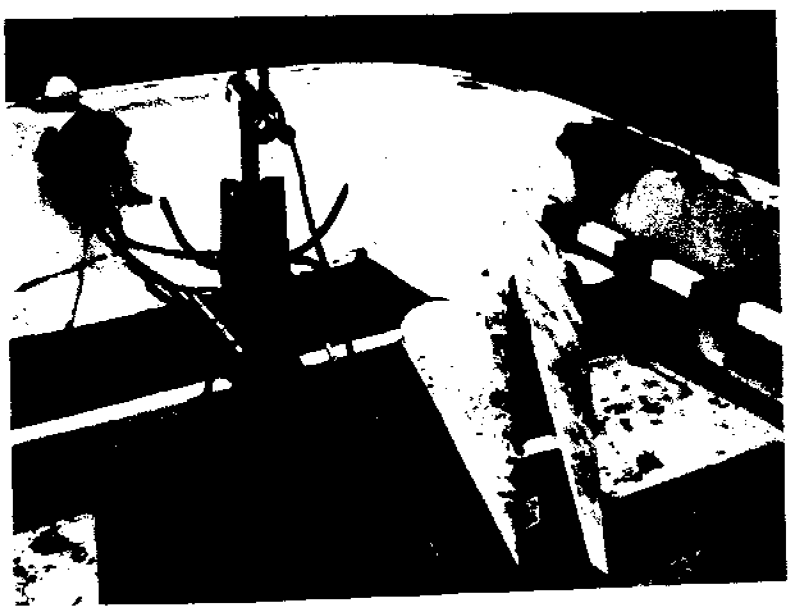


Figure 5. Photographs of the current meter, weight, and Danforth anchors (upper and retrieval system, including grappling hook and current meter (low

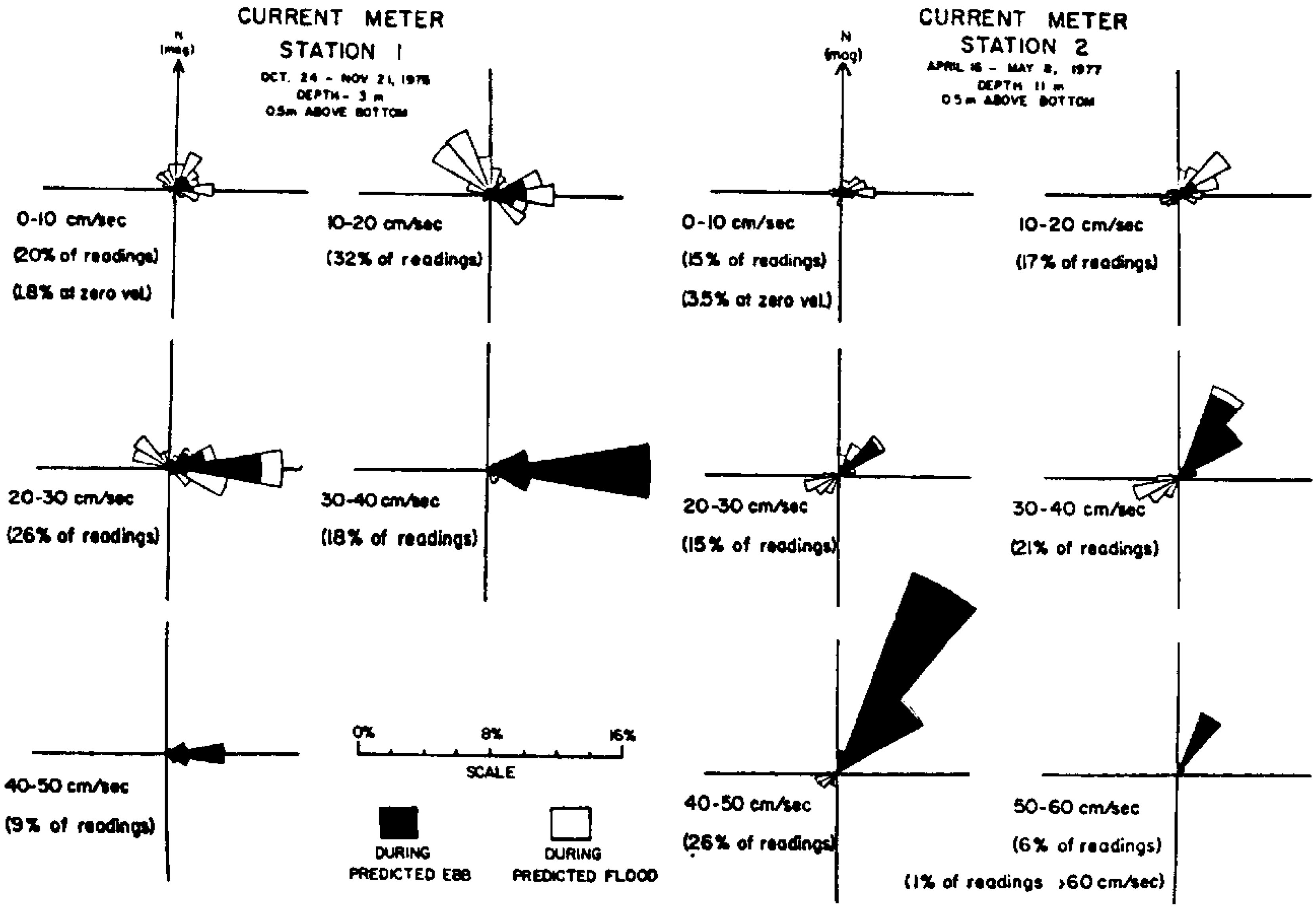


Figure 6. Rose diagram of Current data from Station 1 and 2. Each pie section represents the percentage of the total number of readings that flowed in that direction with that velocity. The white and black areas indicate the percentage of readings recorded during predicted ebb of predicted flood. Note the large number of readings in the "ebb" direction at times of predicted flood, but the absence of the inverse.

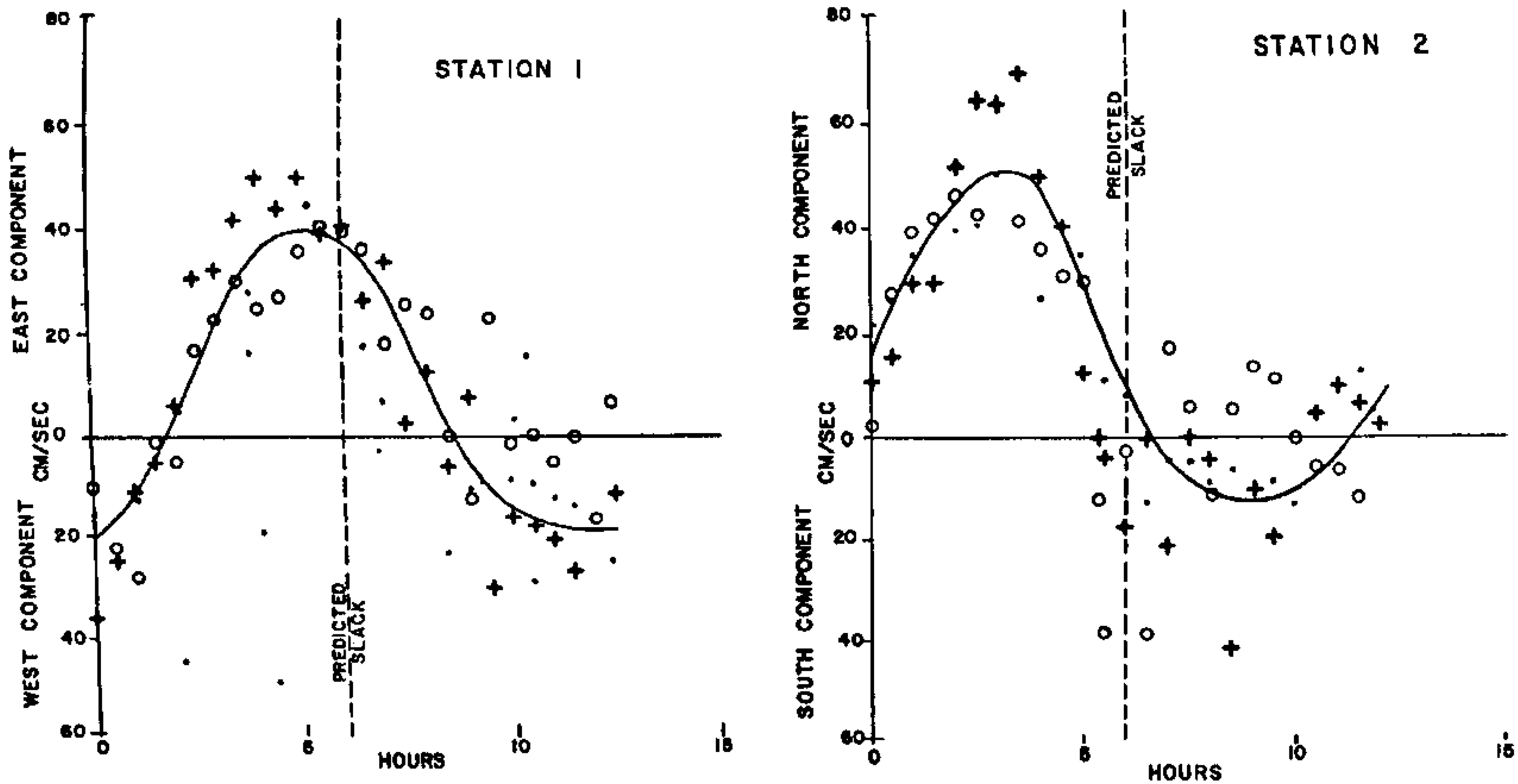


Figure 7. Component plots of data for three tidal cycles and both current meter stations. Data from Station 1 were not taken at the same time as data from Station 2. Station 1 plot is for the east-west components and Station 2 is for the north-south component.

DEPLOYMENT AND RETRIEVAL

The string of anchors and current meter (illustrated in Figure 4) were deployed from a 16-foot Boston Whaler. The first anchor was lowered and allowed to set on the bottom. As the boat was backed into the current, the current meter and weight were carefully lowered over the side. The last anchor was lowered with a loop of 3/8-inch nylon line attached. This line was used to pull all the lines tight and then released. By pulling hard enough to lift the current meter and weight off the bottom, it was assured that the instrument was in an upright position. Before releasing the last line, the location of the current meter was determined by triangulation using a sextant. It was helpful to use a separate buoy to mark the current meter location during deployment. The anchors were oriented in a known compass direction, approximately parallel to estimated maximum current directions.

Retrieval was accomplished by finding the location using the sextant and marking the spot with a buoy. The grappling hook was then dragged perpendicular to the orientation of the anchor lines, adjacent to the buoy. When the line was hooked, the instrument was pulled in. Sometimes it was necessary to slide the grappling hook along the tether line to one of the anchors in order to pull the instrument up easily.

We have had 100 percent success in about 10 deployments. The maximum number of passes with the grappling hook was about six while the typical number is one or two. This technique has been used in water as deep as 15 meters and on sandy and muddy bottoms.

DATA PRESENTATION

Station 1 data were collected during October and November, 1976, for 23 days. The data for Station 2 were collected during April and May, 1977 for 18 days. The General Oceanics current meter was set to measure the currents every 15 minutes for the duration of the measurement period. Thirty minute data intervals were used in the subsequent analysis. The instrument had a power problem on these first two runs which caused them to be shorter than desired. This problem was corrected so that data collected subsequently measured the currents for an entire lunar cycle. The large number of measurements over a long period of time allows the data to accurately represent trends and variability in the current regimes of the Harbor.

The data are presented using rose diagrams with the radius of 20° sectors representing the percentage of readings that were recorded flowing in the indicated direction (Figure 6). Different rose diagrams were drawn for velocity groups at 10 cm/sec increments. All radii are representative of the percentage of the total readings for that station that flowed in the indicated direction with the indicated velocity. In addition, the data in each sector were divided according to whether the readings were recorded during times of predicted flood or ebb tidal currents for surface waters taken from NOS Tide Tables. This was done to help show the time relationship of the data in the rose diagram. The rose plots can be contrasted with the visual representation given in Figure 7, which are plots of three complete tidal cycles using times of predicted slack water before the beginning of ebb tides as the cutoff between tidal cycles. This is an arbitrary division in light of the inaccuracy of the slack water predictions as seen in Figure 6. In addition, Figure 7 shows only a small portion of the data. This makes the plot less reliable as a basis for making generalizations about current flow in the area.

Large amounts of scatter in the data from point to point, coupled with unstable configuration of the current, indicate when wave-induced, high-frequency fluctuations in flow affected the current meter. Currents at Station 2 were generally in the ebb direction for eight hours and the flood direction for four hours. Station 1 data are difficult to evaluate for duration of flood and ebb because of the shallow depth of the instrument, resulting in wave-induced "noise," especially at low velocities. This made dividing ebb duration from flood duration difficult.

PRELIMINARY FINDINGS

The data presented in Figures 6 and 7 show a strong dominance of ebb tides in Breakwater Harbor. Velocities were about 60 percent higher during ebb tides than during flood for both stations. Both current meter stations show an asymmetry between the duration of ebb tide and the duration of flood tide. Figure 7 shows the great variability of flow through a tidal cycle and from tidal cycle to tidal cycle. The rose diagrams in Figure 6 show many readings recorded during predicted flood flowing in the "ebb" direction. The reverse situation was not found during predicted ebb. This indicates that a large eddy develops around the western end of the inner breakwater on flooding tides producing eastward flow in the Harbor. Flooding tides are always greatly reduced, if not reversed, because of the geometry of the Harbor and its entrances. Current data from north of the spit tip show a dominance of ebb tides, but the dominance is not nearly as pronounced as in Breakwater Harbor.

Reduction in flood tides produces a longer duration of slack or low-velocity flow than otherwise would be present. At Station 1, more than 50 percent of the readings had velocities less than 20 cm/sec. This creates a great potential for the settling of suspended particles within the Harbor, allowing for more de-watering and compaction. These factors produce a large potential for sedimentation and reduce the likelihood of resuspension during a tidal cycle.

With high current velocities occurring mostly on ebb tides, coarse-grained material is not transported into the Harbor from the largest source of coarse sediment, Cape Henlopen. Sand is carried by littoral processes around the tip of the Cape and across the tidal flat. Velocities within the Harbor are generally not high enough to transport sand on flooding tides. This accounts for the sharp transition from sand to silts and clays adjacent to the tidal flat areas in the eastern harbor. Sediment which is transported off the tidal flat on flooding tide is not carried into the Harbor, but rather is deposited adjacent to the tidal flat. On ebbing tides, sand which is transported off the tidal flat is carried out of the Harbor around the eastern end of the breakwater.

CONCLUSIONS

With long term data, general statements about the dominant flow patterns within Breakwater Harbor can be made. Because of the large variability, current measurements of one of two tidal cycles are not likely to accurately represent the flow regime.

The data acquisition costs are well within the range of most estuarine research budgets, and a great amount of data can be obtained at low cost when the instrumentation and equipment are kept simple. Data reduction from photographic film is time consuming, but in the saturated labor market of a university graduate program, this may not be a major problem.

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APPENDICES

1. Basic Research Goals of the Physical Oceanographic Community Engaged in Current Measurement. Christopher N. K. Mooers

2. Discussion of the Concept of Standards Relative to the Measurement of Water Velocity. William Woodward

3. Conference Participants

4. Conference Program

5. Results of the Pre-Conference Questionnaire

BASIC RESEARCH GOALS OF THE PHYSICAL OCEANOGRAPHIC COMMUNITY ENGAGED IN CURRENT MEASUREMENT[1]

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This is a short essay to place in perspective the oceanographic community's basic research aspirations vis-a-vis current measurement.

The scientific goal of the physical oceanographic community is prediction of ocean circulation. The terms prediction and ocean circulation are deliberately used in an imprecise fashion because prediction is an evolving capability, and because ocean circulation encompasses a large range of scales of motion. The term prediction covers both forecasts (prognostic models) and hindcasts (diagnostic models). Forecasts are both more valuable and more difficult than hindcasts because there is generally less empirical information available for use in them. Hindcasts have intrinsic value for assessing environmental calamities, such as oil spills. The prediction capability depends upon supply and demand--the supply of predictive means, and the demand for a certain quality and quantity of predictive information. The predictive means are provided by theory, experiment, and observation. The theory provides a model. In the beginning, the model may be descriptive, heuristic, and qualitative. Contemporary models are generally quantitative and represented by a set of partial differential equations and boundary and initial conditions. The set of equations must be solved with inevitable restrictions on space and time scales or processes which can be resolved. Processes on unresolved scales of motion must be approximated as a function of known variables (or "parameterized") for incorporation into the model's system of equations. This requires understanding of the processes, particularly their relationship to, and interaction with the larger, resolved scales of motion. Specific process theories are investigated, and process experiments, in the field or laboratory, are conducted to test hypotheses whose validity is essential to particular parameterization schemes.

[1]Discussion at the Conference indicated a need to clarify to the nonoceanographic community, the basic research objectives of physical oceanography.

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Much of the present and prospective basic oceanic research is in this area of process and parameterization studies, a topic to be returned to below. Observations as distinct from experiments enter, too. Here observations include either of two extremes: exploratory studies to chart the major features of the physical geography of some portion of the ocean, or routine monitoring at some critical or representative points to develop a statistical climatology of the state of the ocean, to provide boundary and initial conditions for model operation, or to provide verification data to test and modify models. (Sharp delineation of field experiments, exploratory studies, or routine monitoring is not always possible.)

The demand for circulation predictions has been driven by the supply of predictive means, a quite natural situation of interaction and iteration between suppliers and an expanding market. In recent times, the demand has begun to exceed the supply in certain topic areas; for example, the storm-driven currents on continental shelves which are needed by the forces-on-structures-and-beaches and the water quality communities. The U.S. Navy seeks a global ocean circulation forecast capability by 2000; surely, the USN must consider this important for effective and competitive naval warfare operations in the future. As mankind has become conscious of the delicate dependence of civilization on the tenuous global climate, and of the natural and society-induced vagaries of the climate, a predictive understanding of climate has begun to be sought. In the quest for a quantitative understanding of climatic variations, it was quickly realized that, because of the ocean's large heat capacity compared to that of the atmosphere, the ocean plays a major if not dominant role in the global climate. This in turn means that high quality ocean circulation and air-sea exchange models are necessary to predict the global climate. Even traditional commodities have new value and increased requirements. For example, the advent of supertankers and increased recreational boating places more importance on accurate predictions of tides and tidal currents in shallow seas and estuaries. With extended national jurisdiction to 200 nautical miles offshore, new and old resources come under management pressure. For example, more quantitative methods for fisheries management are priority items. These methods include improved circulation forecasts to account for the year-to-year variability in coastal upwelling which is so influential in fisheries production. At least from the ocean scientists' viewpoint, everywhere we look, we see growing demands for circulation predictions and, hence, a mounting agenda of circulation problems to be understood to some level of prediction.

Rather independent of particular applications, but with at least a subconscious awareness of potential applications, the physical oceanographic community has been striving to describe the kinematics and understand the dynamics of the general (average, large-scale) circulation of the ocean. In the open ocean, it has been recognized that synoptic scale circulation (eddies and planetary (vorticity) waves) with scales of approximately 100 km in the horizontal, 1 km in the vertical, and 100 days in time, strongly interact with the general circulation. This synoptic scale circulation may or may not be resolved in future operational models of the oceanic general circulation or air-sea models of the climate. If not resolved, its effects will have to be parameterized. In any event, the synoptic scale circulation will have to be understood. In the coastal ocean, there is a vigorous, storm-driven transient circulation, with scales of approximately 100 km in the horizontal, 100 m in the vertical, and 10 days in time. This transient circulation, as well as the general circulation in the coastal ocean, must also be understood for prediction. In the past decade, and for the foreseeable future, much of the effort in current measurement has and will address the kinematics and dynamics of the synoptic and transient circulations of the open and coastal oceans, respectively. There is also an element of statistical climatology in analyzing the geographical variability of these circulation components. For these purposes, the contemporary accuracy and sampling rates of current measurements are adequate, but continuous record lengths of the order of a few years are required. Both Eulerian and Lagrangian systems play a role in these measurements. In both the open and coastal ocean areas, important questions of momentum, heat, and mass exchange across the air-sea boundary and their subsequent dispersion from the surface boundary layer to the ocean interior remain open. Similarly, the mixing of the water column and resuspension and advection of sediments in the boundary layer near the sea bottom are not fully understood. For the turbulence studies required in the surface and bottom boundary layers, very precise and rapid current measurements are required for modest record durations of a few days. There are other processes important to circulation generation and dissipation, such as oceanic fronts and internal waves, which are studied with other specialized current measurement systems.

Results from the various process field experiments are incorporated in process and circulation model development efforts as opportunity permits. Physical oceanography is in an early stage of development, and an operational forecast service does not exist in any comprehensive sense as it does in meteorology. However, a few products of the climatological and hindcast varieties are available on a regular basis. As the prediction capability evolves in coming decades, increasingly useful circulation prediction products will become available through federal agencies as applications people exploit the basic research findings.

DISCUSSION OF THE CONCEPT OF STANDARDS RELATIVE TO THE MEASUREMENT OF WATER VELOCITY

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For the measurement of any variable, a knowledge of the accuracy of a measuring device implies the existence of another device of greater known accuracy to which the performance of the first is compared. Underlying such a sequence of devices, are absolute standards based on physical constants and rational definitions. None of these "devices" exist for the measurement of water velocity. The reasons for this include the complexity of water velocity measurement (sometimes referred to as the broadband nature of the signal), the embryonic state of current measurement, and the lack of effort dedicated to solving the problem.

A generally accepted "standard" for water speed is the measurement of time and distance of a land-based carriage that tows a current meter through still water. Because this approach considers only the steady flow case, it is not worthy of the title "current measurement standard." It does allow determination of the accuracy of an important aspect of current measurement.

A difficulty with the towing carriage method is that additional means are required to determine the "stillness" of the water. This implies the need for some type of current measuring device of known accuracy which could be towed simultaneously with the instrument being tested. Based on the above discussion of the concept of a standard, this additional device could be called a "steady flow current measurement laboratory standard."

The above briefly describes only one part of the problem. The additional problems of how the tow carriage technique relates to motions encountered in the field, and how you can determine the accuracy of those instrument techniques that do not lend themselves to tow tank testing, are beyond the scope of this writing.

Because the tow carriage considers only the steady flow portion of the signal spectrum, there is a need for methods to address the non-steady

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(usually referred to as the dynamic) portion of the spectrum. While these procedures do not exist generally, there are several groups attempting to simulate dynamic ocean conditions with mechanical oscillating systems, sometimes combined with tow carriage motions. Again, although the motion of the mechanical system can be measured very accurately, the real need is to accurately measure the relative water motion past the instrument being tested. Hence, as before, there is a need for an additional device capable of measuring the water motion, perhaps to be called a "dynamic current measurement laboratory standard." This device must be responsive to a broad range of time and spatial scales and may or may not be the same piece of hardware as the steady flow standard above. The comparison criteria for the dynamic response may involve the auto- and cross-spectra of variables, as well as the regression of variables.

The previous discussion has centered around laboratory standards. An additional area of concern is that of in situ or field standard hardware or facilities. A popular method involves field deployment of two or more current measurement systems in close proximity and the subsequent comparison of results. This technique does not provide an absolute determination of performance. A device of known accuracy or a calibrated flow field could be used to determine absolute performance. Either of these might be considered a field standard.

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Working Conference on CURRENT MEASUREMENTS
Sponsored by the NOAA Office of Ocean Engineering
with the Delaware Sea Grant College Program
University of Delaware Conference Center, Newark, DE
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WEDNESDAY, JANUARY 11. All sessions in Room 128

0845 **GENERAL SESSION**

Welcome/Opening Remarks
C. N. K. Mooers, University of Delaware
William Woodward, NOAA/Office of Ocean Engineering

"Capabilities of Some Existing Near-Surface Current Sensors"
James McCullough, Woods Hole Oceanographic Institution

When current meters are used to measure mean horizontal currents in surface gravity waves, immunity to the vertical component of flow is important, even though the net vertical flow averages to zero and is normal to the desired horizontal components. A technique for estimating the magnitude of the errors introduced by imperfect rejection of the off-axis flows (cross-talk) from measurements of the current meter vertical and horizontal "cosine" response is presented. The predicted dynamic response is shown to compare favorably with laboratory measurements. The measured steady state vertical cosine response functions for several popular current sensors are then summarized and used to estimate the magnitude of wave-induced errors in horizontal mean current measurements.

"Review of the Performance of an Acoustic Current Meter"
Gerald Appell, NOAA/National Ocean Survey

The Test and Evaluation Laboratory of NOAA/NOS recently completed a limited performance evaluation of three Neil Brown Instrument Systems Acoustic Current Meters (NBIS ACM-1) for the NOAA Data Buoy Office. Steady flow calibrations were performed on the four cardinal measurement axes as well as directivity response evaluation in both the horizontal and vertical planes. Calibrations were performed on the solid state compass, used for magnetic heading reference in the current meters. Environmental tests were conducted in accordance with mil-std 167B for vibration testing and environmental temperatures tests were guided by mil-std 810C. The methods and procedures for accomplishment of these tests are discussed and evaluation results are graphically displayed.

Break

1100 **SCIENTIFIC RESEARCH**

Session Chairman: **Nick Fofonoff, Woods Hole Oceanographic Institution**

"Mooring Motion Influences on Current Measurements"
David Halpern, NOAA/PMEL, and Dale Pillsbury, Oregon State University

1145 *Lunch in Room 101A*

1330 *Session Resumes in Room 128*

"Physical Oceanographic Research using the Attended Profiling Current Meter (APCM) and the Cyclesonde"
John C. Van Leer, University of Miami

About half the physical oceanographic observations at the University of Miami are current profile measurements. These measurements are gathered by two distinct methods: the Attended Profiling Current Meter (APCM), which has been primarily developed and used by Dr. Walter Duing in his studies of intense ocean currents such as the Gulf Stream, the Equatorial Current and the Somali Current where near-surface current meter moorings are impractical or high vertical resolution velocity data are required; the second method involves the use of an automatic unattended current profiler - the Cyclesonde. The Cyclesonde, developed by John Van Leer, has been

Posters on display in Room 128 throughout the conference.

used to study current profiles on continental shelves and in the upper 300 meters where long time series of CTD/velocity profiles are desired or where profile array data with a single ship is available. Time series profiles are particularly useful in studying inertial waves, mixing processes, bottom and surface boundary layers or complex mean flow patterns associated with fronts. About 20,000 velocity profiles have been collected by APCM and Cyclesonde techniques.

The principal source of error in the APCM is navigational uncertainty in the ship's position, which is required to convert the velocity profile relative to the ship into absolute velocity profiles. Other errors include time lag, angle offset, rotor shading and surface wave pump up. The roller coupling used in both methods greatly reduce the surface wave noise introduced in the speed sensor at depths below the zone of direct wave orbital influence. Typical APCM errors are 3-5 cm and Cyclesonde errors are 1-3 cm/sec, compared to fixed level current meters or other profiling techniques.

"Suitability of Presently Available Current Meters for Turbulent Mixing Studies"

J. Dungan Smith, University of Washington

This paper is concerned with the procurement of information on turbulent mixing in the boundary layers of the ocean, that is, near the sea surface, near the sea bed, in coastal regions and in estuaries. In such problems natural fluctuations with periods ranging from a few tenths of a second to a few weeks are of greatest concern with specific emphasis on continuous time series over periods of at least 30 minutes in duration. For useful measurements in this area, calibrated accuracies of 0.1 cm per second usually are required. Presently my group is employing mechanical, acoustic and electromagnetic current meters for our turbulence studies, none of which are entirely satisfactory; however, the latter have yielded scientifically acceptable data under a wide variety of geophysical situations, and we have found them to be much more precise than commercial sensors of the other two types. For flow problems in which turbulence measurements are of primary concern, the type of instrument frame on which the sensors are mounted often is as important as the instruments themselves. Precise current meters located in the wake of an instrument support arm or a cable or deployed in the disturbed pressure field caused by a section of the instrument frame produce results that are just as inaccurate as judiciously spaced sensors with less desirable response characteristics. When deployed with a proper understanding of their characteristics and shortcomings and from suitable support devices, instruments, such as our pulse current meters, often can be used to procure results of the scientifically required accuracy. However, when employed in this fashion, it is essential that the investigator have a thorough understanding of the instruments based on a testing program of his own design and carried out in his own laboratory. Moreover, he must have a good theoretical understanding of the operation of his instrument in order to permit exploitation of the test results and to avoid misunderstanding them as well as their implications in regard to field deployment. Further, interactions between sensor, sensor support and flow fields must be understood under the conditions that are to be faced in the field. It is one thing to know how a current meter works when fixed to a rigid mount, and another to use it reliably from a movable frame even when the motions of the latter are monitored by precision position and orientation measuring devices as is typical of the more innovative current oceanographic uses. Here, one must not only understand the deficiencies of both systems but also what additional errors can be caused by coupling the two systems and how they can be minimized under the situations of particular interest. Thus, in the field of ocean turbulence, the situation is neither particularly favorable to the easy procurement of the desired scientific measurements nor entirely bleak.

"Shallow Current Measurements"

C. D. Winant, R. E. Davis, and R. Weller, Scripps Institution of Oceanography

The dynamics of mixed layers and the variability of coastal current systems are two important problems which require the measurement of near surface currents. Near the surface, the wave field generates a current field of higher frequency than the current field of interest, leading to the requirements for a current meter which properly averages motion at frequencies higher than the sampling frequency. A mechanical meter which measures two orthogonal components of the current has been developed, tested and compared with other current meters. Results show the meter to perform well under conditions in which it is expected to be used. Two versions have been developed, one for use in shallow water, on a mooring which does not rotate with respect to the bottom; another for deep ocean measurements, in which mooring rotation is accounted for in the averaging scheme.

Break

"Deep Ocean Velocity Profiles From EM and Acoustic Doppler Measurements"
Thomas B. Sanford, Robert G. Drever, and John H. Dunlap, Woods Hole Oceanographic Institution

An instrument is described for measuring profiles of horizontal velocity as a function of depth in the deep ocean. The method is a hybrid technique based on the principles of electromagnetic induction and acoustic Doppler and is mobile since not dependent on bottom-installed equipment. The EM method measures weak electric currents in the sea induced by the motion of the water through the earth's magnetic field. The resulting velocity profile reveals the velocity shears but is relative to an unknown, depth-independent reference velocity. The reference velocity is determined by acoustic Doppler measurements of the absolute velocity of the instrument as it nears the seafloor. The two methods are incorporated into a single freely-falling probe which measures and internally records the electric and acoustic signals and other variables such as temperature and vehicle orientation. The method yields velocity determinations every 5 - 10 m with an uncertainty of about ± cm/s. A round trip in 6000 m of water lasts about 3 hours. Data from this method have been used to study mid-ocean eddies, internal waves, and the Gulf Stream

"SOFAR Floats As Tracers of Ocean Currents"
Thomas Rossby and Donald Dorson, University of Rhode Island, and Douglas Webb and Albert Bradley, Woods Hole Oceanographic Institution

"CMICE 76 -- A Current Meter Intercomparison"
Robert Beardsley, Woods Hole Oceanographic Institution, William Boicourt, The Johns Hopkins University Chesapeake Bay Institute, and Jon Scott, SUNY/Albany.

A current meter intercomparison experiment (called CMICE 76) was conducted about 6 km off the southern coast of Long Island near 40° 47' N, 72° 30' W during February and March, 1976. A total of 20 current meters were deployed on 6 moorings set in a roughly linear array parallel to the local coastline and topography. The instruments included the Aanderaa RCM-4, the AMF VACM, the Brookhaven National Laboratory spar buoy system utilizing cylindrical and spherical Marsh-McBirney electromagnetic sensors, the EG&G 850 and CT-3, and the Chesapeake Bay Institute modified ENDECO 105. Local mean water depth was 27.8 m and current meters were clustered near 4 depth levels (3.5 m, 7.4 m, 15.7 m, and 25.0 m). Wave data was also obtained at the array site and 10 m wind and tidal data was obtained from nearby coastal stations. Intercomparisons of 1 hr vector average velocities measured with similar instruments deployed near the same depth level indicated sufficient horizontal homogeneity that most differences in the observed current data have been attributed to real differences in instrument and mooring performance. Detailed discussions of the observed data, instrument and mooring characteristics and performance, and the effect of surface wave and wave-induced mooring motion on different measurement systems are presented.

"Eddy Energy Levels"
William J. Schmitz Jr. and Jerome P. Dean, Woods Hole Oceanographic Institution

Eddies, or fluctuations in ocean currents at frequencies less than a cycle per day, have been observed to be comparatively energetic, spatially inhomogeneous, and connected to the general ocean circulation in the western North Atlantic. The development of reliable, long-term moored instrument capabilities has played a significant role in establishing these results.

A continuing priority on quality control can have a significant effect on the success of a field program designed to exploit an operational technique. Unfavorable transients in system performance can be minimized by close liaison between manufacturer and user, in all stages of the production process. Shortcuts in the quality control loop are probably false economy ; likely budgets are a few percent of the cost of published data.

1700 *Cocktails in the lobby*

THURSDAY, JANUARY 12. All sessions in Room 128.

0800 OCEAN ENGINEERING/CONSTRUCTION

Session Chairman: **Richard I. Scarlet, EG&G, Environmental Consultants**

"The Incompleat Current Meter"
Richard I. Scarlet

Engineering and construction activities in the ocean require information on currents over a wide range of speeds, depths, and time scales. Many current measurement programs are hampered by lack of complete integrated systems to acquire the necessary data. Measurement accuracy is frequently degraded by mooring motions. Mooring suspensions for near-surface and near-bottom measurements are difficult or incompatible with other requirements. Data recording techniques limit deployment periods or undersample processes. Telemetry of data or system status is rarely available.

Unlike scientific studies, which may choose to focus on some aspects of the currents at the expense of others, engineering studies must determine all those features of the currents which will impact the intended activities or structures. Examples of the effects of all these instrument limitations on particular studies have been encountered in recent EG&G studies. Methods to surmount these difficulties have been developed, but better current measurement systems could provide considerable improvements.

"Ocean Current Measurements in Support of Hydrocarbon Exploration and Production"
R.A. Stacy and W. Spring, Mobil Research & Development Corporation

The exploration and production of hydrocarbons in offshore areas is affected by both average and severe ocean currents. Current measurements, for design information, are obtained either through joint industry programs or individual company efforts. The length of the measurement programs vary according to the specific application. Measurement programs typically use reliable, state-of-the-art moorings and instruments.

This paper discusses industry's need for current data, the required accuracy, and some typical examples of efforts. Also discussed are the concepts of proprietary data and the necessity for timely access to data obtained during government and government-sponsored measurement programs. Comments are presented as to how this conference can aid in fulfilling the mutual as well as exclusive goals of government, industry, and academia.

"Deficiences In Current Meter Technology Used To Support Design and Installation of Marine Structures"
C.F. McFarlane and Matthew Howard, Interstate Electronics Corporation

Industry commonly uses current measurement data to properly design and safely install marine structures. The ocean engineer's informational requirements emphasize maximum current velocities and durations with less stringent requirements placed on the data's absolute accuracy and resolution. While reduced accuracy is acceptable, the data acquired must truly represent the ocean dynamics. In this type of application, the reliability and system cost, not sensor accuracy, become the trade-off consideration by which the current sensor components of a system are selected. This reliability is expressed not only in system design but also in instrument ruggedness, ability to detect failures prior to installation, component reliability and commonality, and ease of servicing at sea. Our experiences have shown major deficiencies in the areas of power supplies, tape transport reliability and commonality, and errors derived in the encoding and translation process. All of the deficiencies cause errors that may not be entirely evident without rigid data processing controls.

"Current Measurement: A Necessary Step in Offshore Facility Design, Construction and Operation"
Frank Rose, Continental Oil Company

The movement of the offshore industry into frontier areas and harsher environments has given way to increasing concern over current induced forces for design, construction and operation of offshore facilities. The historical approach to design current determination is slowly being replaced by computational techniques which consider all components of currents with their respective time of occurrence and direction. From a construction standpoint, there is an increasing requirement for near real time data that will be helpful for facility installation. For facility operation, the need is for a good statistical base as well as near real time data for critical operations. This paper discusses indutry's current data requirements as related to the design, construction and operational phases of offshore facilities.

"Consideration of Current Measurement Techniques For Offshore Construction"
David McKeehan, R.J. Brown & Associates of America

Techniques for obtaining reliable and accurate current measurements have become increasingly available to the offshore construction community, but in order to maintain cost competitiveness, the duration of most programs is limited to periods of one month or less. Design velocities must therefore be derived from data void of seasonal signals. The culprit responsible for high current survey cost is quite often the cost for the deployment and recovery vessel and not instrumentation. Accordingly, the natural inclination is to curtail the measurement program to suit available support. Although such compromises are often justified, the trend to deep water construction has fathered the need for longer continuous recording programs. The objective of this paper is to compare existing techniques with a hypothetical data set required for the design of a typical offshore platform and associated pipeline system. Technical weaknesses in several contemporary techniques are discussed along with their economic tradeoffs.

Break

"Current Measurements In Support of Fixed Platform Design and Construction"
G.Z. Forristall, Shell Development Company, and R.C. Hamilton, Evans-Hamilton Inc.

Storm-driven currents can be an important part of the design hydrodynamics flow field for fixed platforms. In addition, the currents which exist during platform construction can significantly affect the installation. Planning for the installation of a large platform off the Mississippi Delta was facilitated by climatological current data collected with electromagnetic and Aanderra meters which were supported from a semisubmersible drilling rig and from a subsurface mooring. In addition, Cyclesondes and electromagnetic current meters were used to provide real time current data during the installation of the base section of the structure.

Once a platform is in place, it provides an excellent site for the study of near surface storm-driven currents and waves. The fast response time of electromagnetic current meters makes them seem ideally suited for this application and their effectiveness has been demonstrated through five years of experience at three sites in the Gulf of Mexico. Early problems with reliability of the meters during long-term unattended operation have now been mostly eliminated. During tropical storm Delia, surface currents over two m/sec were measured. The electromagnetic current meters also provide information on the kinematics of storm waves. Comparison of the measured particle velocities with wave theories shows that the directional spread of the wave energy is important. The measured particle velocity spectra agree with the predictions of linear theory to within a few percent over the energetic frequency range, increasing confidence in the current measurements.

"Ocean Currents As They Bear On Environmental Hazards and Offshore Platform Verification"
Paul Teleki, U.S. Geological Survey

1130 Lunch in Room 101-A

"NOAA Coastal Current Mapping Radar"
Donald L. Barrick, NOAA/Environmental Research Laboratories

1300 Session Resumes in Room 128

ENVIRONMENTAL IMPACT ASSESSMENT

Session Chairman: **J.O. Blanton, Skidaway Institute of Oceanography**

"The Role of Current Measurements in the Assessment of Environmental Impact"

J.O. Blanton

Pollutants ejected into the oceanic environment are dispersed and transported by the water movements induced by wind forces and tides, which are two of the important factors. Whether the pollutants cause an impact on the environment depends primarily upon where they are carried and how much they are diluted along the way. We expect current measurements to tell us not only something about the trajectories a given pollutant is likely to follow, but also something about the variations in the trajectories and the variations in the currents that are likely to affect the dilution of a pollutant. This information is provided by techniques that follow the movement of water (Lagrangian) and ones that measure water movement past a given point (Eulerian). This paper focuses attention on the latter, primarily because instrumentation measuring currents at fixed points are amenable to providing the required length of records over many months. This yields information on seasonal changes in circulation as well as detailed data on variations occurring over several seconds or minutes.

Current measurements must provide data on variations over seconds to hours to properly assess the dilution characteristics of the current under a wide range of conditions. At the same time, we must average these measurements to provide information on the response of the currents over many weather cycles to obtain the long-term mean currents. This wide range of requirements dictates that current meters must record rapidly and unattended over periods of several months.

"Shallow Water Current Measurement Techniques in Moderate and High Energy Wave Environments"

Frank Gremse and Ian C. Macfarlane, Dames & Moore

Current measurements in areas offshore of open exposed coastlines can easily be biased to varying degrees by orbital wave motion. Because most coastal facilities are constructed in relatively shallow water, environmental assessments require that special techniques be used to obtain accurate current information.

Such data have been collected for both short durations, and extended periods of time at many locations throughout the world. These shallow water sites include Point Conception, San Onofre, and San Francisco Bay, California; Cook Inlet and the Gulf of Alaska; Kaneohe Bay, Hawaii; and locations in the Persian Gulf and the Mediterranean coast of Spain.

Current directions and speeds have been measured using both Eulerian and Lagrangian methods. Eulerian (point measurements) data have been obtained by side cast measurements; that is, current meters have been lowered over the side of the survey boat at each of several sampling locations, and profiles of current speed and direction have been recorded. Simultaneously recorded in situ measurements enable predictions of overall current patterns to be made for relatively long periods of time using computer techniques. The second method of current measurement is the tracking of parcels of water, or the Lagrangian method. Drogues have been placed at various depths in the water column, and tracked using precision radionavigation equipment.

In addition to obtaining environmental baseline information, the current measurements have been combined with other physical, chemical, and marine biological data to support studies of effluent dispersion, dredging effects studies, and to develop mitigation measures which have been incorporated into engineering design.

"Current Measurements for the Ocean Thermal Energy Conversion Program"

Robert Molinari, NOAA/Atlantic Oceanographic and Meteorological Laboratories, and Lloyd Lewis, Department of Energy

The Ocean Thermal Energy Conversion (OTEC) Program of the Department of Energy is directed toward obtaining electrical power from a heat engine driven by the temperature differential between warm surface and colder subsurface waters. Preliminary design concepts envision a large surface plant, moored and/or actively propelled, attached to a long (order of 100 m's) cold water pipe. Water is pumped into the plant at the surface and bottom of the pipe, and discharged at some mid-depth. The designer of an OTEC plant must consider current conditions in order to minimize both the effect of the plant on the environment, and the effect of the environment on the plant. For instance, current information is required to evaluate the effect of the plant effluent on the environment. Similarly, the dynamic loading on the plant caused by ambient currents must be computed in order to design a suitable mooring or propulsion system. Current data also are necessary to design a cold water pipe which will neither collapse nor bend.

The observational programs developed for obtaining current velocity information at a site in the South Atlantic and another in the Gulf of Mexico are presented. An actively propelled OTEC plant is proposed for the South Atlantic site, while a moored plant is proposed for the Gulf of Mexico, so the data requirements for each site are different. A mooring array is presented which will be used to gather preliminary site-specific current data below 100 m at both sites. Three moorings arranged in a triangle are desired, with three meters on two moorings, and five on the other. The vertical distribution of meters is such as to obtain maximum coverage in the upper layers (100 m - 300 m) where current loading on the plant and plant loading on the environment are probably greatest. Satellite tracked drifting buoys are to be used to obtain surface current data in the South Atlantic, and current profile stations obtained during servicing of the current meters are to be used in the Gulf of Mexico.

Break

"Current Meter Measurements for Environmental Studies"
Bruce Magnell, EG&G, Environmental Consultants

Environmental impact studies differ from scientific or engineering studies in the uses to which the data are put, and because they may become the object of legal proceedings. This imposes unique requirements on the type and accuracy of current sensors. An environmental study must be done by any company wishing to build a major facility. Data and impact analyses are turned over to regulatory agencies, who in turn review or enlarge the analyses and issue their own Environmental Impact Statement. Typical analyses for coastal facilities are concerned with dispersion of thermal or effluent plumes; probability of advection of effluent to inhabited or otherwise critical areas; determination of mean velocities, tidal velocities, and other "climatological" parameters; and establishment of predictive modeling capability, for use in hindcast studies and for extrapolation to extreme conditions. Issuance of construction permits follows public hearings, at which opponents may attack the conclusions indirectly, by attacking the accuracy or adequacy of the data itself. Major current meter considerations thus are: (1) There is a need to accurately measure low velocities, which are important in dispersion studies; (2) There is a need for commercially available Lagrangian sensors, for direct measurement of probability of advective impact; and (3) There is a need for traceability in current meter calibrations, to avoid needless exposure of data to unwarranted criticism. On a higher plane, there is also a need for a methodology for current measurements in environmental studies, to establish achievable goals and assure credible results.

1445 OPERATIONAL SURVEYS

Session Chairman: **Robert Peloquin, U.S. Naval Oceanographic Office**

"Navy Requirements for Ocean Current Surveys"
Robert Peloquin

Navy requirements for ocean current data extend through depths of the oceans in both deep and shallow water. The nature of these requirements impose a global perspective on those requirements which have applicability ranging from ocean engineering to operational problems. The time scales of interest typically range from hours to months and space scales are on the order of several kilometers to hundreds of kilometers. The current measurement capability has recently been enhanced to improve measurement accuracy and to enlarge our measurement capability to improve data quality, and to increase the record length of our measurements. The Navy has an interest in the improvement of current measurement technology, particularly that which reduces costs and facilitates the handling of equipment.

"NOS Year-Round Circulatory Surveys"
Lewis Walker and Bruce Parker, NOAA/National Ocean Survey

"Operational" or "circulatory" surveys are carried out year-round by the National Ocean Survey, on both coasts of the United States, including Alaska. Each survey completely covers a specific area, usually an estuary, for a period ranging from two months to several years, obtaining current measurements along with simultaneous tide, salinity, temperature, and weather data. These measurements are made at selected locations and depths in order to obtain a reasonably complete three-dimensional description of the dynamic properties of the body of water, that can be used for environmental purposes as well as for navigation. Analysis results of these data are also included in the Tide and Tidal Current Tables and Tidal Current Charts published by NOS.

Formerly the Coast and Geodetic Survey, the National Ocean Survey has been taking current measurements on a regular basis since 1844 and has used a number of current measuring devides, from the early current pole to the present Aanderra and TICUS current meters now being used on the West and East Coasts, respectively. NOS is presently reviewing available and prototype current sensors in preparation for an upgrading of its current measurement systems in the near future.

In addition to the usual current measurement problems that affect all users (e.g., the effects of noise, mooring motion and drag, uncertain dynamic response characteristics of the sensors, accuracy, etc.), NOS must also cope with instrument errors that interrupt the processing scheme setup for the handling by technicians of the huge quantity of data it receives year-round. For example, in the past if a current sensor was not equipped with an independent interval counter or hour marker, the loss of one or more data points in a current record would create additional hours of work in order to accurately assign time to the data series. Time determination is critical for NOS since accurate tidal current predicitions must be made based on these data. Also, frequent errors in the recorded data values, due to bit drop or other electronic or mechanical causes, though correctable using computerized statistical editing techniques, require considerable computer time to do so and occasionally hand editing as well.

These problems and others, as well as NOS's on-board and in-house processing schemes, are described.

"Comparing A Few Recording Current Meters in San Francisco Bay, California"
Ralph T. Cheng, U.S. Geological Survey

A team of research scientists in the U.S. Geological Survey uses San Francisco Bay, California, as an outdoor laboratory to study complicated interactions of physical, chemical, and biological processes which take place in an estuarine environment. A current meter comparison study was conceived because of the need to select a suitable current meter to meet field requirements for current measurements in the Bay. The study took place in south San Francisco Bay, California, in the spring of 1977.

An instrument tower which was designed to support instruments free from the conventional mooring line motions was constructed and emplaced in south San Francisco Bay. During a period of two months, four types of recording current meters have been used in the tests. The four types were: (1) Savonious rotor, (2) Tethered shoud-impeller, (3) drag-inclinometer, and (4) electromagnetic current meters. With the exception of the electro-magnetic current meter, one of each type was mounted on the instrument tower, and one of each type was deployed on moorings near the instrument tower. In addition, a wind anemometer and a recording tide gauge were also installed on the tower.

This paper discusses the characteristics of each instrument and the accuracy that each instrument can provide when used in an estuarine environment. We pay special attention to our experiences in the field operation with respect to handling of the instruments and to our experiences working up the raw data in the post deployment data analysis.

1700 Cocktails in the lobby

FRIDAY, JANUARY 13

0830 WORKING SESSIONS

SURFACE/NEAR-SURFACE MEASUREMENTS in Room 128
Moderators: **William Boicourt and Robert Beardsley**

OCEAN INTERIOR/BOTTOM MEASUREMENTS in Room 101-B
Moderator: **William Schmitz**

Purpose of Working Sessions

- To provide expert opinions on the effectiveness of and deficiencies in existing current measurement technology relative to the needs of the community.
- To identify specific limitations in technology.
- To recommend appropriate tasks that should be undertaken to address the limitations identified.

Panels

The panel membership has been selected to include individuals whose experience and capability make them well qualified to speak authoritatively on various aspects of current measurement technology. It is their job, under the guidance of the moderators, to stimulate discussion and to provide their expert opinions in conjunction with the session members in response to the specific questions put forth by the moderators.

The moderators will have the job of presenting the specific questions, provided to them by the conference committee, to the session members and the panel, and assuring that the ensuing discussions remain on track.

The panel moderators will summarize the work sessions in a final plenary session. The work sessions will be recorded both by the participant rapporteurs and magnetic tape for subsequent workshop documentation.

Questions for Working Sessions

I. What is the mechanism used to establish accuracy requirements for current measurement?
  A. A review of existing technology to see what you can or are supposed to be able to get?
    - Is a lack of knowledge of a system's operating characteristics a problem?
  B. An analysis of measurements to be made
    - Do we know enough about natural variability to be able to specify stringent accuracies for current measurement? (This question is intended to get at the root of: Is technology driving the measurement needs or vice versa?)

II. What are the limitations of present current measurement technology in your current meter applications and upon what is your answer based? (This question is to solicit subjective judgments of technology and to determine the basis for these judgments).

III. What are the most important development efforts to be pursued?
  - Sensing (transducer) techniques
  - Data logging techniques
  - Mooring design
  - Lagrangian techniques
  - Increase testing and evaluation of existing devices
  - Build cheaper, less accurate instruments
  - Standards (laboratory and field)
  - Remote sensing techniques (satellite, aircraft, radar, etc.)

  (This question is to define priorities of what best can we do with a small amount of resources)

Questions for Working Sessions, continued

IV. Are there serious gaps in the typical existing current measurement technology development process outlined below?

- In-house concept generation
- In-house hardware development of a few prototypes which are then used or sold as operational systems

Examples of gaps:

- Poor or nonexistent market analysis causing unresponsive technology development
- Good technology going to waste because there is no mechanism that exists to provide for transition engineering of technology that was funded and developed (likely with government funds) for a special project. In other words, the community never has general and full access to this technology.
- Insufficient testing during the development process.

V. Are the ongoing development activities, especially in industry, responsive to the needs of a broad user community?

- Are the resulting instruments too expensive?
  Is reliability a problem?
- How do we quantify the economics of current meter data acquisition?

(Questions IV and V are intended to find out whether technology development should or can be more efficient and responsive)

Policy Issues

I. Is a comprehensive, coordinated development program for current measurement technology needed?

- Is money all that is needed vs. a comprehensive plan and coordinated activities?
- Are improved and accessible calibration (testing) facilities required?
- Are coordinated intercomparison experiments needed?

II. What is required to give investigators confidence in off-the-shelf equipment?

- Will there always be a need for one-of-the-kind equipment due to special requirements?

III. Would there be some benefit from trying to improve the coordination (at least the information exchange) among those involved in current measurement technology development?

- Newsletters
- Symposia

IV. What should be the nature of a development program?

- Dollars to industry
- Dollars to institutions
- RFPs or individual initiative (free enterprise)

1145 Lunch in Room 101-A

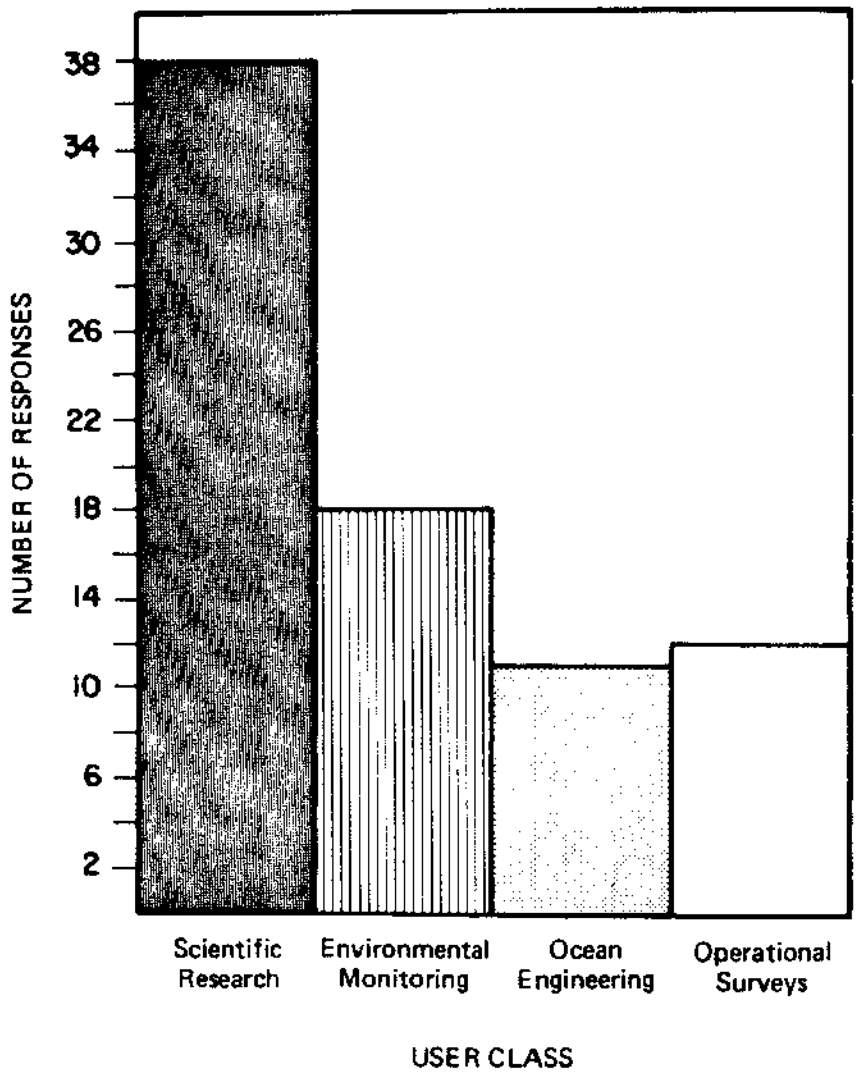
1300 Closing Plenary Session in Room 128. Summary of Working Sessions.

1500 Conference Closes

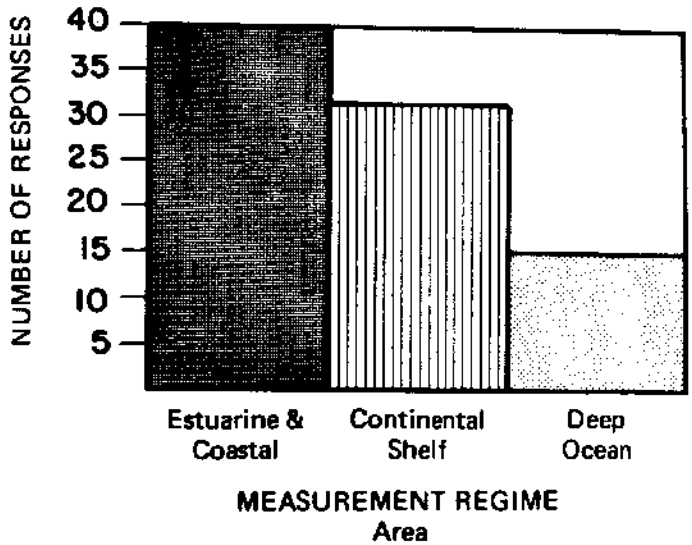
RESULTS OF THE PRE-CONFERENCE QUESTIONNAIRE

People who registered for the Working Conference on Current Measurement were asked to complete a questionnaire about their needs and problems in making current measurements. The responses are summarized in the following pages. The intent of this survey was to provide a general idea of current measurement needs and applications, an estimate of the uncertainty of measured data and a summary of problem areas.

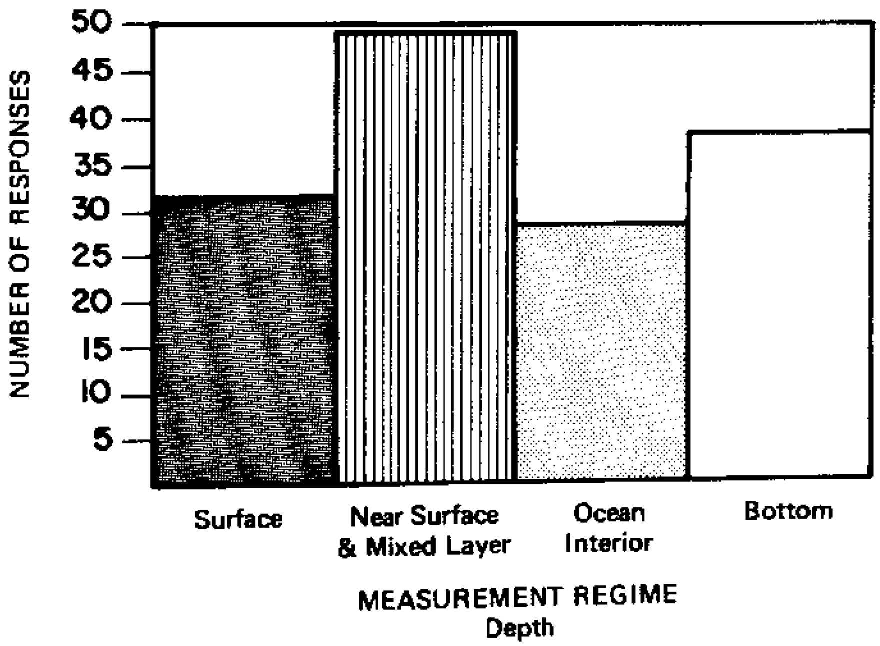
A total of 108 questionnaires were answered.



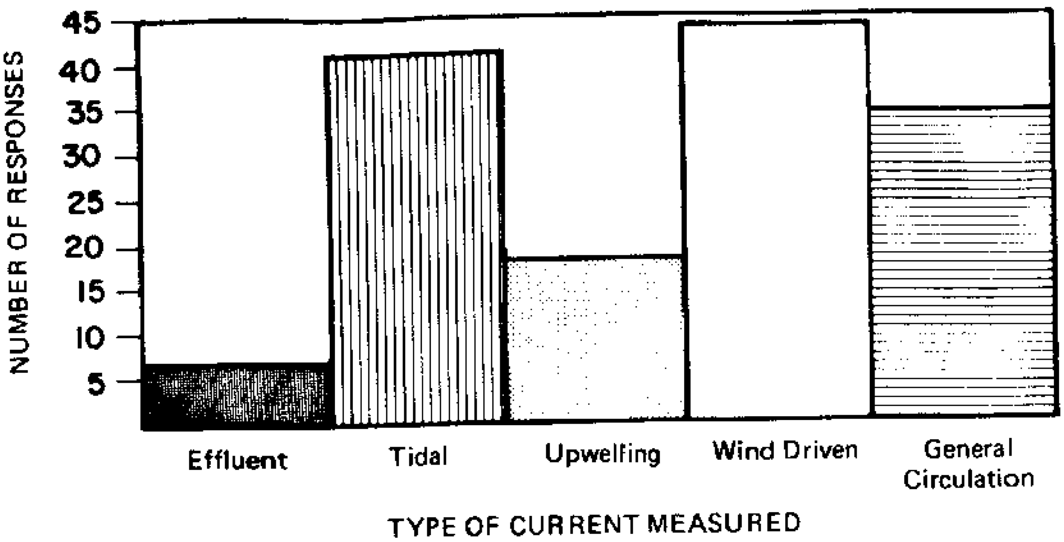
NUMBER OF RESPONSES
38
34
30
26
22
18
14
10
6
2
Scientific Research
Environmental Monitoring
Ocean Engineering
Operational Surveys
USER CLASS

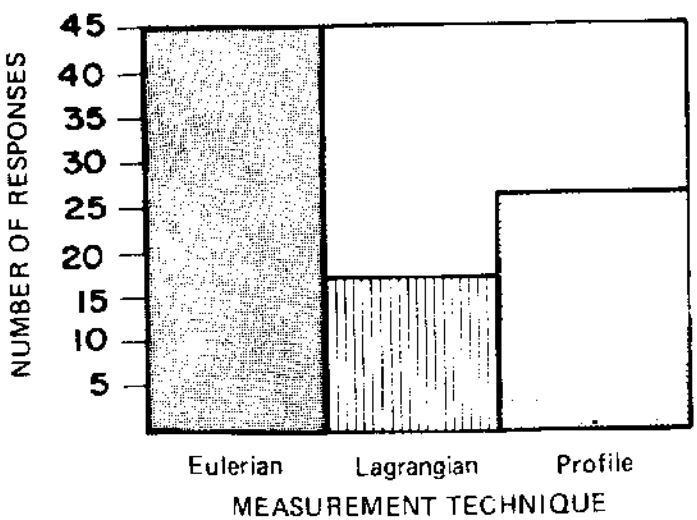


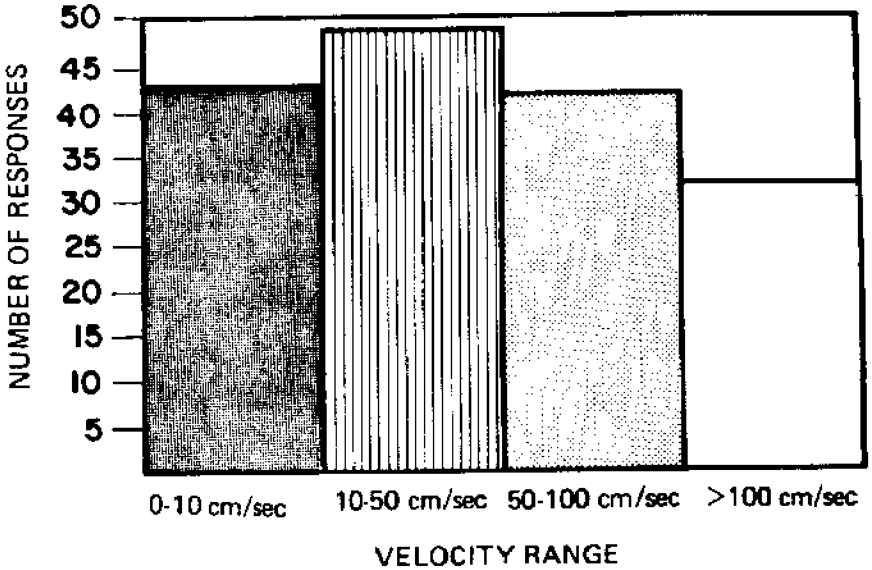
NUMBER OF RESPONSES
40
35
30
25
20
15
10
5
Estuarine & Coastal
Continental Shelf
Deep Ocean
MEASUREMENT REGIME
Area

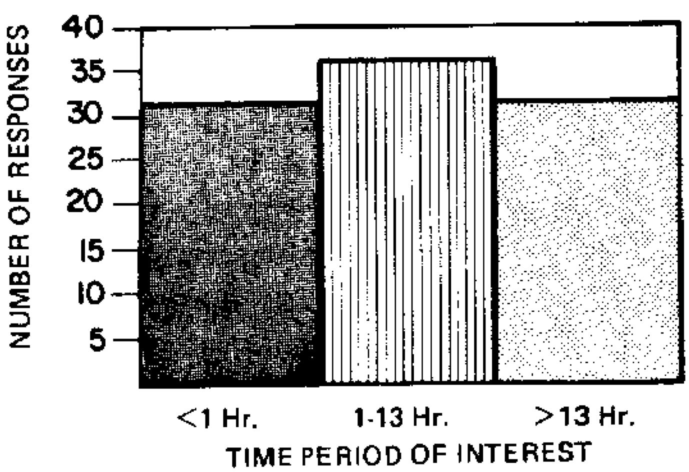


NUMBER OF RESPONSES
50
45
40
35
30
25
20
15
10
5
Surface
Near Surface & Mixed Layer
Ocean Interior
Bottom
MEASUREMENT REGIME
Depth

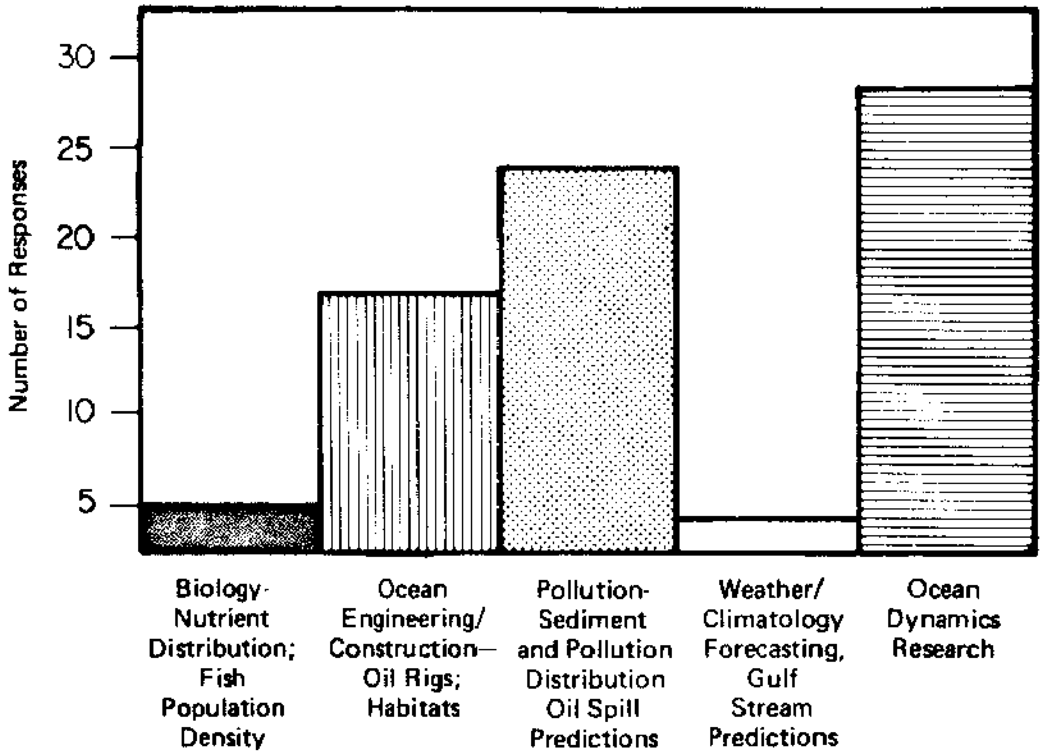

45
40
35
30
25
20
15
10
5
NUMBER OF RESPONSES
Effluent
Tidal
Upwelling
Wind Driven
General Circulation
TYPE OF CURRENT MEASURED


45
40
35
30
25
20
15
10
5
NUMBER OF RESPONSES
Eulerian
Lagrangian
Profile
MEASUREMENT TECHNIQUE


50
45
40
35
30
25
20
15
10
5
NUMBER OF RESPONSES
0-10 cm/sec
10-50 cm/sec
50-100 cm/sec
>100 cm/sec
VELOCITY RANGE


40
35
30
25
20
15
10
5
NUMBER OF RESPONSES
<1 Hr.
1-13 Hr.
>13 Hr.
TIME PERIOD OF INTEREST

Question A: SPECIFIC MEASUREMENT APPLICATION



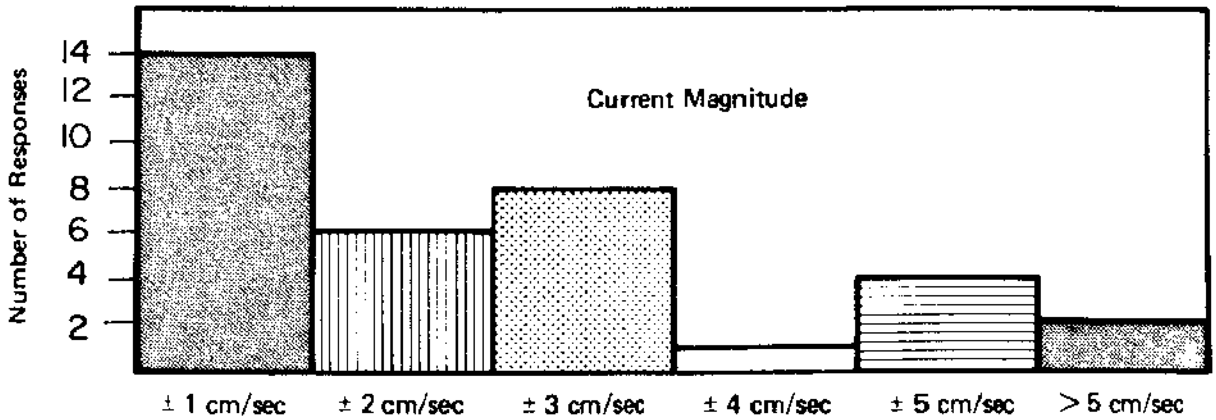
RESPONSE SUMMARY: The following were the specific answers most frequently found in the main categories:

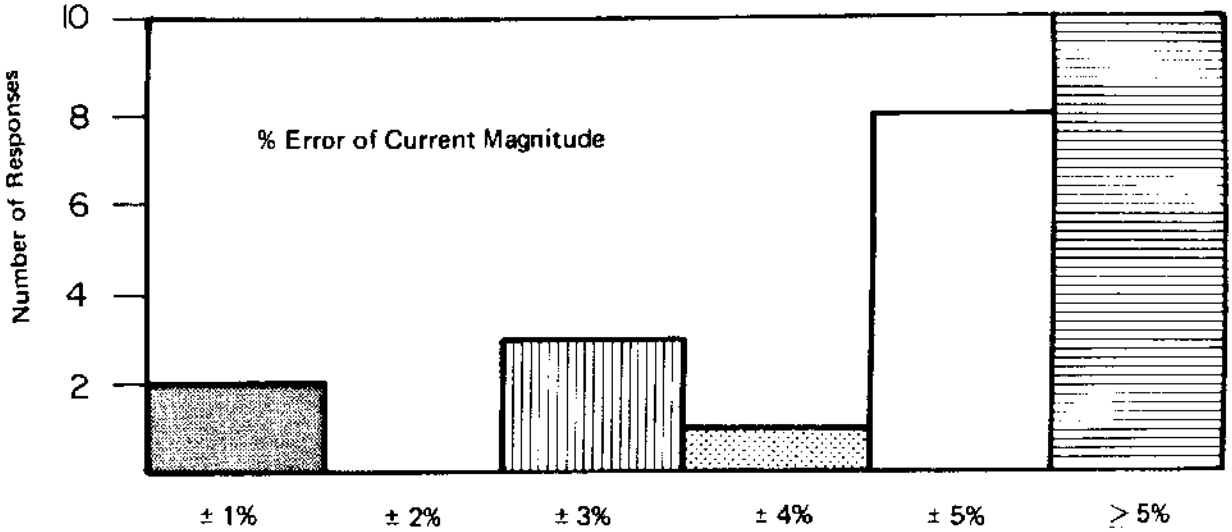
Ocean Dynamics Research: continental shelf and nearshore circulation dynamics

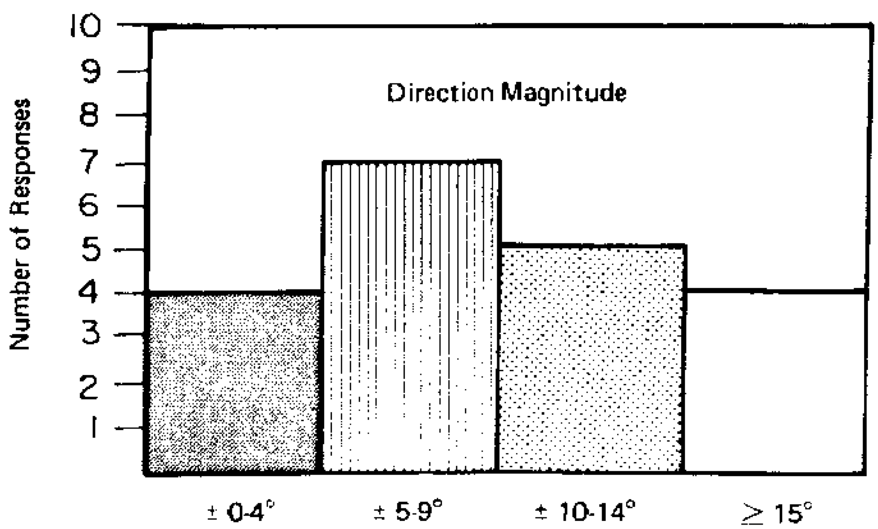
Pollution/Sediment Distributions: Oil spill movement predictions; environmental impact studies

Ocean Engineering/Construction: Offshore construction of drilling platforms and pipelines; ocean thermal energy conversion research

Question B-1: LEVEL OF UNCERTAINTY





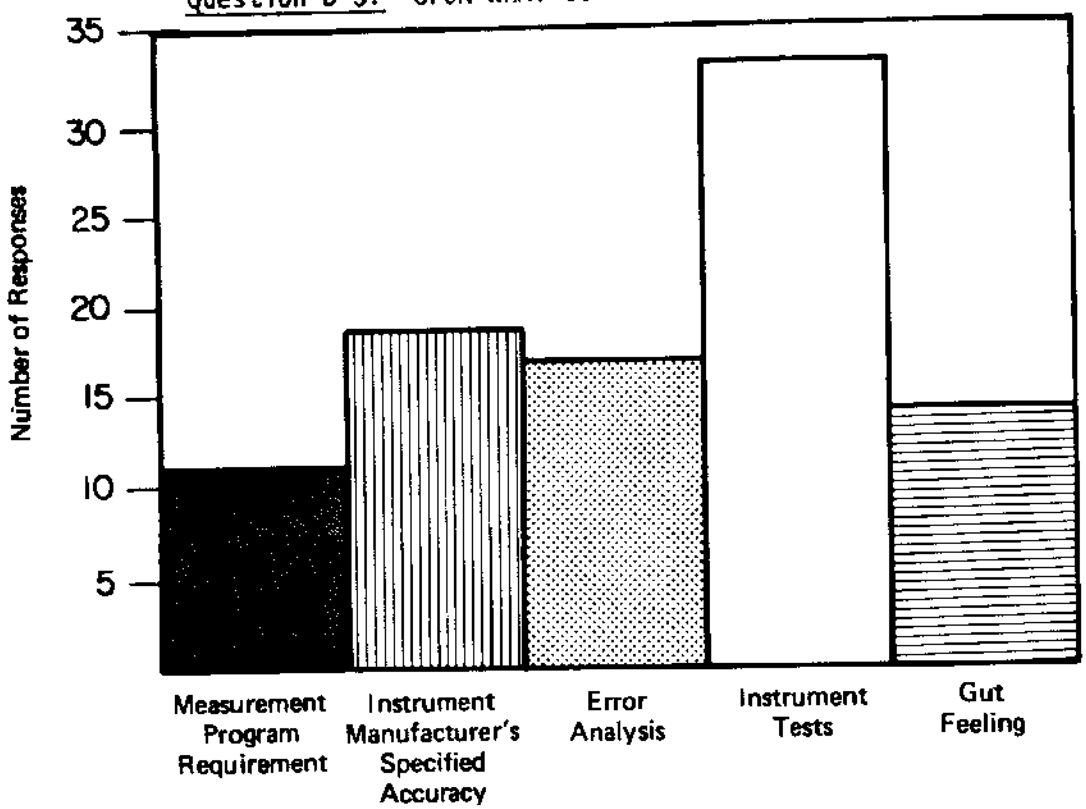


Question B-2: DO YOU CONSIDER THIS A PRECISION ACCURACY (ABILITY OF INSTRUMENT TO REPEAT A MEASUREMENT) OR ABSOLUTE ACCURACY (REFERENCED TO A STANDARD?

27 said absolute accuracy (48 percent)

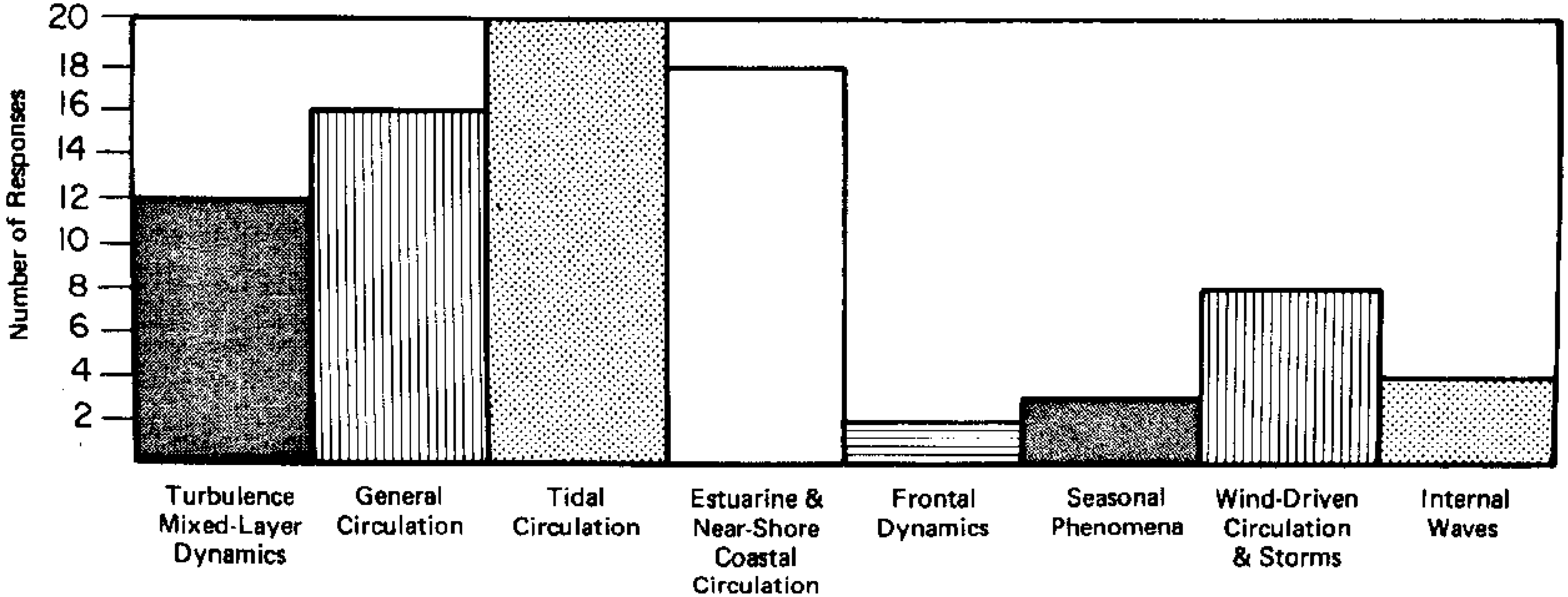
29 said precision accuracy (52 percent)

Question B-3: UPON WHAT IS YOUR ANSWER TO B-2 BASED?

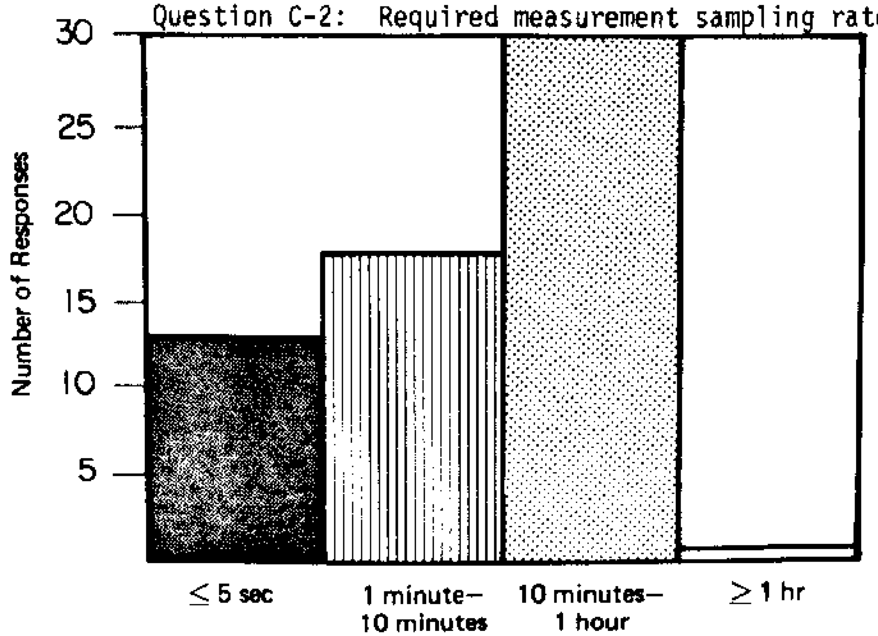


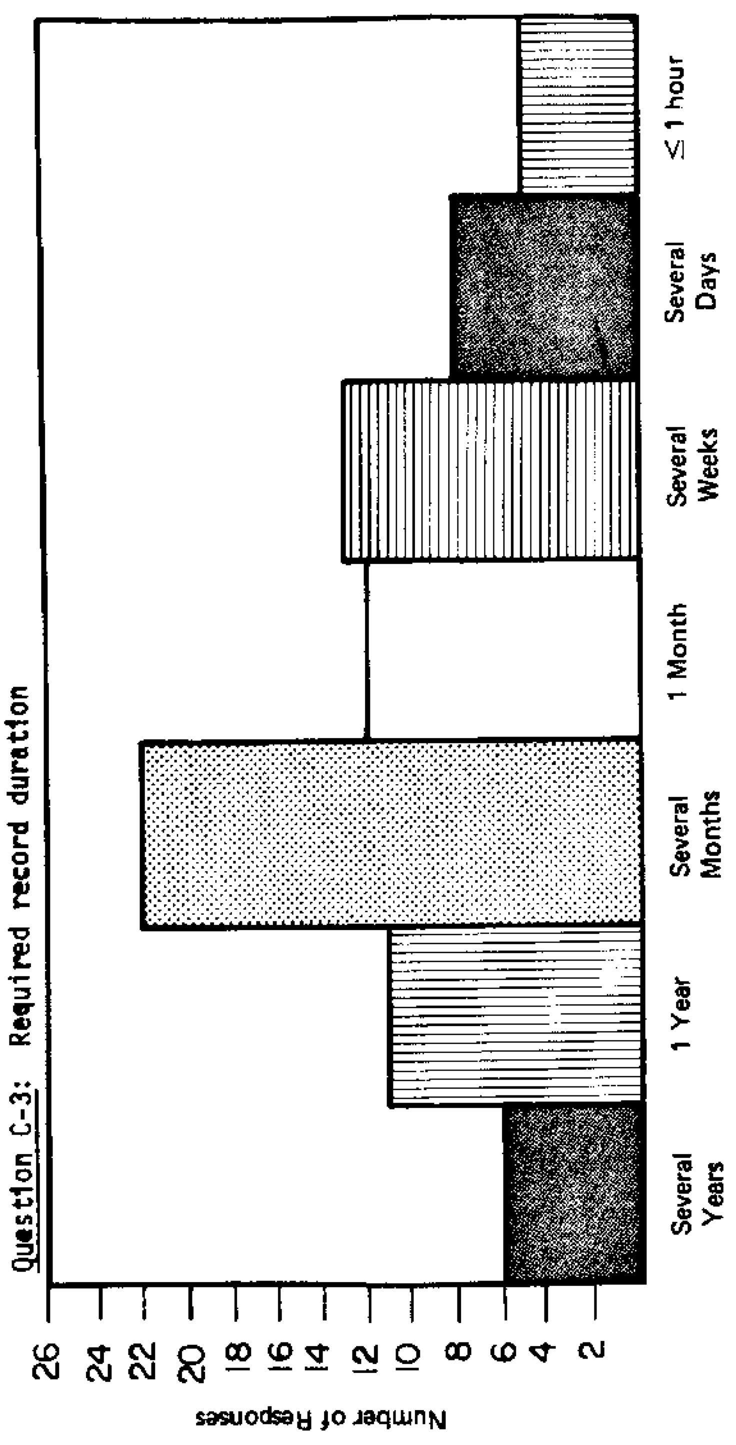
<u>Question C</u>: MEASUREMENT SAMPLING

<u>Question C-1</u>: Scales and phenomena of interest



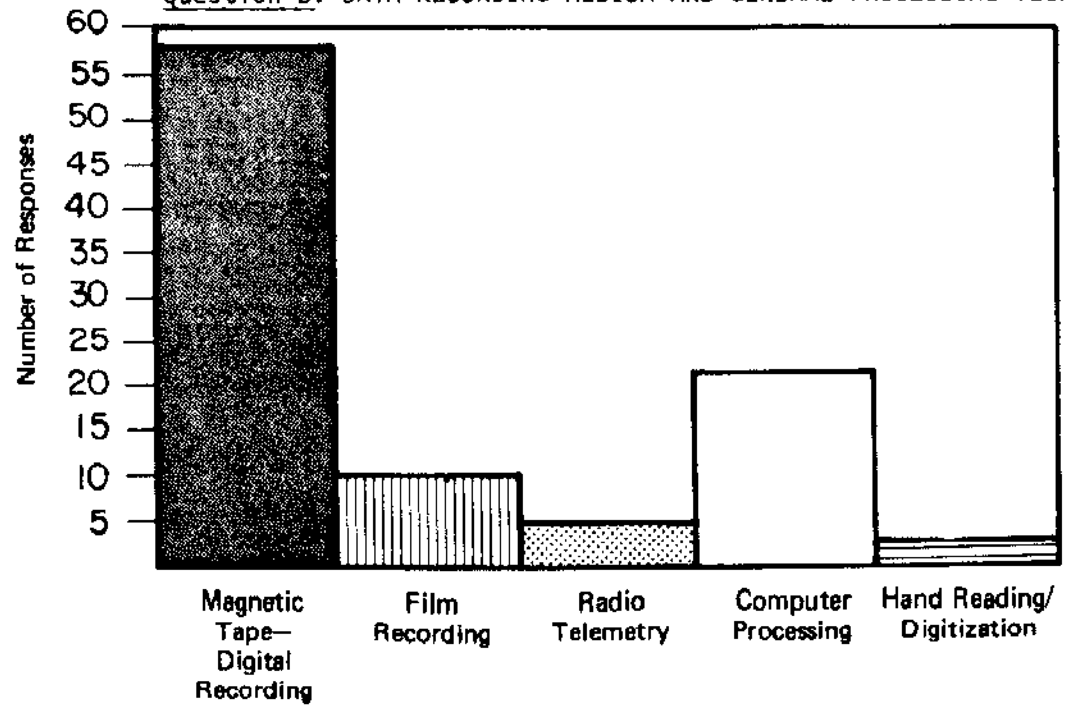
Question C-2: Required measurement sampling rate



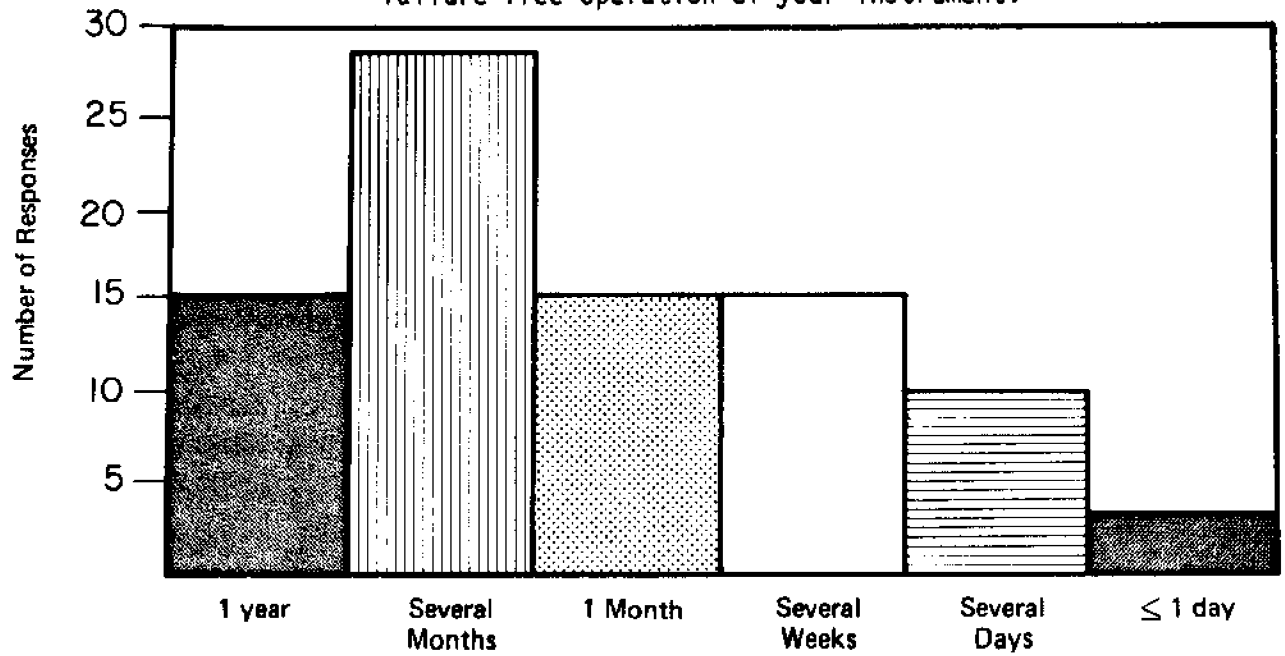


Question C-3: Required record duration
Number of Responses
26
24
22
20
18
16
14
12
10
8
6
4
2
Several Years
1 Year
Several Months
1 Month
Several Weeks
Several Days
≤ 1 hour

Question D: DATA RECORDING MEDIUM AND GENERAL PROCESSING TECHNIQUE



Question E: RELIABILITY. Describe the length of time that you typically require failure-free operation of your instrument.



Question F: DESCRIBE BRIEFLY WHAT IN YOUR VIEW ARE THE MOST SIGNIFICANT PROBLEMS IN MAKING CURRENT MEASUREMENTS.