# LECTURES BY FERRIS WEBSTER
# UNIVERSITY OF LIEGE, MARCH 17-20, 1970

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## I.-INTRODUCTION TO THE WOODS HOLE OCEANOGRAPHIC INSTITUTION MOORED ARRAY EXPERIMENTS

### Introductory remarks.

Since about 1959, first under the direction of Dr. William S. Richardson, and then of Dr. Nicholas P. Fofonoff, a sequence of experiments has been carried out at the Woods Hole Oceanographic Institution using moored current meters to observe the dynamics of deep-sea processes. The results to date have provided quantitative estimates of the spectrum of horizontal ocean currents over the range of time scales from a few seconds to several months. In addition, the studies have provided new information about oceanic phenomena such as tides, inertial oscillations, internal waves and turbulence. These results will be the principal subject of my lectures.

The scientific results which will be discussed are the work of many people, and would not have been possible without the support of the members of the engineering, sea operations, and data processing groups in the project at Woods Hole.

Because most of the work which will be discussed has already been reported in the oceanographic literature these notes will be brief and there will be extensive references to published reports.

There are a number of references of recent work which may not yet be published which should serve to complement the bibliography in the references.

## Instrumentation and Techniques.

The original instrumentation and techniques were described by Richardson, et al (1963) and the results of early work were summarized by Fofonoff (1968a). Briefly, the observational technique consists of inserting recording oceanographic instruments, such as current meters, temperature, and pressure recorders, into the lines of deep-sea moorings having buoys at the ocean surface or below. Over the course of several years the mooring techniques have become highly developed (Berteaux and Walden, 1969; Berteaux, 1968) and losses of equipment have recently been significantly less than was the case a few years ago.

The present procedure is to set deep-sea moorings with instrumentation for periods of from two to four months. At the end of this time the mooring is retrieved and the data is recovered from inside the instruments for computer processing (Maltais, 1969).

The principal instrumentation used is current meters. These have evolved from Richardson's original design and are now manufactured in the United States by the Geodyne division of E.G. and G. Corporation. The response characteristics of the instrument have been studied by Fofonoff and Ercan (1967).

A few measurements have been made with temperature records (Fofonoff, 1969) and pressure recorders are used to monitor the depth of instruments on moorings having subsurface floats. Some measurements have also been made of mooring line parameters, such as line tension (Millard, 1969), principally for engineering studies of deep-sea moorings. Measurements of winds with anemometers mounted on surface buoys have beeb very useful for defining some air-sea interaction processes, and results from these will be discussed.

## Measurement Procedures.

The questions of sampling (the time between observations) and of quantizing (the accuracy with which the measurements are made) are very important in setting up a systematic program of measurements. In any series of measurements of time series there is a danger that high-frequency noise components may appear in the form of low-frequency signal if the sampling rate is too infrequent. This process is called aliasing and is a well-known pitfall in time-series measurements. In the case of measurements collected with moored instruments it is possible for badly-designed sampling procedures to completely obscure the character of the oceanic phenomenon being studied (Webster, 1964).

A sampling procedure has been developed for moored current meters (Webster, 1967) which matches the conflicting requirements of data storage capacity, long-term operation, and frequent measurements. The procedure is based on prior knowledge of spectrum of ocean currents. Measurements have shown that the spectrum has a large concentration of kinetic energy at high frequencies (periods of about 5 to 10 seconds) but a minimum of energy below those frequencies down to the frequencies of principal oceanographic interest (periods of a few hours).

The sampling method used is one in which the current meter is regularly turned on at widely-spaced intervals, during each of which it collects a burst of rapidly-sampled measurements. By working with values averaged over the burst of samples, it is possible to obtain time series in which the high-frequency energy is essentially removed without serious distortion of the low-frequency signals of interest. A similar procedure for sampling winds for surface buoys has been developed by Millard (1968).

The problem of quantizing, or the accuracy with which the data are recorded is less insidious a problem than that of sampling. Nevertheless, care has to be taken that the roundoff error in a serie of measurements is not so great that processes having low energy levels are not completely obscured by the "noise" generated by the coarseness of the recording.

Decisions about experimental design: duration of measurement, separation of samples in time and space, and precision of measurement, can be crucially important in deciding the effectiveness of a systematic program of time-series measurements in the ocean.

## The Site D current measurement program.

Since 1965, the program of current measurements at the Woods Hole Oceanographic Institution has centered upon repeated measurements at a single location: Site D, 39° 20'N, 70°W. This location is about 50 km. south of the Continental Shelf south of Woods Hole and is about 175 km. north of the mean axis of the Gulf Stream. The advantages of using this location are that it is in deep water (about 2,600 m. depth) and is within easy overnight passage of ships from Woods Hole. There is also the advantage that successful mooring techniques have been developed for the Site D region that do not necessarily work in other regions of the Atlantic Ocean. Furthermore, it is useful to collect repeated measurements at a single site; such measurements can be used to examine those oceanographic properties that can only be identified using statistical procedures.

Disadvantages of Site D are that it is close to both the Continental Shelf and the Gulf Stream and that the currents are influenced by both. To an unknown extent then, Site D cannot be considered to be representative of true open-ocean conditions.

Other deep-sea mooring sites have been used from time to time. In particular, attempts have been made to set up a set of stations in the western North Atlantic along the 70° West meridian. Because of strong currents, fishbite, and possibly other factors, it has not yet been possible to establish a successful program of measurements at these sites.

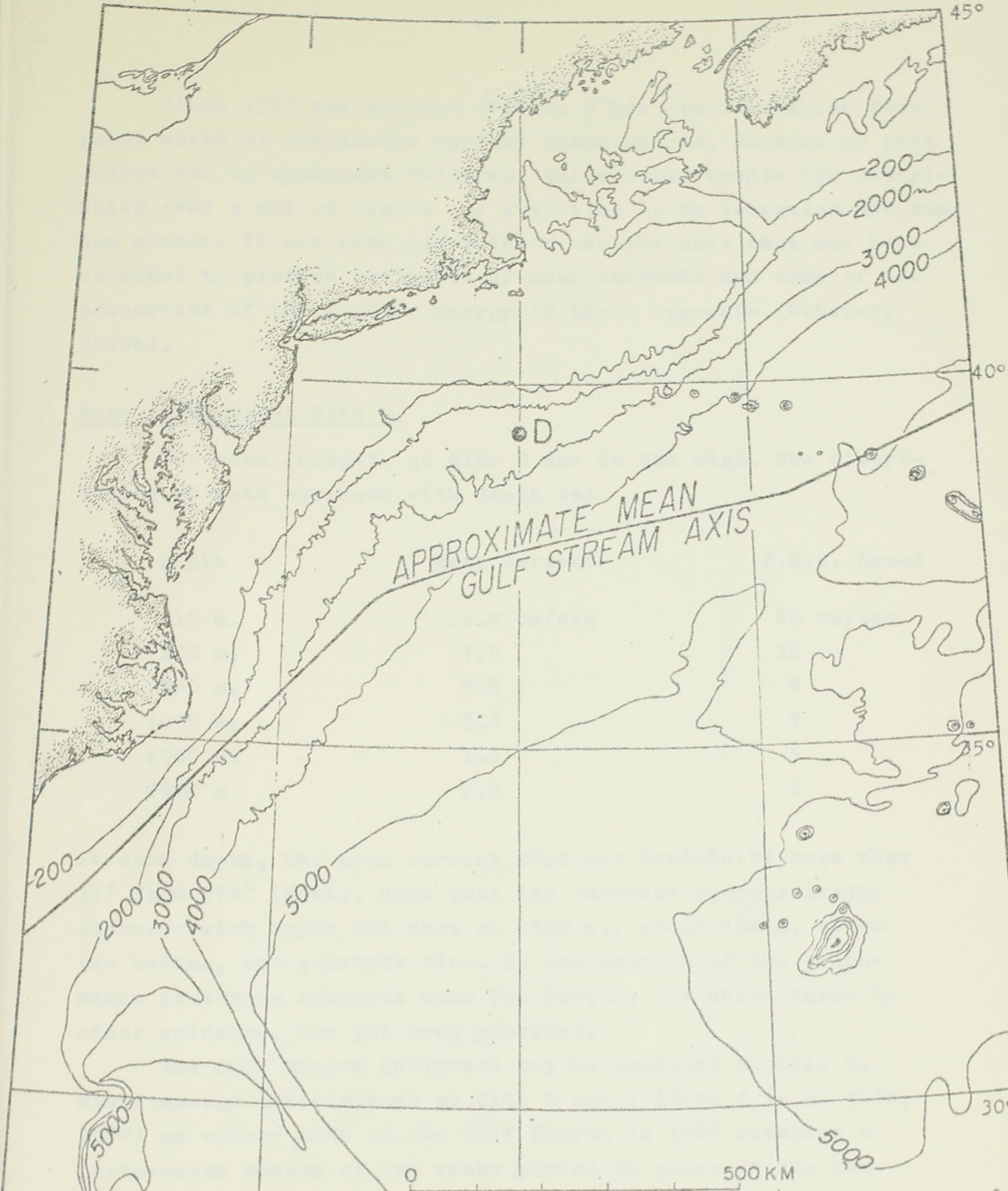


Fig. 1.- Chart showing the location of Site D in the western North Atlantic.

Since 1965 the program at Site D has provided about four years worth of continuous current measurements. Because of data losses due to equipment failures, these measurements are distributed over a set of depths and over time in an irregular and random manner. It has been possible to use the data that has been obtained to produce estimates of mean currents and some of the properties of the kinetic energy of those currents (Webster, 1969b).

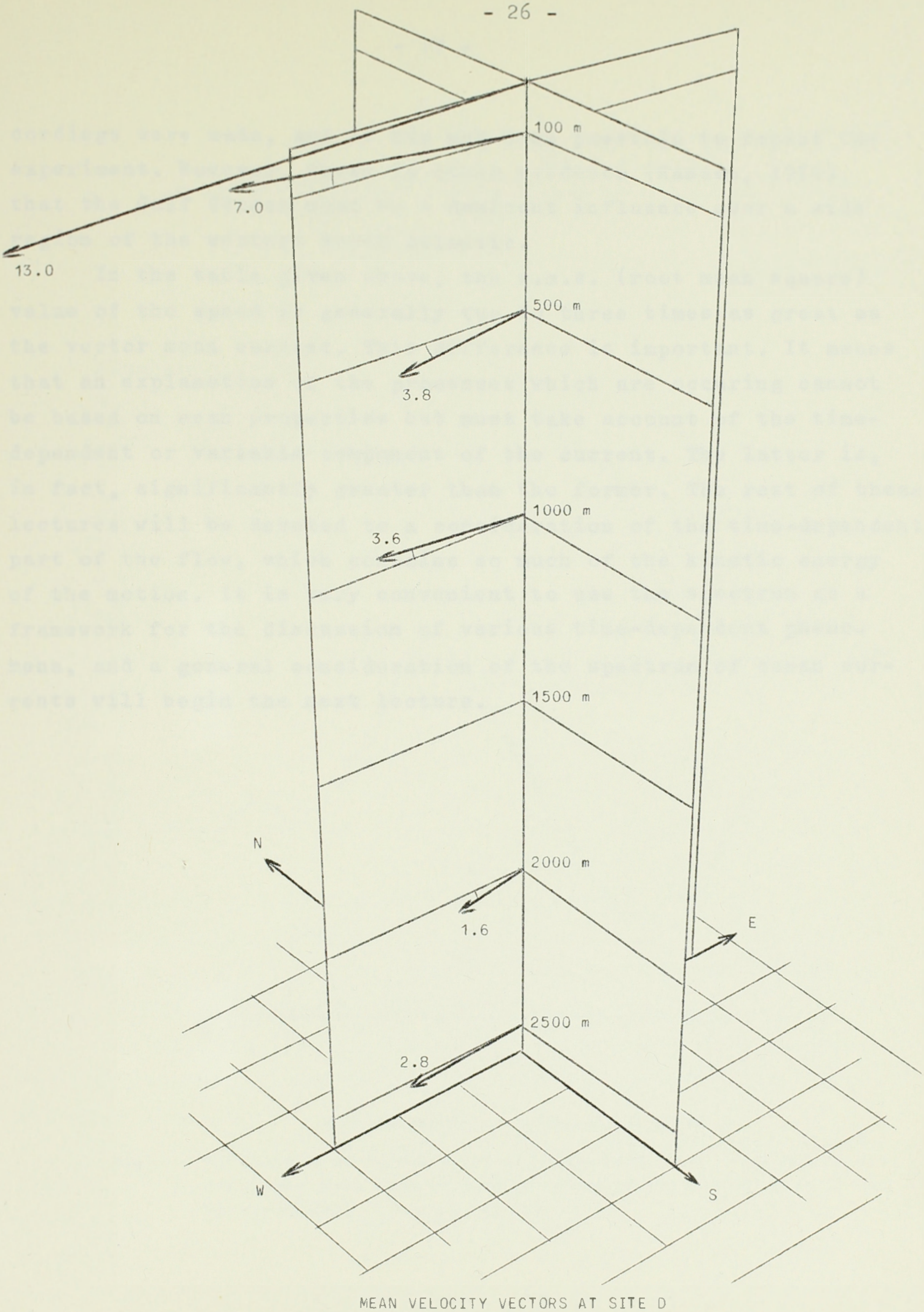
## Mean currents at Site D.

The mean currents at Site D are to the west. The distribution of mean currents with depth is:

| Depth | Mean Current | R.M.S. Speed |
|---|---|---|
| 10 m. | 13.0 cm/sec | 40 cm/sec |
| 100 m. | 7.0 | 18 |
| 500 m. | 3.8 | 8 |
| 1000 m. | 3.6 | 7 |
| 2000 m. | 1.6 | 5 |
| 2500 m. | 2.8 | 6 |

At each depth, the mean current does not deviate by more than 11° from 270° (West). Note that the currents systematically decrease with depth but that at 2500 m., about 100 m. above the bottom, the currents rise. No explanation of the phenomenon of strong currents near the bottom, for which there is other evidence, has yet been provided.

The Gulf Stream influence may be profound at Site D. Simultaneous observations at Site D and J (Site J is at 36°N, 70°W) on either side of the Gulf Stream in 1966 revealed a north-south motion of two weeks period in phase at the two stations. Unfortunately, only two weeks of simultaneous re-

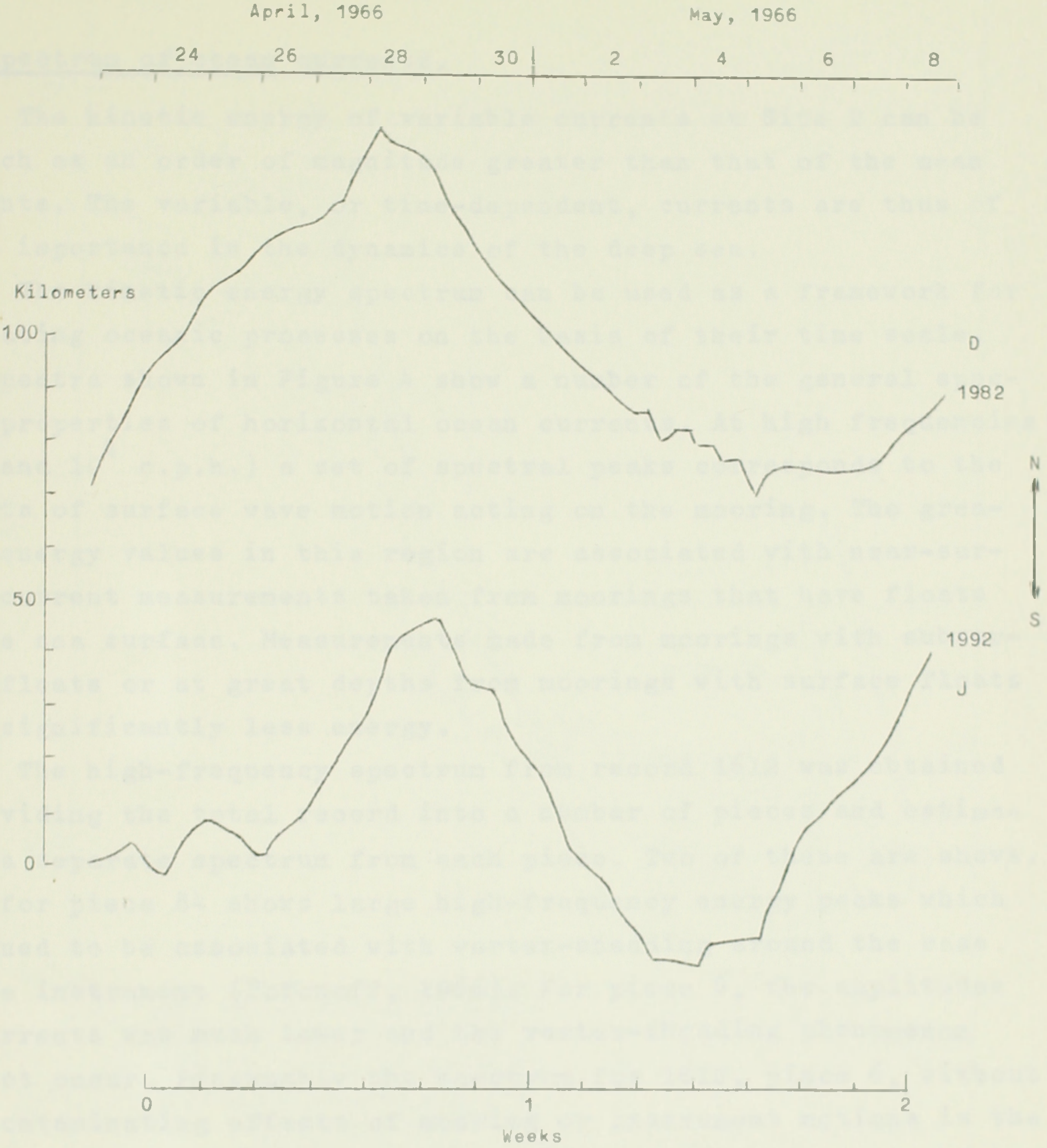


MEAN VELOCITY VECTORS AT SITE D

Fig. 2.- The profile of mean currents at Site D. Note that the currents decrease with depth but increase near the bottom.

cordings were made, and it has not been possible to repeat the experiment. However, there is other evidence (Hansen, 1970) that the Gulf Stream must be a dominant influence over a wide region of the western North Atlantic.

In the table given above, the r.m.s. (root mean square) value of the speed is generally two to three times as great as the vector mean current. This difference is important. It means that an explanation of the processes which are occuring cannot be based on mean properties but must take account of the time-dependent or variable component of the current. The latter is, in fact, significantly greater than the former. The rest of these lectures will be devoted to a consideration of the time-dependent part of the flow, which contains so much of the kinetic energy of the motion. It is very convenient to use the spectrum as a framework for the discussion of various time-dependent phenomena, and a general consideration of the spectrum of ocean currents will begin the next lecture.



N-S EXCURSIONS OF INTEGRATED VELOCITY

Fig. 3.- Simultaneous current measurements from either side of the Gulf Stream. The curves shown were obtained by computing the time integral of the North-component of velocity at each time.

## II.-VARIABILITY OF OCEAN CURRENTS

### The spectrum of ocean currents.

The kinetic energy of variable currents at Site D can be as much as an order of magnitude greater than that of the mean currents. The variable, or time-dependent, currents are thus of great importance in the dynamics of the deep sea.

The kinetic energy spectrum can be used as a framework for separating oceanic processes on the basis of their time scale. The spectra shown in Figure 4 show a number of the general spectral properties of horizontal ocean currents. At high frequencies ($10^2$ and $10^4$ c.p.h.) a set of spectral peaks corresponds to the effects of surface wave motion acting on the mooring. The greatest energy values in this region are associated with near-surface current measurements taken from moorings that have floats on the sea surface. Measurements made from moorings with subsurface floats or at great depths from moorings with surface floats show significantly less energy.

The high-frequency spectrum from record 1612 was obtained by dividing the total record into a number of pieces and estimating a separate spectrum from each piece. Two of these are shown. That for piece 84 shows large high-frequency energy peaks which happened to be associated with vortex-shedding around the case of the instrument (Fofonoff, 1966). For piece 6, the amplitudes of currents was much lower and the vortex-shedding phenomenon did not occur. Presumably the spectrum for 1612, piece 6, without the contaminating effects of mooring or instrument motions is the closest representation of the true high-frequency spectrum of horizontal currents.

For frequencies of about $10^{-1}$ c.p.h. and higher, the kinetic energy may drop proportional to $f^{-5/3}$. (A straight line with a slope of $-5/3$ on log-log graph paper). The similarity between this slope and that of homogeneous isotropic turbulence as postulated by Kolmogorov suggests that it might be fruitful to treat

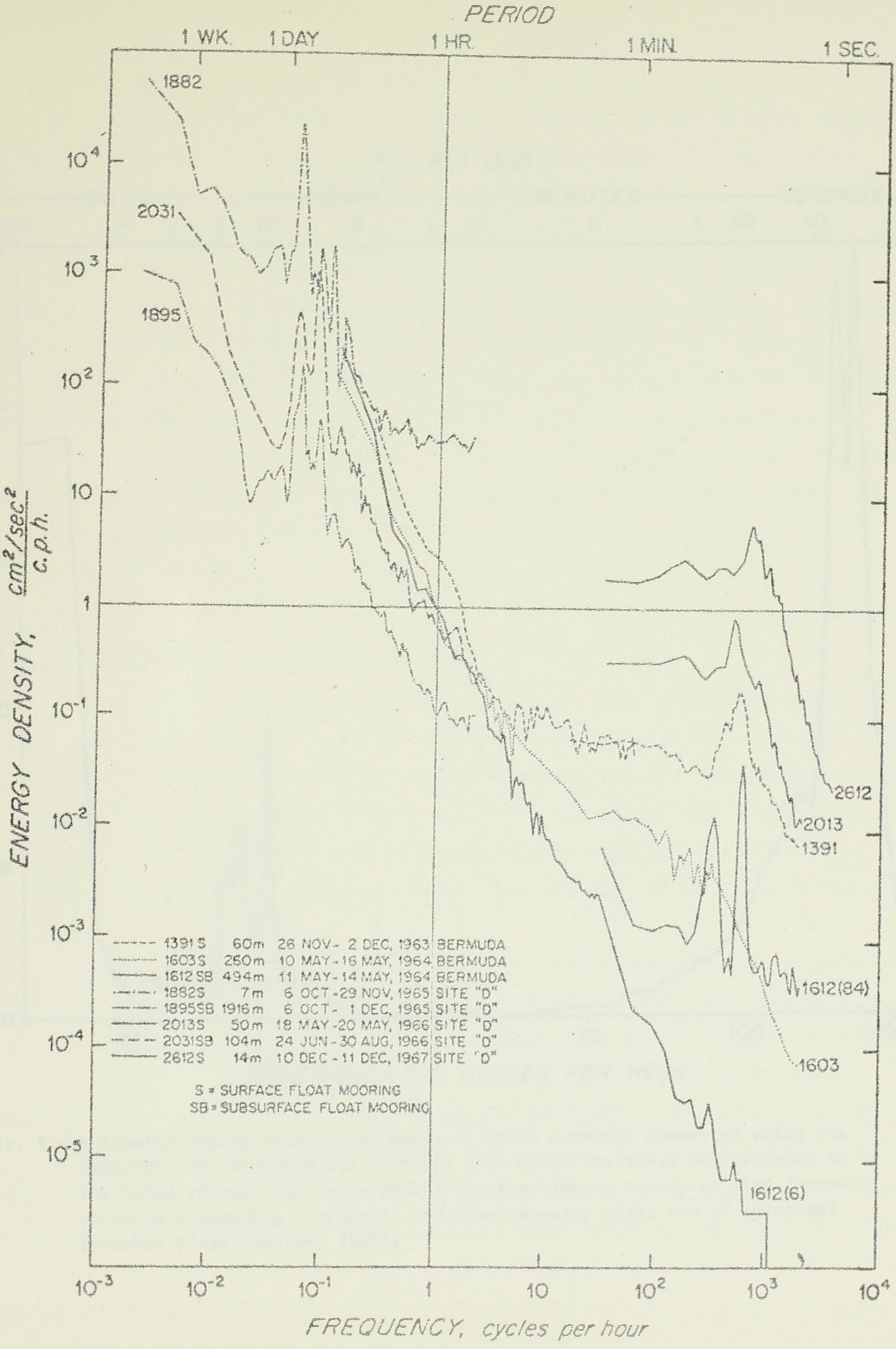


Fig. 4.- Examples of horizontal energy spectra of ocean currents collected under a variety of conditions (from Fofonoff, 1968b).

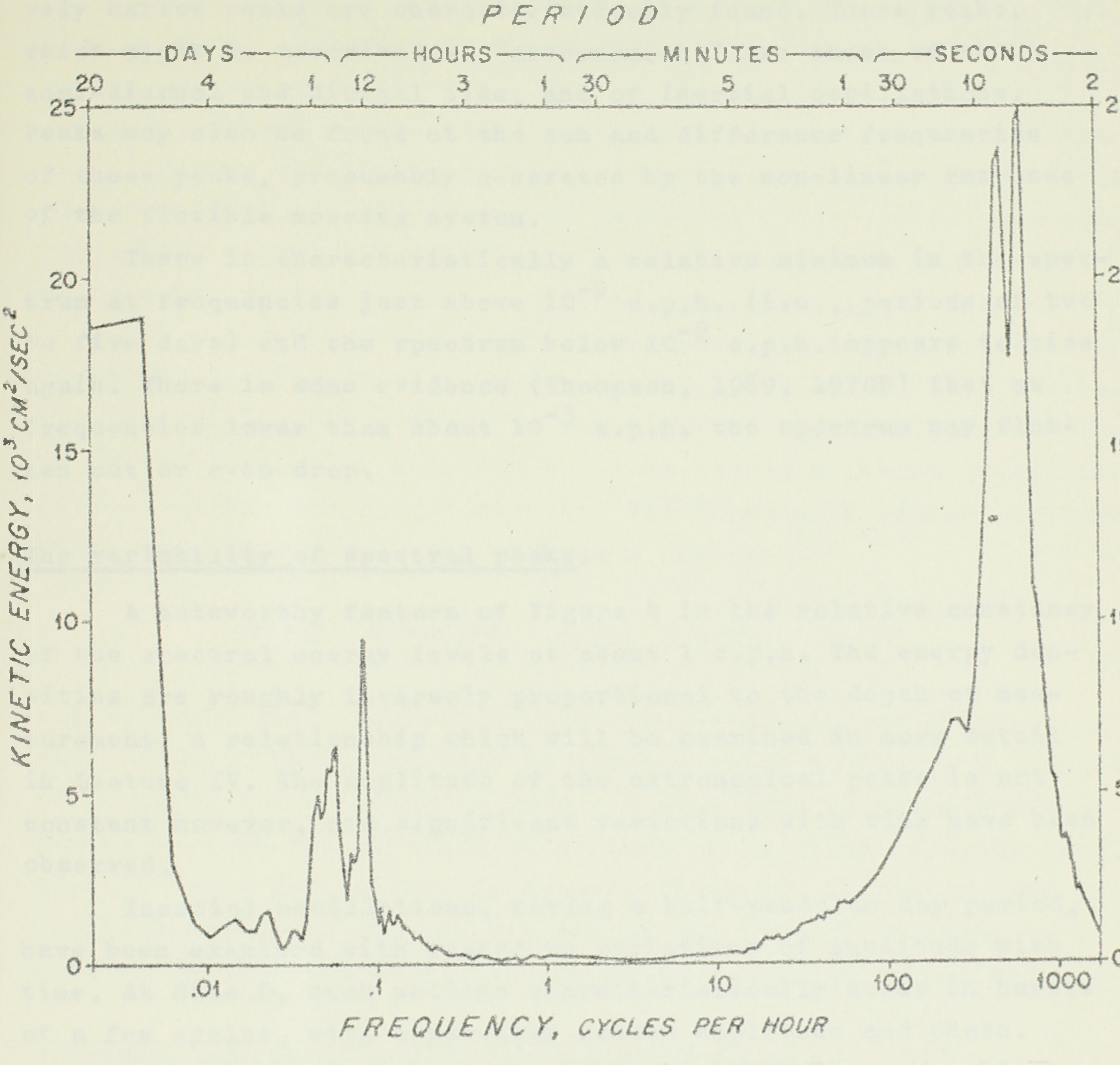


Fig. 5.- A kinetic energy spectrum of measured ocean currents presented using the logarithm of frequency but with the area under the curve proportional to the total energy. The large amount of wave-induced energy at high frequency presents a sampling problem if the low-frequency peaks are of principal interest (from Webster, 1967).

processes in this region of the spectrum as turbulence.

At frequencies just below $10^{-1}$ c.p.h., a number of relatively narrow peaks are characteristically found. These peaks, which might be described as "astronomical" are those of the semi-diurnal and diurnal tide, and of inertial oscillations. Peaks may also be found at the sum and difference frequencies of these peaks, presumably generated by the non-linear response of the flexible mooring system.

There is characteristically a relative minimum in the spectrum at frequencies just above $10^{-2}$ c.p.h. (i.e., periods of two to five days) and the spectrum below $10^{-2}$ c.p.h. appears to rise again. There is some evidence (Thompson, 1969, 1970b) that at frequencies lower than about $10^{-3}$ c.p.h. the spectrum may flatten out or even drop.

## The variability of spectral peaks.

A noteworthy feature of Figure 4 is the relative constancy of the spectral energy levels at about 1 c.p.h. The energy densities are roughly inversely proportional to the depth of measurement, a relationship which will be examined in more detail in Lecture IV. The amplitude of the astronomical peaks is not constant however, and significant variations with time have been observed.

Inertial oscillations, having a half-pendulum day period, have been examined with regard to variations of amplitude with time. At Site D, such motions characteristically occur in bursts of a few cycles, with apparently random amplitude and phase. Treating motions of this kind quantitatively presents problems, since from one point of view the processes are not stationary. It may be more accurate to regard them as non-Gaussian in that both tides and inertial oscillations may appear at random times in the manner of a Poisson process. Little work has yet been done to explore this point of view.

For describing time-varying quasi-periodic processes, the method of complex demodulation (Tukey, 1961, Granger and Hatanaka, 1964, Perkins, 1970), has proven effective. With this method, a frequency band of interest is shifted to zero frequency, and the result is run through a low-pass filter. The resultant complex-valued series gives the phase and amplitude of the frequency of interest. If one chooses the local inertial frequency at latitude $\Phi$ (sin $\Phi$ /12 hours) as the frequency for complex demodulation, time variations in amplitude and phase can be detected. More importantly, departures from local inertial frequency can easily be detected by the existence of slow systematic phase change.

It would be of inteterest to measure the generation and decay times associated with each burst of inertial or tidal motions. This is extremely difficult in practice. To separate such motions of other time scales requires a record having a length of several periods of the motion of interest. The "frequency window" through which complex demodulation defines a signal is

$$W(f) = \frac{\sin \omega T/2}{\omega T/2} \quad \text{where } \omega = 2\pi f$$

and T is the time over which each complex demodulate estimate is made. Such a window can only be sharply tuned for large T. However, it is often not possible to obtain enough data to provide sharp tuning because the duration of a burst of inertial or tidal energy may only be a few periods in length. Since the length of data needed to resolve the motions may exceed the natural lifetime of the motion, it is often impossible to resolve generation and decay times.

## Coherence of currents over spatial separations.

The spatial variability of ocean currents is more difficult to measure than time variability. It is relatively easy to collect a time series of measurements at a fixed point. The corresponding problem of collecting a spatial series at a fixed time is extremely difficult in the deep sea and has not yet been accomplished on an extensive scale.

In order to explore spatial variability the coherence between simultaneous time series at a pair of points is often used. By such means an elementary picture of the extent of spatial coherent motions can be built up. However, the ultimate results fall short of the information which a full spatial spectrum might provide.

For a pair of vector time series, such as a pair of current meter records, the full description of the cross spectrum between them must take account of each combination of component pairs. The full specification of a complete cross-spectrum between two vector series can be expressed as a 16-term matrix (Webster, 1968a). An alternative formulation, in which the cross-spectrum is expressed as the sum of two counter-rotating components has been used by Mooers (1969), and is particularly well suited for treating rotating phenomena such as inertial oscillations.

At low frequencies, there can be apparent coherence over several thousand meters vertically and many kilometers horizontally (Webster, 1969a) and Figure 6 shows a set of progressive vector diagrams showing vertical coherence between 500 m. and 2000 m. at Site D.

A simple experiment examining the horizontal and vertical coherence of currents at inertial frequency is summarized in Figure 7 (Webster, 1968a). These results were interpreted as showing a generally low vertical coherence as contrasted with a relatively high horizontal coherence for inertial motions. Later investigations, for example by Schott, have shown that factors such as stratification and water depth can be important in controlling the scales of coherence, and that caution must be exercised in interpreting the results from Site D generally.

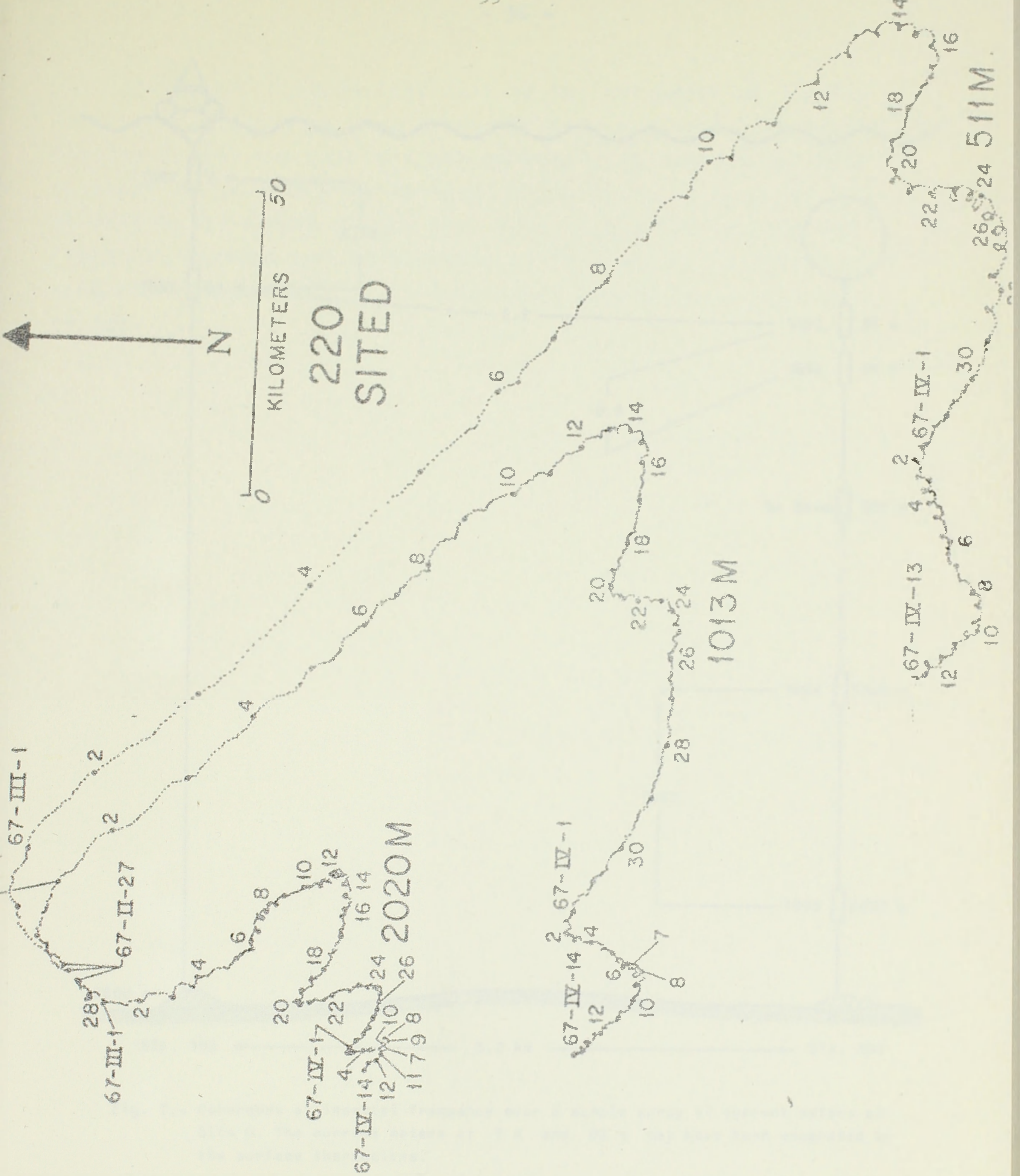


Fig. 6.- Progressive vector diagrams for simultaneous current measurements at nominal depths of 100, 500, 1000 and 2000 m depth. The near-surface observations are apparently not coherent with those at depth, but there is an obvious coherence in low-frequency motions between 500 and 2000 m (from Webster, 1968b).

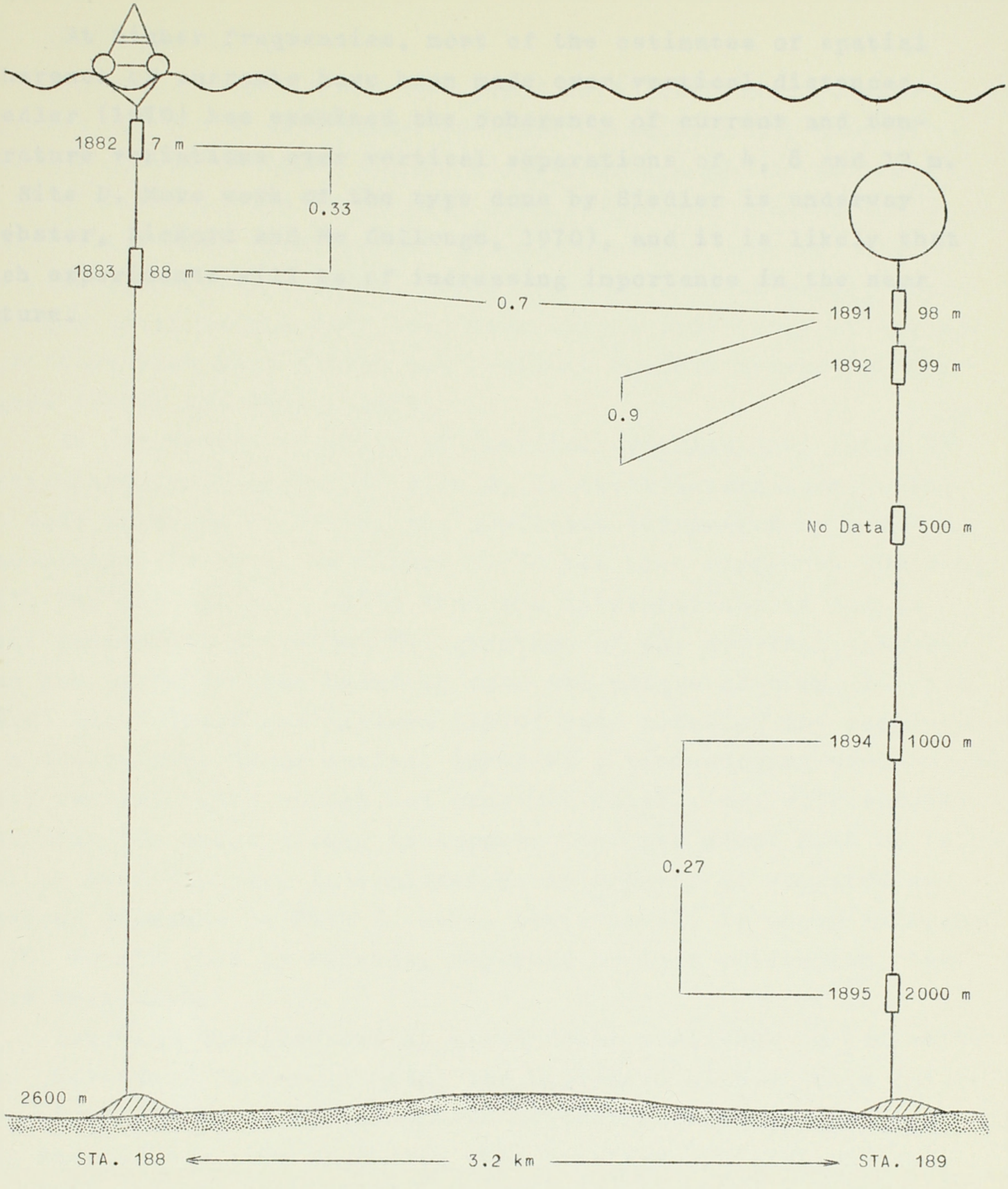


Fig. 7.- Coherence at inertial frequency over a simple array of current meters at Site D. The current meters at 7 m and 88 m may have been separated by the surface thermocline.

At higher frequencies, most of the estimates of spatial coherence of currents have been made over vertical distances. Siedler (1970) has examined the coherence of current and temperature variations over vertical separations of 4, 8 and 12 m. at Site D. More work of the type done by Siedler is underway (Webster, Rickard and Mc Cullough, 1970), and it is likely that such experiments will be of increasing importance in the near future.

## III.-INERTIAL MOTIONS

. Inertial oscillations are found in direct ocean currents wherever current measurements are made systematically over an extended period of time. Figure 8 shows an example of currents at Site D showing intermittently strong inertial oscillations. A review of their occurence in oceans, enclosed seas and lakes was made by Webster (1968a). Since the date of that paper, abundant new observations have been made over a wide range of oceanic conditions with both direct and indirect current measuring techniques (Rooth and Düing, 1970).

An intriguing property of inertial oscillations, which is particularly well marked at Site D, is their intermittence. For the data shown in Figure 8, the amplitude determined by complex demodulation is shown in Figure 9. It has been suggested (Saelen, 1963; Day and Webster, 1965) that the intermittence is due to their generation by winds. The question of the generation mechanism has recently been examined from two points of view. Pollard (1970) and Pollard and Millard (1970) have modelled the response of a homogeneous Ekman surface layer to a time-varying wind stress. Their results, even though not exact in detail, are sufficiently realistic for major events to suggest that the model must be relevant to surface-layer intermittency. An example of computed and observed currents at Site D, using their model, is shown in Figure 10. Recent work by Gonella, reported at this colloquium, supports this view.

Inertial oscillations at great depth also show an intermittent character. So far no model has explained either their intermittent character or the mechanism of energy transfer into the deep sea. It has been suggested that inertial oscillations are the manifestation of globally generated waves which are amplified at their critical or turning latitude (Blandford, 1966). In such a process, it would be expected that energy should be propagated along known ray paths. This possibility has recently been investigated by Perkins (1970).

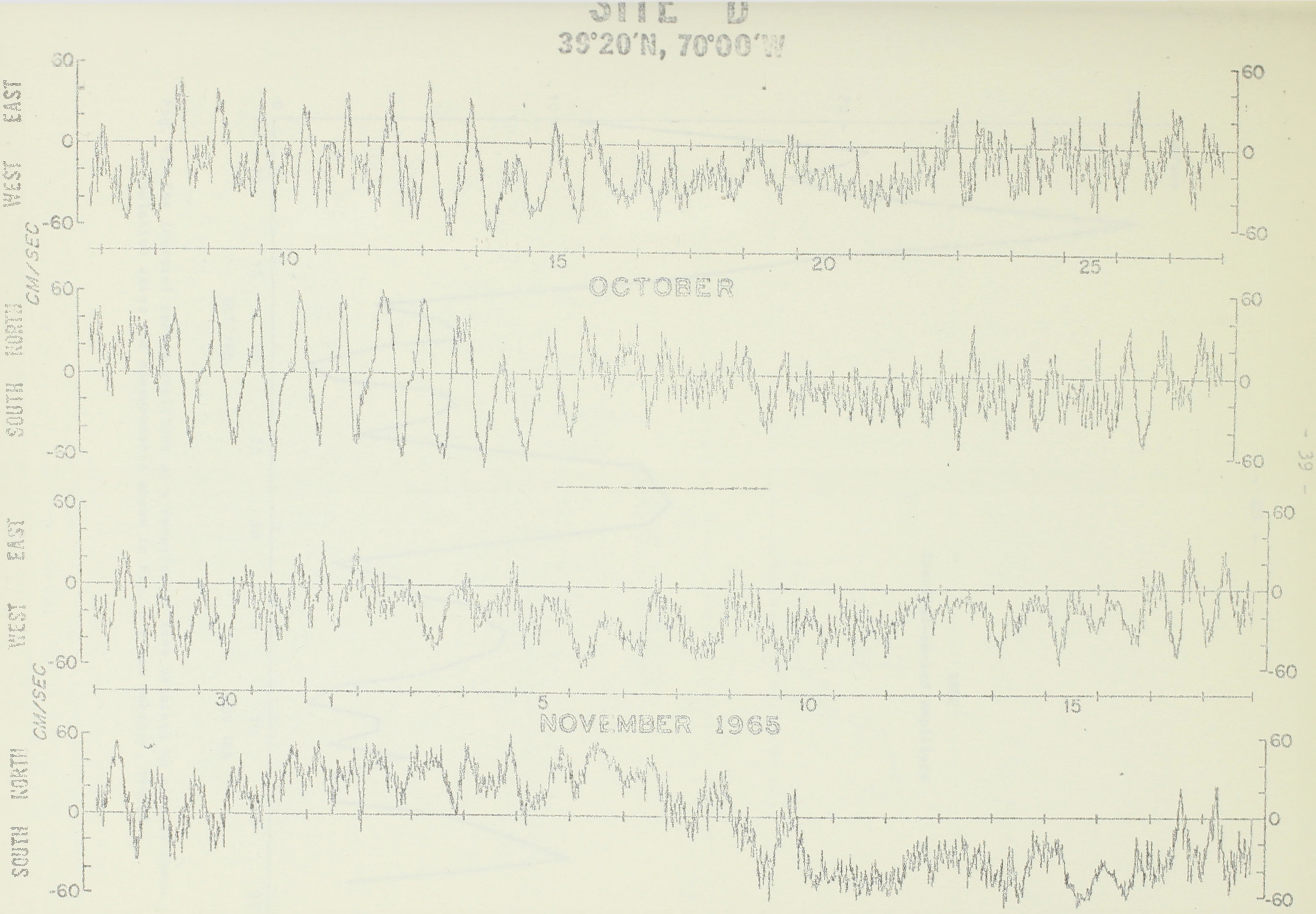


Fig. 8.- An example of currents measured at a depth of 7 m at Site D (1882). The first several days show large-amplitude inertial oscillations. Note the intermittency of occurrence of inertial oscillations (from Webster, 1968a).

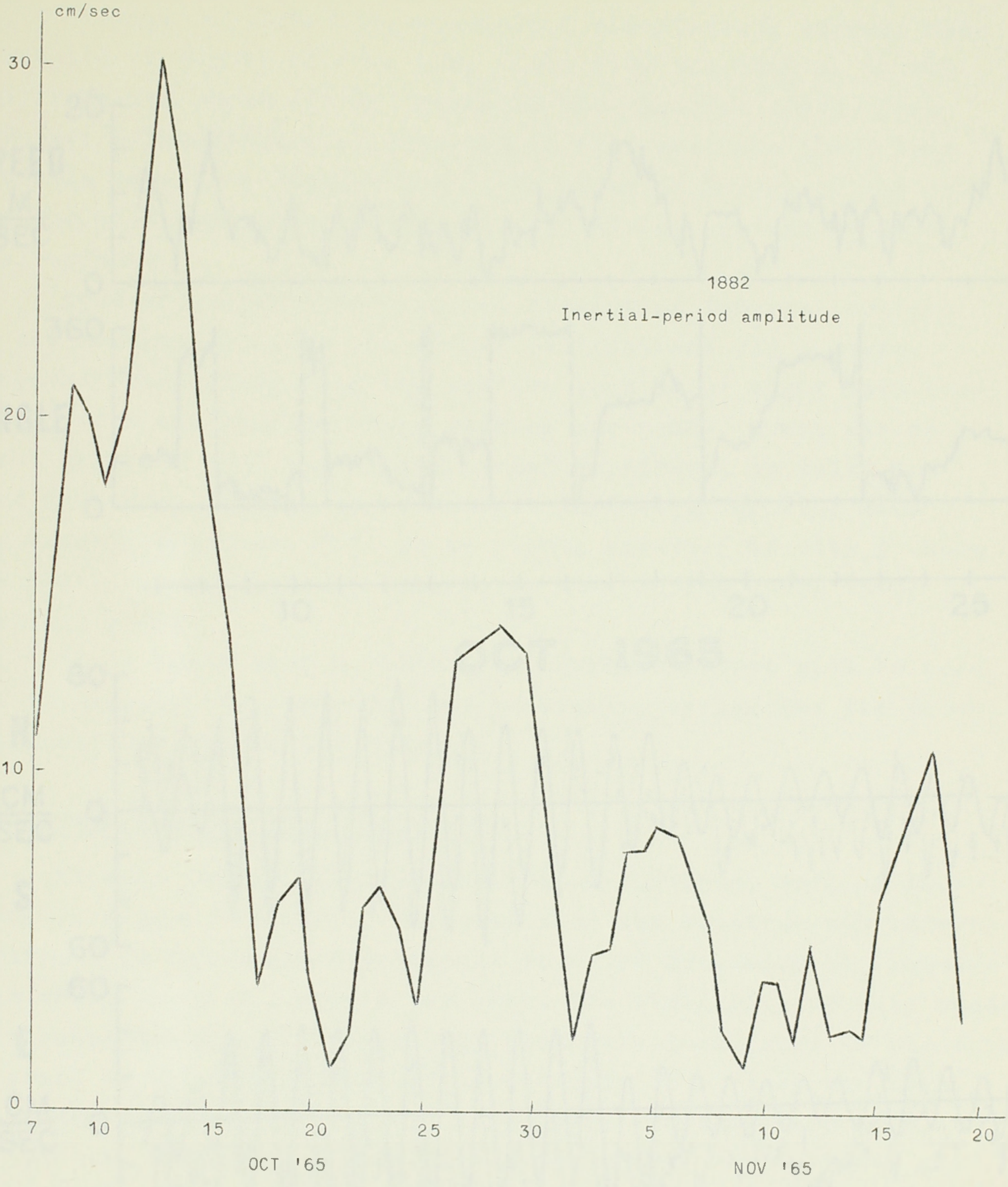


Fig. 9.- The inertial period amplitude as a function of time obtained by complex demodulation using the measurements shown in Fig. 8 (from Webster, 1968a).

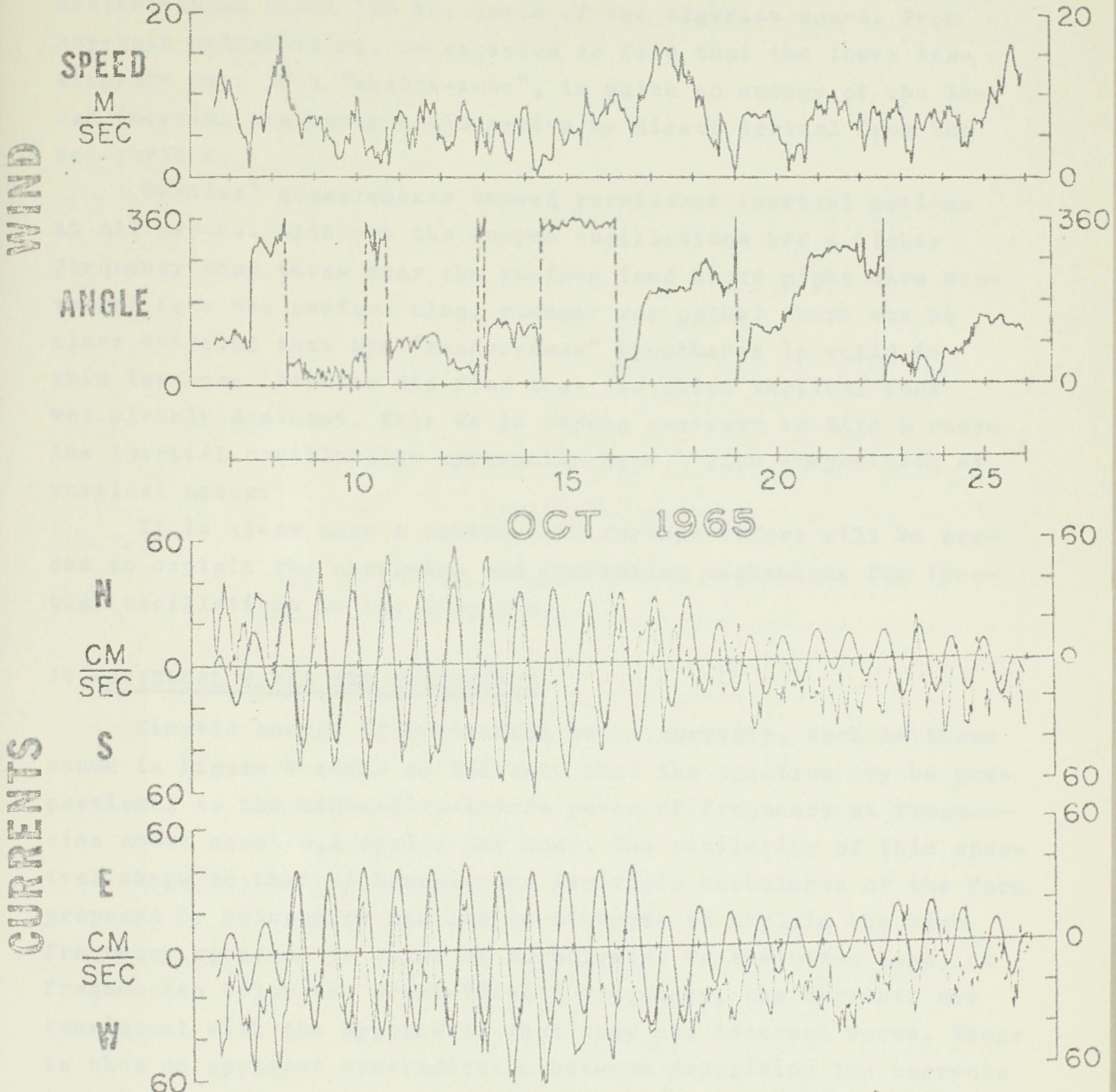


Fig. 10.- The data of figure 8 modelled using Pollard and Millard's model with eight-day damping. In the lower part of the figure, the light irregular line is the observed current and the heavy smoother line is the computed current (from Pollard and Millard, 1970).

Perkins collected two-month-long simultaneous current measurements at depths of 200, 700, 1200, 1700 and 2200 m. in the Mediterranean about 100 km. north of the Algerian coast. From ray-path calculations, he expected to find that the lower instruments were in a "shadow-zone", in which no energy of the local inertial frequency could arrive by direct arrival from the sea surface.

Perkins' measurements showed persistent inertial motions at all depths. Although the deeper oscillations had a higher frequency than those near the surface (and hence might have travelled from the surface along steeper ray paths) there was no clear evidence that the "shadow-zone" hypothesis is valid in this instance. Perkins did find that the third vertical mode was clearly dominant. This is in strong contrast to Site D where the inertial oscillations apparently have a rich composition of vertical modes.

It is clear that a substantial further effort will be needed to explain the occurence and generating mechanisms for inertial oscillations in the deep sea.

## IV.-INTERNAL WAVES AND TURBULENCE

Kinetic energy of horizontal ocean currents, such as those shown in Figure 4 seems to indicate that the spectrum may be proportional to the minus-five-thirds power of frequency at frequencies above about 0.1 cycles per hour. The similarity of this spectral shape to that of homogeneous isotropic turbulence of the form proposed by Kolmogorov has led to attempts to explain the high frequency spectrum in terms of turbulence. On the other hand, at frequencies below the Brunt-Väisälä frequency, the currents are consistent with the hypothesis that they are internal waves. There is thus an apparent contradiction between describing the currents in terms of internal waves or of turbulence.

## Vertical profiles.

Vertical profiles of horizontal kinetic energy are proportional to vertical profiles of the Brunt-Väisälä frequency (Webster, 1969b). A comparison between the vertical profile of horizontal kinetic energy, shown in Figure 11 with that of Brunt-Väisälä frequency, shown in Figure 12 shows this relationship. (The straight lines having a slope of $z^{-0.7}$ on both are arbitrary). Such a result might be expected for wavelike motions (Munk and Phillips, 1968). On the other hand, recent work by Rooth (unpublished so far) suggests that a similar result would be obtained for either internal waves or turbulence if conservation of energy flux is maintained throughout the water column.

The relative constancy of kinetic energy level at any given depth is striking in view of the large variations in surface winds which presumably are a principal driving mechanism. The mechanism which controls the level of kinetic energy has not yet been discovered.

The time-dependent motion at Site D is not horizontally isotropic at frequencies lower than one cycle per day. In the surface layer, north-south (V) components have a larger variance than east -west (u) components ; at mid-depths, the u-variance is greater ; at greater depths the variances are approximately equal. This pattern may be due to the interaction of low-frequency processes with the continental shelf, which is about 50 km. north of Site D.

## Homogeneous isotropic turbulence.

The interpretation of the $f^{-5/3}$ region of the spectrum in terms of homogeneous isotropic turbulence is unsatisfactory. Below the Brunt-Väisälä frequency, the stratification imposes a constraint on vertical movement so that the motion is not three-dimensionally isotropic. Furthermore, the transformation from wavenumber, in which Kolmogorov's hypothesis is stated, to frequency in which the observed spectra are expressed, is only possible if there is a large mean advecting velocity past the point

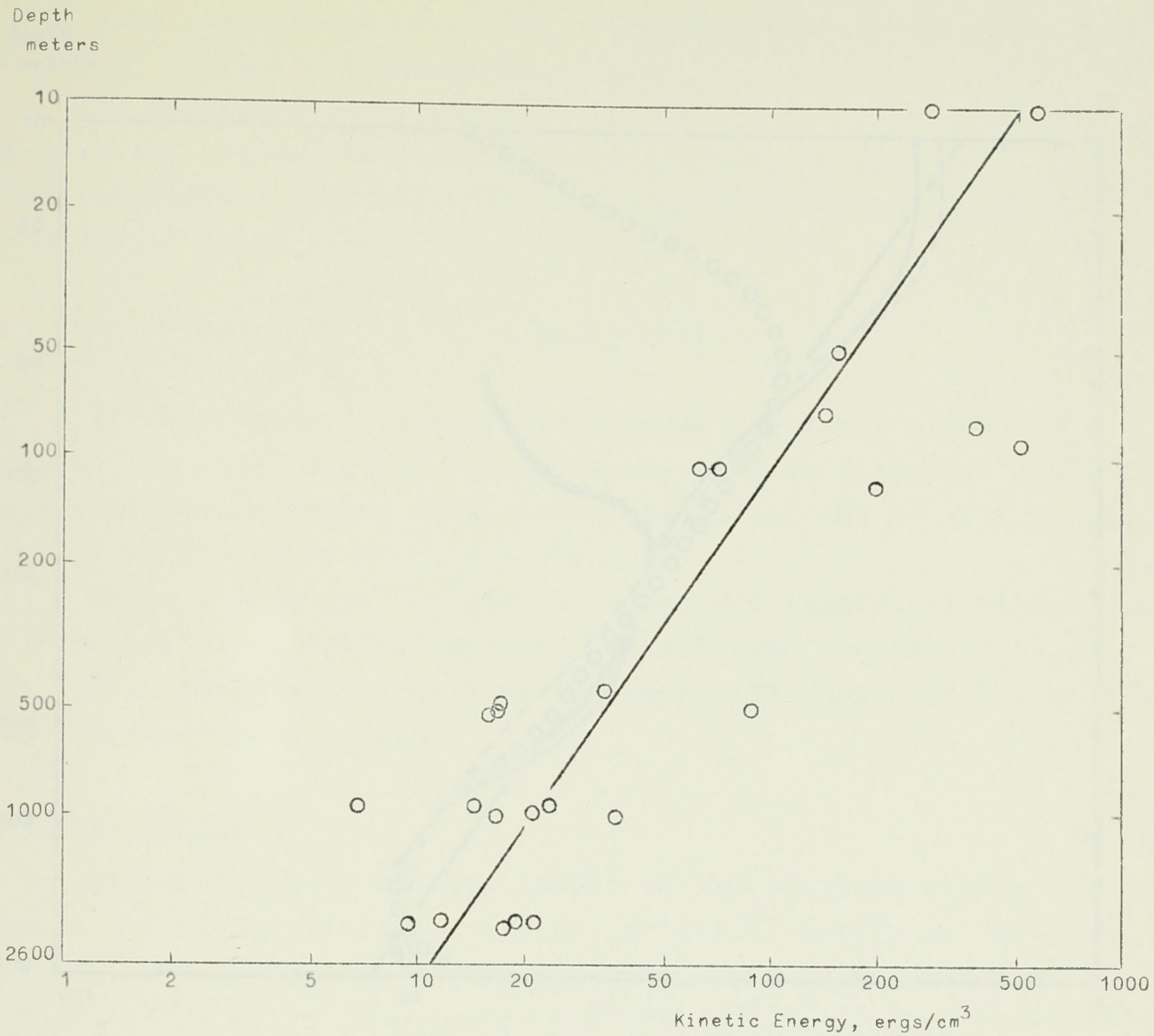


Fig. 11.- Measurements of horizontal kinetic energy vs. depth at Site D. Each point is the average obtained from one current meter record, usually from 6 to 8 weeks duration. The line fitted through the points is proportional to $Z^{-0.7}$ (from Webster, 1969b).

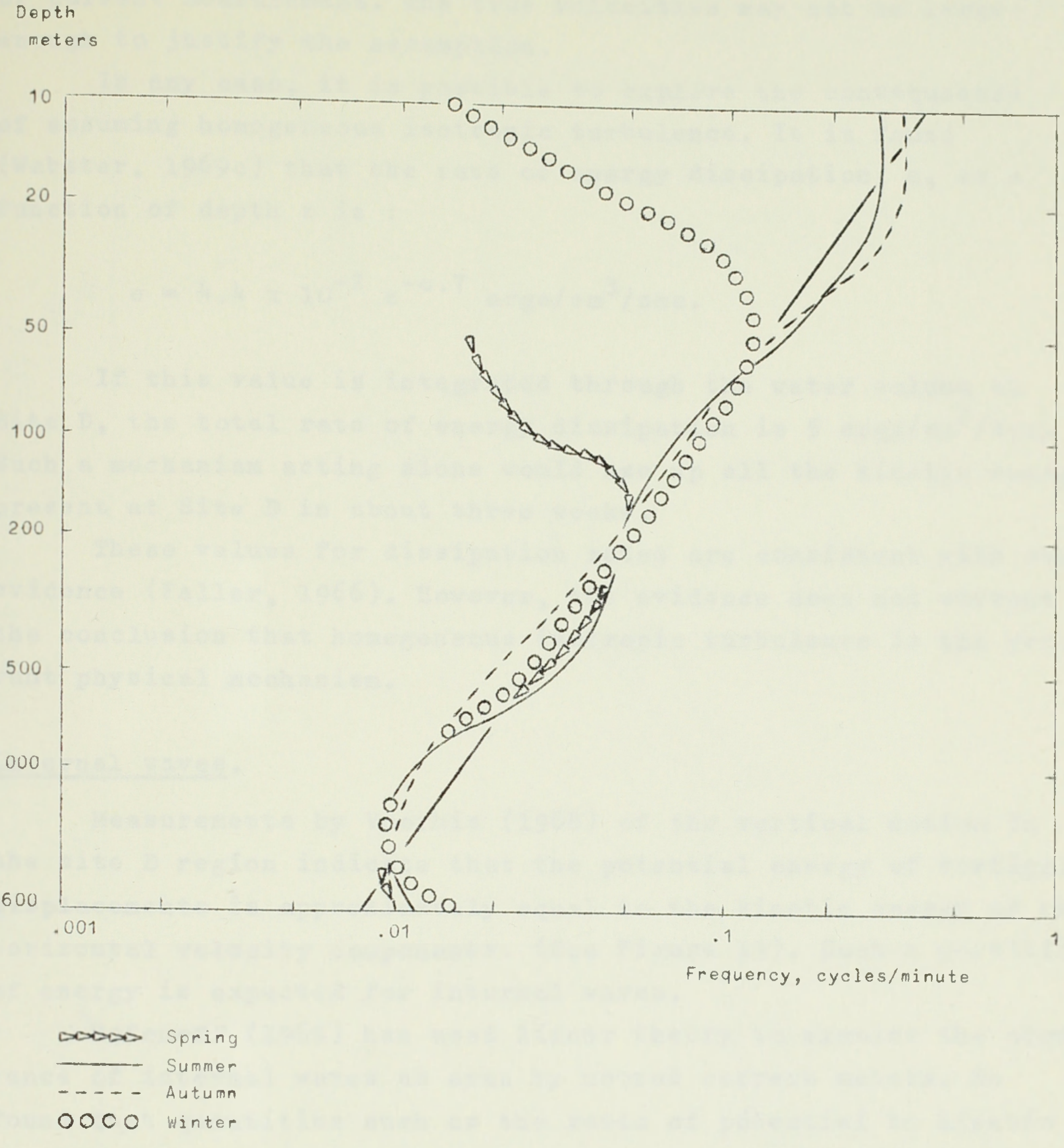


Fig. 12.- Profiles of the Brunt-Vaisala frequency at Site D at four seasons. A line proportional to $Z^{-0.7}$ has been drawn across the figure (from Webster, 1969b).

of current measurement. The true velocities may not be large enough to justify the assumption.

In any case, it is possible to explore the consequences of assuming homogeneous isotropic turbulence. It is found (Webster, 1969c) that the rate of energy dissipation, e, as a function of depth z is :

$$e = 4.4 \times 10^{-2} z^{-0.7} \text{ ergs/cm}^3\text{/sec.}$$

If this value is integrated through the water column at Site D, the total rate of energy dissipation is 5 ergs/cm$^2$/sec. Such a mechanism acting alone would use up all the kinetic energy present at Site D in about three weeks.

These values for dissipation rates are consistent with other evidence (Faller, 1966). However, the evidence does not warrant the conclusion that homogeneous isotropic turbulence is the relevant physical mechanism.

## Internal waves.

Measurements by Voorhis (1968) of the vertical motion in the site D region indicate that the potential energy of vertical displacements is approximately equal to the kinetic energy of the horizontal velocity components. (See Figure 13). Such a partition of energy is expected for internal waves.

Fofonoff (1969) has used linear theory to examine the occurence of internal waves as seen by moored current meters. He found that quantities such as the ratio of potential to kinetic energy and the coherence between velocity components do not involve amplitudes explicitly and can be compared with similar ratios computed from observations. On the basis of measured temperature and current fluctuations Fofonoff concluded that the observed spectra between inertial and Brunt-Väisälä frequencies are

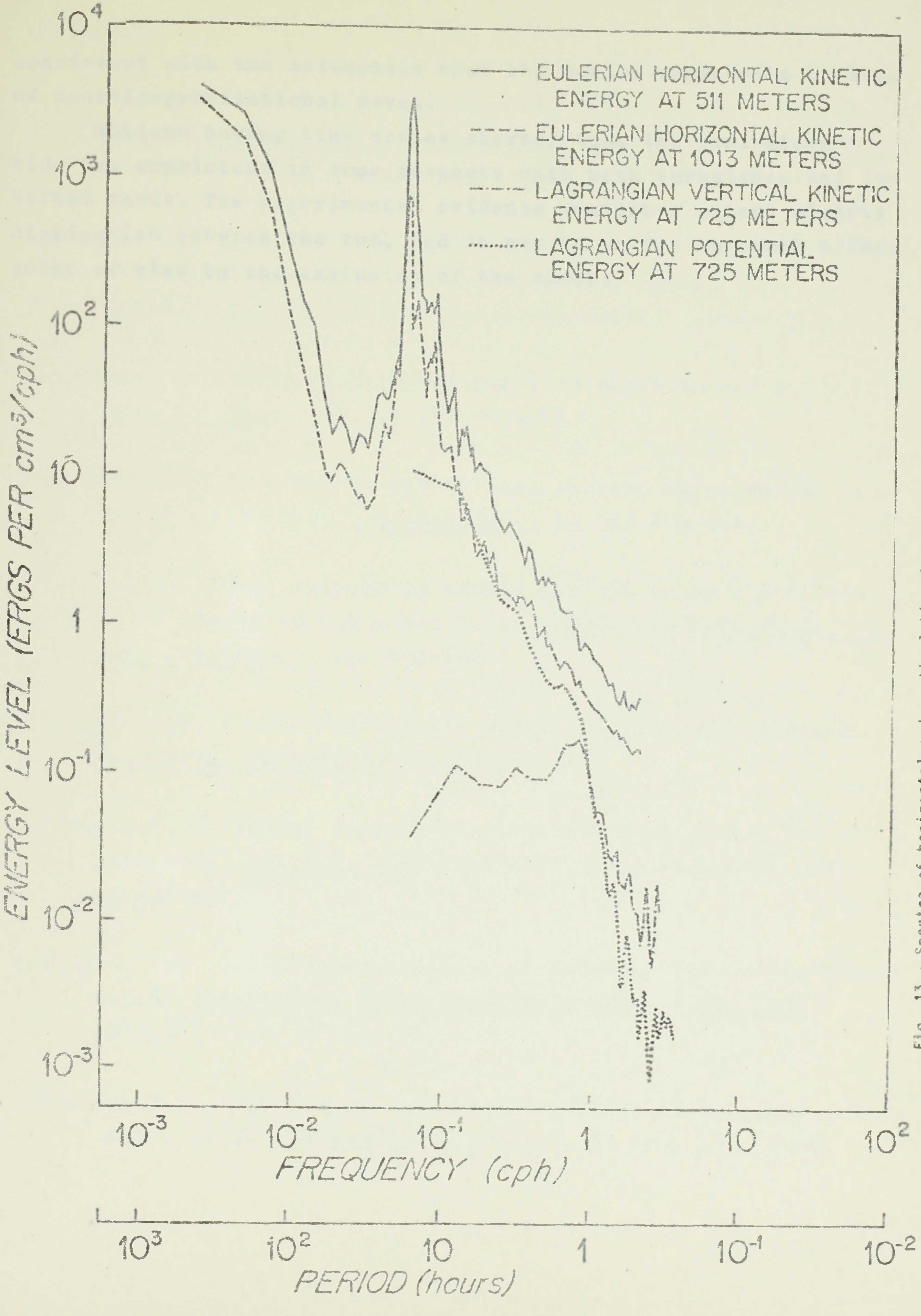


Fig. 13.- Spectra of horizontal and vertical kinetic energy and of vertical potential energy. Over the range of frequencies from the inertial frequency to the Brunt-Väisälä frequency, there is an approximate equipartition of energy (from Voorhis, 1968).

consistent with the assumption that the motion represents a field of inertio-gravitational waves.

Motions having time scales shorter than the semi-diurnal tide are consistent in some respects with both turbulence and internal waves. The experimental evidence available cannot clearly distinguish between the two, and it may be unwise to adopt either point of view to the exclusion of the other.

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