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FIELD EVALUATION OF AN ELECTROMAGNETIC CURRENT METER BASED VERTICAL PROFILER

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Management Perspective

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The need to investigate the role played bysuspended sediments in the transport and fate of contaminants in lakes has led to the measurement of current in shallow water and in nearshore areas where surface wave influences are crucial to the dynamics of resuspension. The standard mechanical current meters are inappropriate for these high energy zones. A new generation of solid state current meters has been brought on the market to fulfill these needs.

This paper concerns a field evaluation of a vertical profiling system constructed from three such devices operating on the electro-magnetic induction principle. The results are not encouraging in our careful field evaluation. We do not recommend further deployment of these meters for this purpose and encourage the development and testing of other devices.

This study is relative to contaminated sediments and the Upper Great Lakes and connecting channels studies.

ABSTRACT

A current profiler consisting of a vertical array of three electromagnetic current meters has been evaluated through an intercomparison of the three sensors, with reference to nearby current and wave data and by comparison to recent laboratory performance tests (Aubrey and Trowbridge, 1985). Mean flow estimates are too uncertain and variable to allow bottom boundary layer shear stress to be estimated by the conventional logarithmic-law method. As well as unexplained sudden shifts in the mean speed response, the comparison with standard current meter data indicates possible long-term reduction in response due to fouling of the sensors by biological growth. The directional response was less sensitive to fouling effects. The oscillatory response on one occasion after field deployment for 17 days indicates a reduction in response from 41 to 45% at a period of oscillation of three seconds in a combined steady and oscillatory flow field. This study demonstrates that despite careful laboratory calibration, electromagnetic current meters are not at present suitable for quantitative study of dynamics of sediment resuspension in near-bottom shallow water environments.

SOMMAIRE

Pour évaluer le rendement d'un enregistreur de profils composé d'un arrangement vertical de trois courantomètres électromagnétiques, on a comparé entre eux les trois capteurs, puis on a comparé les résultats à des données sur des courants et des vagues obtenues un peu plus loin et, enfin, à des résultats d'essais de rendement effectués récemment en laboratoire (Aubrey et Trowbridge, 1985). Les estimations d'écoulements moyens sont trop incertaines et variables pour permettre d'évaluer la force de cisaillement dans la couche de limite de fond par la méthode logarithmique habituelle. En plus de changements soudains et inexplicables dans la vitesse moyenne de réactions, la comparaison avec des courantomètre standards indique une possibilité qu'il y ait réduction à long terme du temps de réaction occasionnée par l'encrassement des capteurs par des éléments biologiques. Par contre, la réponse de directivité semble moins susceptible d'être modifiée par l'effet d'encrassement. Après un essai de 17 jours en conditions réelles, on a remarqué à une reprise que la réponse d'oscillation était réduite de 41 à 45 p. 100 pendant une période d'oscillation de trois secondes, dans un champ d'écoulements stationnaires et oscillants combinés. Cette étude démontre qu'en dépit des précautions particulières prises pour l'étalonnage en laboratoire, les courantomètres électromagnétiques ne conviennent pas, à l'heure actuelle, aux études quantitatives de la dynamique de remise en suspension des sédiments dans des milieux près des fonds en eau peu profonde.

INTRODUCTION

Field investigations of the vertical structure of current in deep water areas in lakes have employed a single instrument raised and lowered through the water column (Hamblin and Kuehnel, 1980; Royer et al., 1986) when the primary interest has been the region below the immediate influence of waves. The need to investigate the role played by suspended sediments in the transport and fate of contaminants in lakes has led to the measurement of currents in shallow water and in the nearshore zone where surface wave influences are crucial to the dynamics of sediment resuspension. In the case of the wave dominated zone, current profiles based on a single roving instrument do not provide the statistical stability required to determine such parameters as the mean vertical shear; arrays of fixed-point sensors are more suitable. This approach to profile measurement imposes additional demands on the accuracy of the current sensors beyond those of the more conventional profilers where good relative accuracy is more important than absolute accuracy.

In order to investigate the current structure in a shallow wave-influenced lake, (Lake St. Clair, maximum depth 6.5 m) we employed a vertical current profiler based on three two-axes 0.105 m diameter electromagnetic current meters (Marsh-McBirney Model MM551) during the early autumn of 1985. At approximately the same time an independent study of the same instrument was reported by Aubrey and

Trowbridge (1985). Our evaluation of the performance of the electromagnetic current meter under field conditions thus serves as a complement to that of Aubrey and Trowbridge under more controlled laboratory conditions.

The above-mentioned three electromagnetic current meters when combined with three temperature sensors and a data logger capable of recording bursts of one-second samples over a period of 20 minutes once every three hours has been termed the MCATS (Moveable Current and Temperature System) and is described in detail by White (1980). This system was placed in the middle of Lake St. Clair at latitude 42°24'17" and longitude 82°41'49" from September 11 to October 1, 1985. A schematic view of the profiler and the three levels of measurement are shown in Figure 1. Besides the direct intercomparison of electromagnetic sensors, the field evaluation of the performance of this system relies upon the contemporaneous collection of supporting data in the vicinity of the MCATS site. Several self-recording acoustic current meters were moored at a height of 1 m above the bottom within 3 to 4 km of the experimental location. The calibration and field performance of the acoustical current meter has been reported by Bull and Valdmanis (1986). Wave-induced pressures at a depth of approximately 2 m below the surface were recorded at one-half second intervals over 20 minute periods also once every three hours. The accuracy of wave heights measured by this system is 0.1 cm (Aanderaa Instruments Ltd., 1978). Additionally, wind speeds and directions as well as other meteorological parameters were measured at a nearby meteorological buoy [CCIW, 1985]. The background environmental conditions at the experimental site are presented in Figure 2 in terms of the significant wave height, the wave period, the orbital velocity at the bottom as inferred from linear wave theory from the period, water depth and wave height and the components of the surface wind stress. It is evident that meteorological conditions are quite variable during the experimental period with storms of moderate intensity occurring on September 12 and 26 being separated by a notable calm period on September 15.

At the peak wave event of September 24 shown in Figure 2, the wave-induced boundary layer thickness was 4 cm according to the formula of Dean and Perlin (1986). On other occasions, the wave boundary layer thickness was much less. As will be evident shortly, typical mean currents were in the order of 10 cm/s resulting in a turbulent boundary layer thickness of several meters. Thus the electromagnetic current meters, situated at heights of 20, 30 and 40 cm above the bottom, were usually within the turbulent boundary layer but above the surface wave boundary layer.

In the following, the evaluation is organized along the lines of Aubrey and Trowbridge with a discussion of the mean and oscillatory responses following the calibration procedure.

CALIBRATION PROCEDURE

The three Marsh-McBirney electromagnetic current meters were calibrated in field configuration in order to eliminate any possible cross-coupling effects between instruments in the tow tank facility at the National Water Research Institute. Towing speeds of 2.5, 5, 10, 15, 25 and 50 cm/s were run with 30 degree increments in heading. The calibration facility is considered to be accurate to within 0.1 cm/s. However, no facility exists at the laboratory to determine either the oscillatory response or the influence of background turbulence on such a system. The zero speed stability of spheres was examined by immersion in the tow tank at rest over a period of 60 hr. The least squares fit with a three segment linear curve to the tow tank data resulted in a lower residual then a single linear curve, a finding that is in agreement with Aubrey and Trowbridge. A three-segment curve was fitted individually to each of the two axes of the three current meters resulting in six calibration formulae. The two break points separating the three linear segments occurred at velocities of approximately -25 and +25 cm/s. The magnitude of the break point is lower than that reported by Aubrey and Trowbridge for the 10.5 cm diameter sphere and is closer to the 4.5 cm sphere.

The standard deviations of the electromagnetic sensors were ±0.45 cm/s in the linear segment -25 to 25 and ±0.2 cm/s for speeds larger than 25 cm/s. Finally, the zero speed test based on a 9-hr segment resulted in offsets ranging from 0.1 to 0.4 cm/s and zero speed stabilities of ±0.13 cm/s.

FIELD RESULTS

a. Low Frequency Response

Mean currents from the averages of the 20-minute electromagnetic current meters were compared to acoustic current meters at a depth of 1 m and at three locations surrounding the experimental site at distances of 3.5 to 4 km. Since the current regime is nearly identical at the three locations the closest station (no. 20) has been chosen for detailed comparison in Figure 3. The response at the beginning of the experiment shows that the electromagnetic instrument's gain is at least a factor of two too high despite the fact that EM current meters are much closer to the boundary than the acoustic current meters. This overestimation of the current in a field setting is surprising since Aubrey and Trowbridge show that in the presence of freestream turbulence and oscillatory motion the steady response decreases. The gain factor slowly decreases over the experimental period until the last four days when the acoustic and EM currents are in reasonable agreement. An unexplained abrupt shift in speed response may be noted on September 27. A similar but not as large decrease in response has been attributed to biologically related fouling of the electromagnetic sensors by Aubrey and Trowbridge (1985). It is possible that biological growth is more rapid in Lake St. Clair. Fluctuations in speed are in general comparible in the two series. Maximum random differences of 5 cm/s in mean speeds occur between the three electromagnetic sensors. Unexpectedly the speed at the intermediate level at 30 cm was found to be less than that at the lowest (20 cm) level initially but larger than the mean at the highest (40 cm) level at the end of the experiment. Consequently, only a portion of the 5 cm/s speed difference may be attributed to boundary layer shear.

The comparison between the directional response of the two types of current meters appears to be more satisfactory. Apparently the directional behaviour is less prone to such influences as electronic drift or biological fouling. Again the mid-level electromagnetic current meter is not as close as the other two levels to the acoustical current meter data with directional deviations as large as 60° in mean direction.

OSCILLATORY RESPONSE

For each of the 20-minute sample periods, the standard deviation about the mean flow was computed. While in a few instances the standard deviation exceeded the mean, in general, the standard deviation was about 80% of the mean, possibly indicating that the electromagnetic current meters were located in an energetic region of the turbulent bottom boundary layer. Additional evidence supporting this view was the independence of this ratio to the orbital motions of surface waves shown in Figure 2 but its correlation with the mean flow and therefore the vertical shear. For example, during the period of low mean flow (~4 cm/s) on September 28 at 1800, the standard deviation decreased to 20% of the mean flow. Short segments of the one-second data from each of the above-mentioned episodes at a height of 40 cm above the bottom are shown in Figure 4. For the most intense wave period of September 24, the motion, although highly oscillatory, does not demonstrate the wave-like character with a clearly defined periodicity and groupiness as does the less wavy but lower shear period on September 28. Unfortunately the nearby acoustic current meters were not capable of recording current variance.

Further support for the dominance of boundary layer turbulence over wave motions arises from the coherence between 1200 one-second readings of pairs of current meters during the waviest period on September 24 and the calmest period on September 16. In both cases the coherence is nearly independent of frequency and is about 0.9 for adjacent pairs and 0.8 between the upper and lower current meters.

Under field conditions, it is impossible to separate the response into purely oscillatory and combined oscillatory response as in the laboratory study of Aubrey and Trowbridge (1985). Instead we examine a typical case where the variable motion is 0.8 of the mean as well as an extreme case when the standard deviation is 0.2 of the mean. As a useful check on current meter performance and the extent of fouling, the orbital motion spectra are compared to the orbital motion spectra inferred from wave induced pressure fluctuations and linear wave theory.

In the most windy and wavy period when the standard deviation is 0.8 of the mean, the kinetic energy spectrum of the orbital motions measured by the electromagnetic current meter is compared to the orbital motion spectrum inferred from pressure fluctuations 2 m below the surface in Figure 5. It is evident that either wave currents are not properly measured by the electromagnetic current meters or that they are submerged below the level of turbulent kinetic energy in the bottom boundary layer. The spectra of the middle and lower current meters are nearly identical except that the amplitude of the mid-level spectrum is lower than the bottom level spectrum as also was the case for the mean current. Not shown in Figure 5 are the spectra of the individual current axes, since neither one indicate the presence of wave motion. Nearly all the kinetic energy is in the east component as might be expected during westerly wind forcing.

The results from this high wind episode are in contrast to the moderate wind case on September 28 when the standard deviation of the flow was only 0.2 of the mean. For this period the kinetic energy associated with wind waves is clearly identifiable in the EM current east component spectrum of Figure 6 at a period of three seconds and is 41 percent of the peak of wave orbital spectrum derived from pressure fluctuations. Apparently at this point about three quarters through the experiment, the oscillatory response had decreased by 36%. Similarly, the lower two levels are reduced by 43 and 45% below the response predicted by linear theory. This reduction in response of an oscillatory component in a combined steady oscillatory flow is much larger than the 14.5% decrease reported by Aubrey and Trowbridge. Outside the bottom wave boundary layer, linear theory ought to be valid although somewhat higher than the true orbital velocity (Dean and Perlin, 1986). Apart from the limits of inviscid linear theory, it is possible that the additional reduction may be due to biological fouling as already discussed for the mean response. Interestingly, during this period of northwest wind forcing the north component is much stronger than the east component except at the wave period where the east component of the flow dominates.

DISCUSSION AND CONCLUSIONS

Field deployment of a vertical array of electromagnetic current meters and a comparison of the results with other data has shown that such a system is limited at present to qualitative studies of mechanics of resuspension in lakes. For example, we have found that the wave induced orbital motions are not present above the background of turbulent motions in the open lake environment close to the bottom even during storm conditions except during times when the mean shear is unusually low due to the opposition of wind and hydraulic components of lake circulation.

A major finding of this study is the lack of reliability of a carefully performed laboratory calibration. We can find no explanation for the anomalously high gain on all six channels at the onset of the field deployment. These uncertainties in the calibration of the mean flow apparent in the field response many times larger than the laboratory deviations further imply that it is impossible to estimate the boundary layer shear stress from the logarithmic-law relation since the correlation coefficient squared must be greater than 0.994 to distinguish the shear from the null hypothesis (Aubrey and Trowbridge, 1985) in our system. Furthermore, the quantitative use of higher-order velocity moments for sediment transport measured from such a system would lead to unacceptably large errors (Aubrey and Trowbridge). Until the questions of free-stream turbulence levels and biological fouling of electromagnetic sensors is better understood, the use of these devices in field studies of the dynamics of sediment resuspension is not recommended. The development and field testing of alternate instruments such as the device described by Lemmin *et al*. (1985) should be continued.

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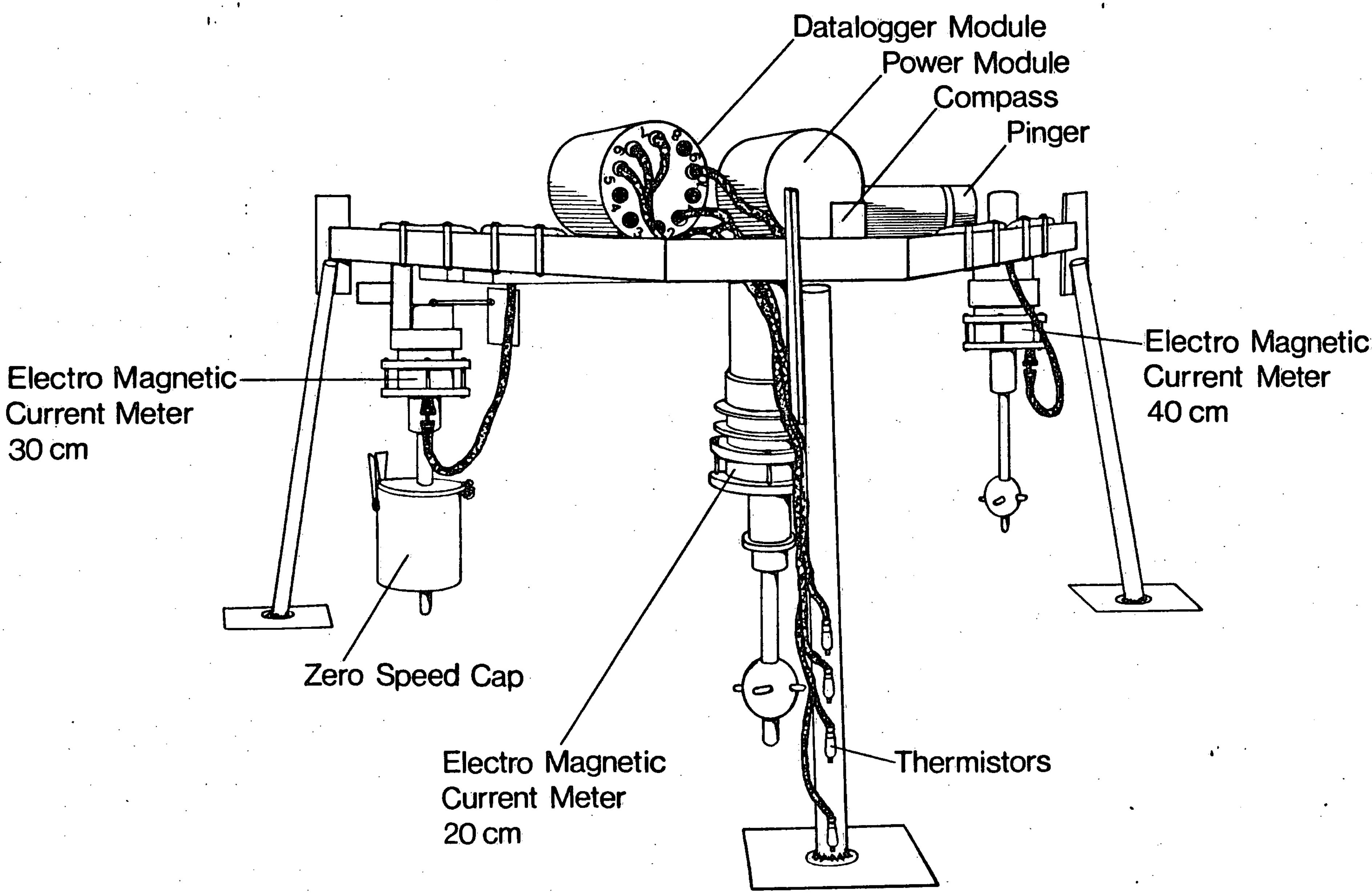
LIST OF FIGURE CAPTIONS

1. Schematic view of the electromagnetic current profiling system.
2. Environmental conditions at the field deployment site during the measurement period.
3. Mean currents, cm/s (a) September 12-16, (b) September 26 to October 1, solid line five-minute means of acoustic current meter at 1 m above bottom, + EM current meter 40 cm above bottom, Δ EM current meter 30 cm above bottom, 0 EM current meter 20 cm above bottom.
4. Electromagnetic current meter 40 cm above bottom, U east component, (cm/s) (a) 00:00 September 24, (b) 18:00 September 28 time in minutes.
5. Frequency spectra of total kinetic energy, solid line from pressure sensor, dashed line from electromagnetic current meter at 40 cm above bottom 00:00 to 00:20 September 24. The 90% confidence interval is indicated.
6. Frequency spectra of total kinetic energy, solid line from pressure sensor, dashed line from electromagnetic current meter at 40 cm above bottom 1800-2100 September 28. The dotted line indicates the east component spectrum. The 90% confidence interval is indicated.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Power Module
Compass
Pinger
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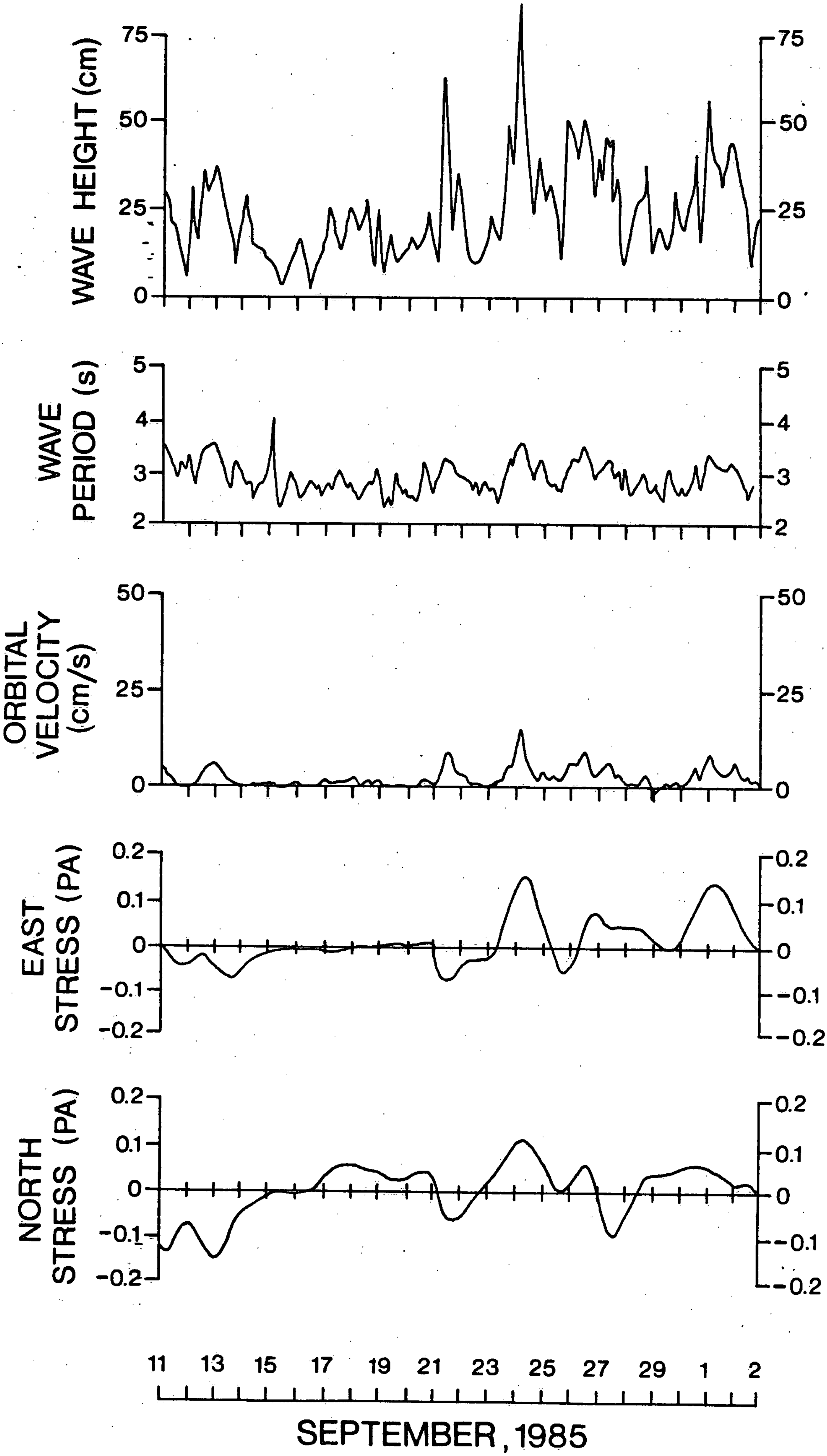
Current Meter
30 cm
Electro Magnetic
Current Meter
40 cm
Zero Speed Cap
Electro Magnetic
Current Meter
20 cm
Thermistors

Fig 1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25
0
WAVE PERIOD (s)
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4
3
2
ORBITAL VELOCITY (cm/s)
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25
0
EAST STRESS (PA)
0.2
0.1
0
-0.1
-0.2
NORTH STRESS (PA)
0.2
0.1
0
-0.1
-0.2
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13
15
17
19
21
23
25
27
29
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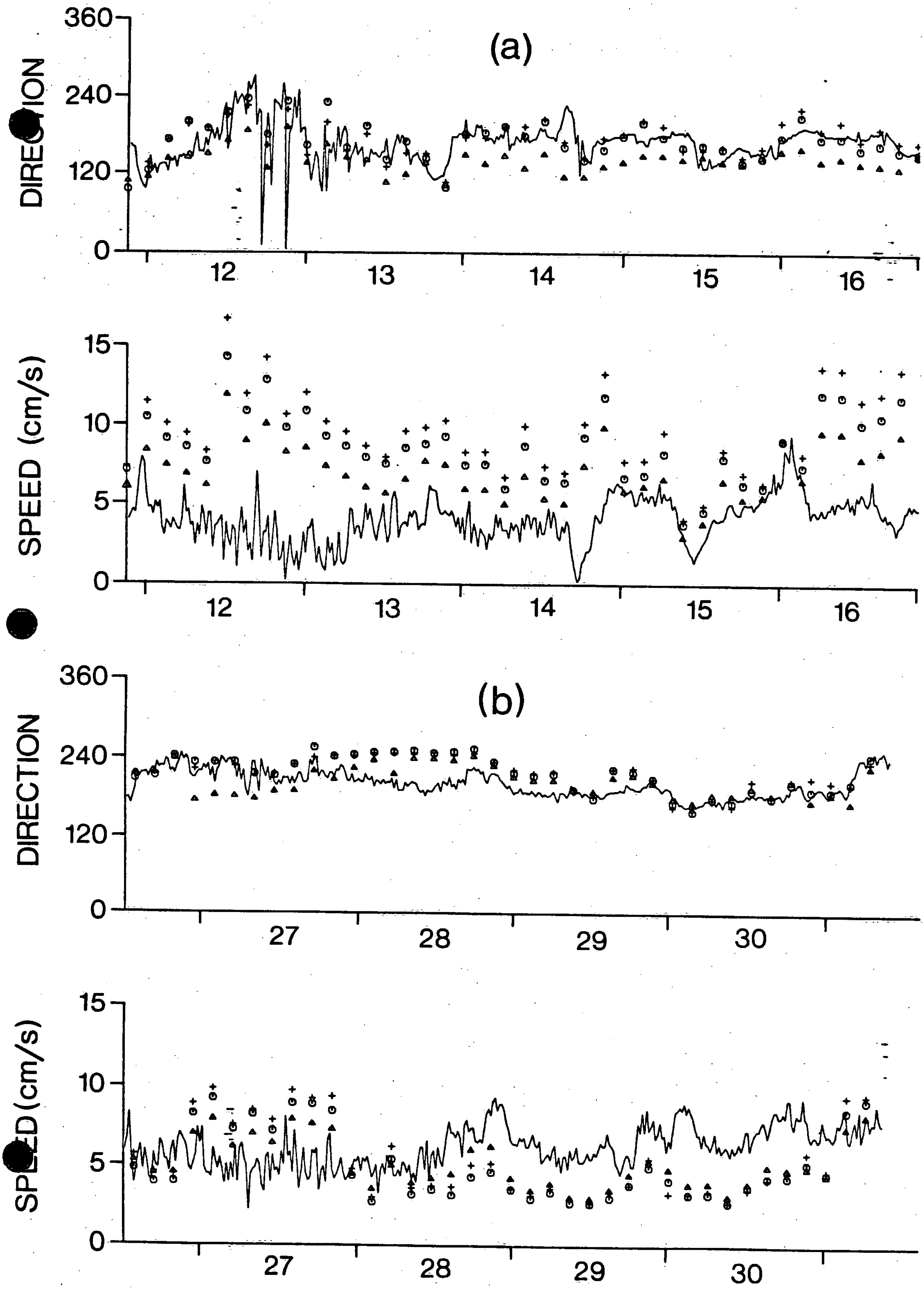
2
SEPTEMBER, 1985

Fig. 2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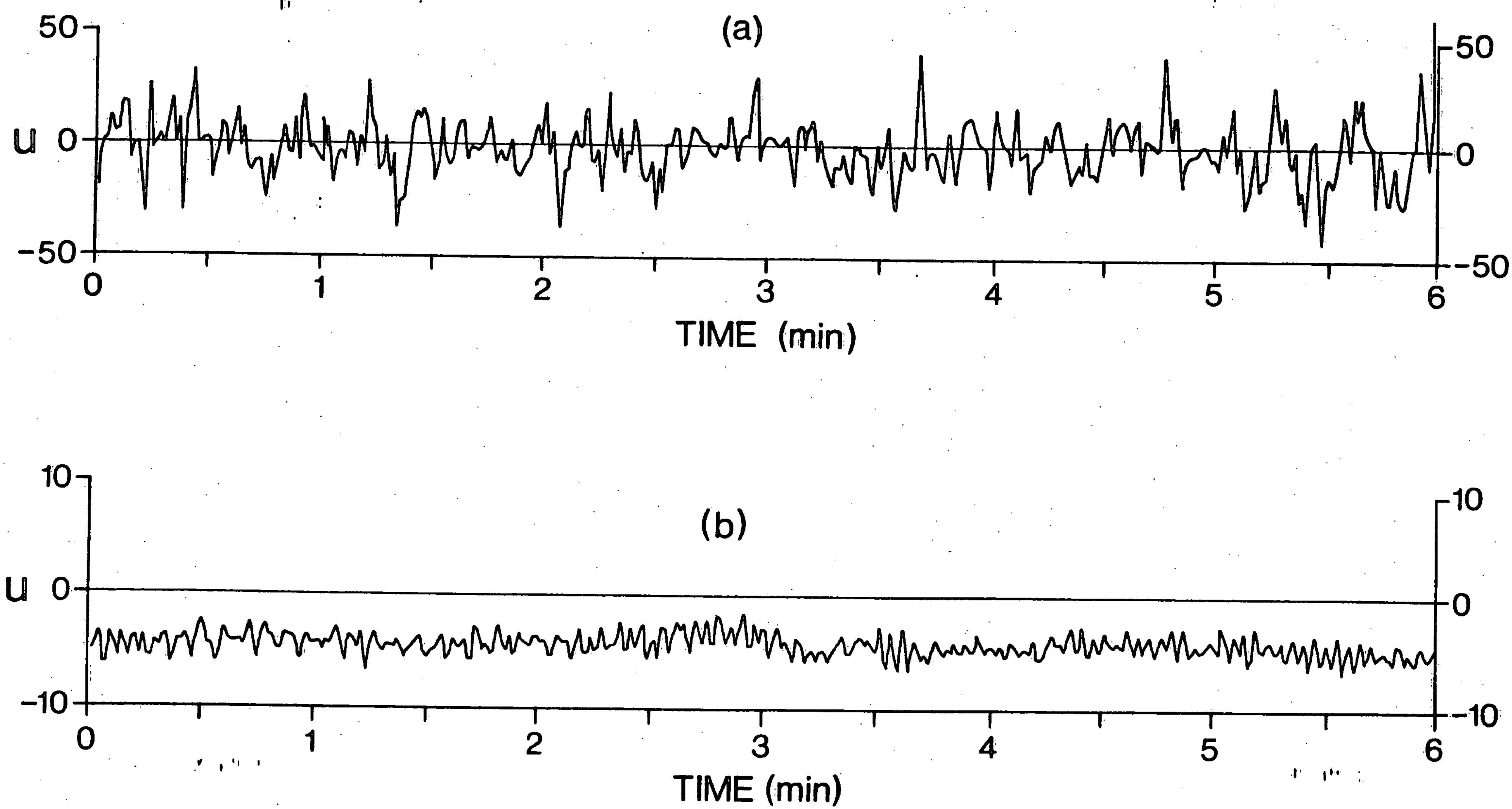
13
14
15
16
SPEED (cm/s)
15
10
5
0
12
13
14
15
16
(b)
DIRECTION
360
240
120
0
27
28
29
30
SPEED (cm/s)
15
10
5
0
27
28
29
30


(a)
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TIME (min)
(b)
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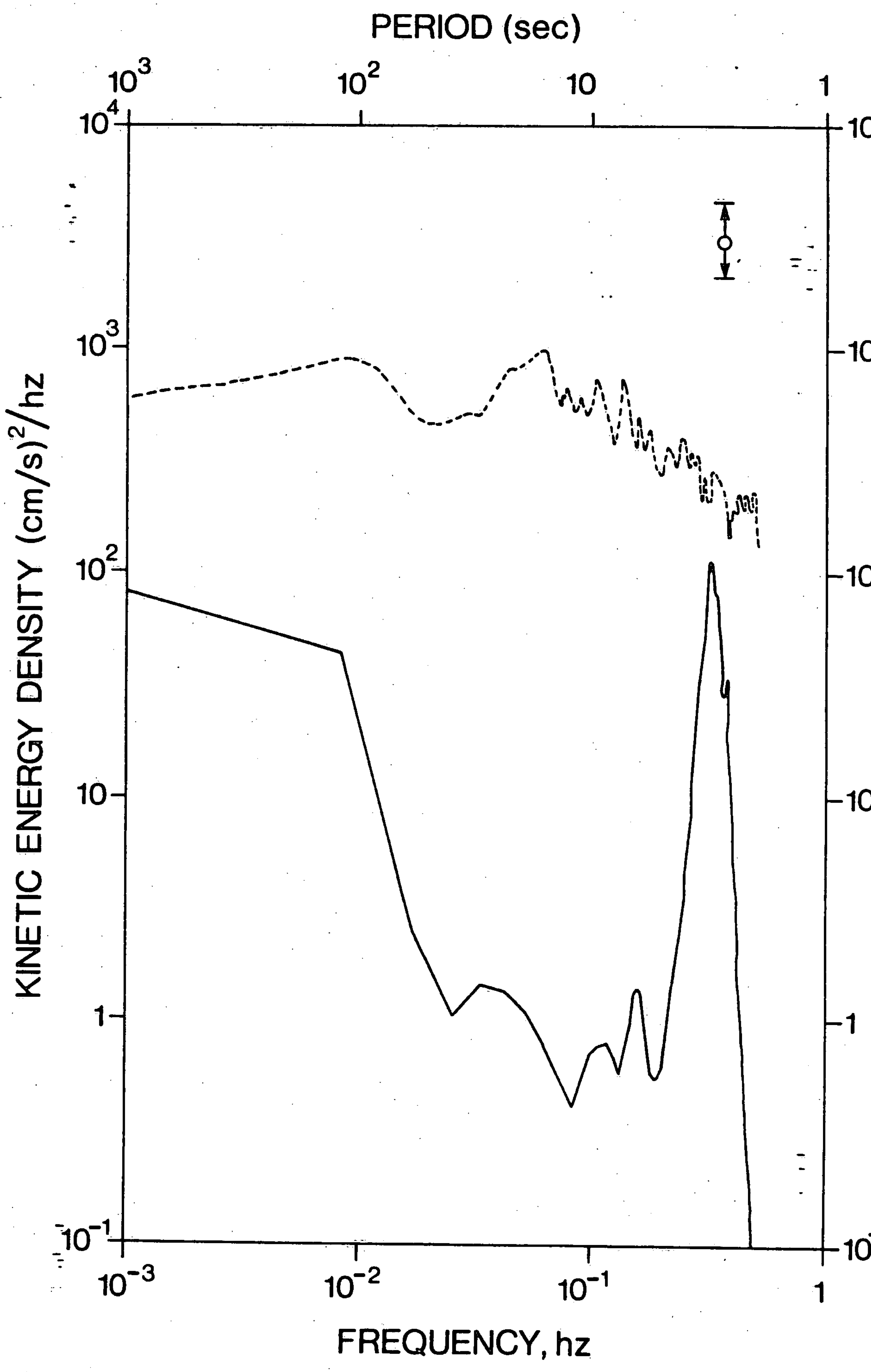
-10
TIME (min)



PERIOD (sec)
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10^2
10
1
10^4
10^3
10^2
10
1
10^-1
KINETIC ENERGY DENSITY (cm/s)^2/hz
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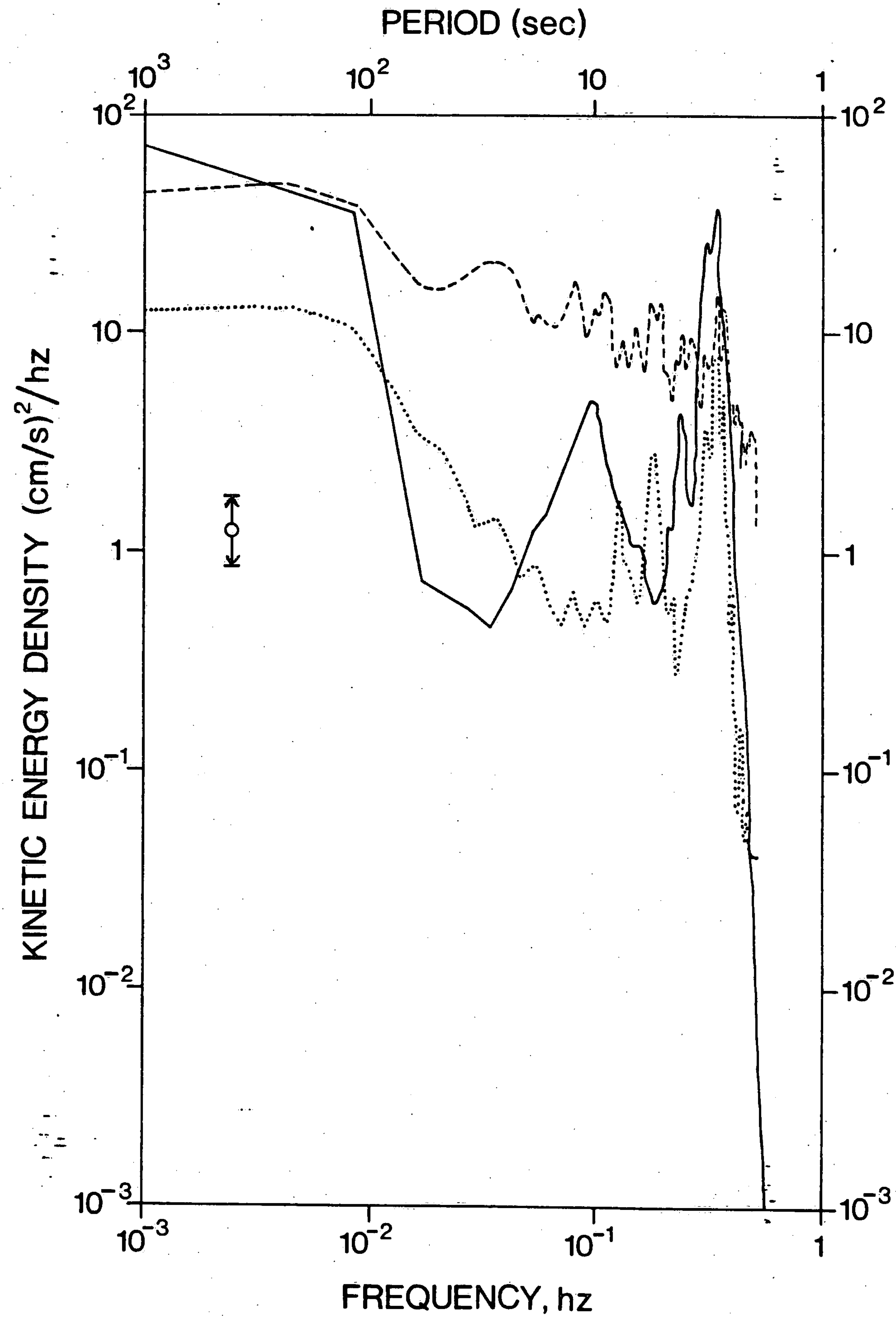
10^-2
10^-1
1
FREQUENCY, hz

Fig 5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10
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10^{-1}
10^{-2}
10^{-3}
KINETIC ENERGY DENSITY $(cm/s)^2/hz$
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10^{-2}
10^{-1}
1
FREQUENCY, hz