I.O.S.

INTERCOMPARISON OF CURRENT METERS IN FAST TIDAL CURRENTS

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REPORT NO 94

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INSTITUTE OF OCEANOGRAPHIC SCIENCES

NATURAL ENVIRONMENT RESEARCH COUNCIL

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ABSTRACT

Six Aanderaa and three vector averaging current meters were deployed for one month in water 45m deep where the M2 tidal current had an amplitude of 0.8 m/s. The mean flow was less than 0.04 m/s but there were two storm surges with currents up to 0.15 m/s. There was good agreement between the meters for tidal and surge currents and in the main for low frequency currents, but an Aanderaa and an AMF VACM with rotors 1.5m apart showed poor agreement for low frequency currents in the direction perpendicular to the tidal flow.

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1. INTRODUCTION

Recording current meters are fundamental to observations of the dynamics of the seas. Since there is no absolute check that the meters function accurately, confidence in them is gained by comparing different types of meter or measuring system in as many different environments as possible. Summaries of several inter-comparisons are given in HALPERN (1977). However, the inter-comparisons mentioned in shelf seas, for instance HALPERN, PILLSBURY & SMITH (1974) and BEARDSLEY, BOICOURT, HUFF & SCOTT (1977) were from regions of weak tidal currents, where the residual was of the order of the tidal flow, and the maximum measured currents were about 0.5 m/s. For most of the European shelf seas tidal currents are strong - up to 2 m/s and even higher in localized areas - and residuals are weak - usually mean currents less than 0.05 m/s but with faster currents on a 2-5 day scale (storm driven). In addition, recent intercomparisons have concentrated on the important, but difficult to measure, near surface layers, QUADFASEL & SCHOTT (1979), whilst many observations have been taken at mid-depth for determining tidal currents and circulation patterns. Two previous intercomparisons of meters at mid-depth in strong tidal currents are RAMSTER & HOWARTH (1975) and BOOTH, HOWARTH, DURRANCE & SIMPSON (1978), where good agreement was found in general for both tidal currents and long term means as observed by Plessey and Aanderaa recording current meters. These two types of current meter have similar designs and sampling schemes but different speed sensors (an impeller and a rotor). In this paper the results from American Machine and Foundry Inc. vector averaging current meters (henceforth referred to as AMF VACM) and Aanderaa RCM4s are compared. These meters have different designs.

The Aanderaa counts the number of revolutions of a rotor over the sample interval and records an instantaneous direction with the meter aligned to the flow by a large vane. The AMF VACM computes the vector average of the current over its sample interval by measuring the current direction with a small vane every one eighth of a revolution of its rotor, calculating the east and north components and summing them. The AMF VACM scheme reduces aliassing from high frequency horizontal currents, for instance from surface gravity waves or mooring motion, (for instance, QUADFASEL & SCHOTT, 1979). The meters were deployed at about mid-depth in water 45m deep. The area has a reasonably flat bottom topography with depths varying between 39 and 45m below chart datum. The M2 tidal current had an amplitude of 0.8 m/s and the mean current was less than 0.04 m/s. The period of observations included some quite stormy weather - leading to surges of over 1m at Liverpool. Section 2 contains the details of the experiment, the data returns, and the mooring performance, section 3 a comparison of tidal currents and section 4 a comparison of residual currents.

2a. EXPERIMENT

A comparison between Lagrangian and Eulerian current measurements took place in October and November 1977 in the Eastern Irish Sea, between Anglesey and the Isle of Man, BOOTH (1978). The Eulerian measurements were made by 6 Aanderaa RCM4s (all fitted with pressure sensors) and by 3 AMF VACMs deployed on four rigs (A,B,C,D) for a month with a minimum rig separation of 9km and a maximum of 20km (Figure 1 and Table 1). On rigs A, B and C an AMF VACM was moored immediately above an Aanderaa at mid-water depth, their rotors being 1.5m apart (see Figure 2 for the mooring configuration). The subsurface buoy was about 12m below the lowest sea level. At rig D there were three Aanderaa meters covering the bottom half of the water column and a bottom mounted pressure recorder.

Neap tides were on 21 October, 5, 19 November and 5 December and spring tides 27 October, 13, 26 November and 12 December. The period was generally windy, Figure 3, with the storms on November 11 and 14 leading to 1.4m and 1.5m surges at Liverpool, HEAPS & JONES (1979).

2b. DATA RETURN

The meters recorded scans every 15 minutes. The longest record (longer than planned, since the meter was not recovered normally but after 3 months was washed ashore attached to its subsurface buoy) was returned from A by the AMF VACM, from 18 October to 14 December - 57 days, but unfortunately the Aanderaa was not recovered. The record was 6 scans short; the time of 5 of the missing scans was determined from the time channel and the records interpolated, but it was not obvious precisely when the remaining scan had been omitted. The AMF VACM at rig B returned only 25 days of good data since on 13 November its compass worked loose and thereafter the directions were unreliable. The Aanderaa meters at rigs B and D returned full length records of good data, as did the pressure recorder at D (these data are displayed in ALCOCK & HOWARTH (1978)). No data from rig C has been used in this paper since the AMF VACM rotor was sticking at low speeds and the Aanderaa meter had become tangled during deployment.

Hence, there was a 62% return of good data with meter faults accounting for 15%, meter losses 11% and faulty deployment 11%. This is a disappointing data return and below what is usually obtained. It meant that a detailed comparison could be made for only one rig, B, and that for 25 days data which is shorter than the convenient 29 days for tidal analysis.

Calibrations were applied to the data which was then edited and filtered to provide hourly values on the hour.

2c. MOORING PERFORMANCE

The AMF VACM was mounted directly into the wire, and hence, if the wire was not vertical, the meter would underestimate speeds, whereas the Aanderaa's spindle was gimballed such that the meter's balance was unaffected by wire angles less than 27°. The low frequency movement of the rig was calculated by subtracting from the Aanderaa's pressure record the tides, as observed by the bottom pressure gauge at D. (ROBINSON's (1979) M2 cotidal map (his Figure 7) indicates that the elevation tide at rig D was a good approximation to that at rig B, with regard to the crudeness of the current meter pressure measurement). The maximum depression of the meter, about 6m, occurred during the spring tides of 13 November when the current was 1.4 m/s. A computer simulation of the mooring also gave a depression of 6m for this current and wire angles of 22° at the AMF VACM and of 35° at the Aanderaa (just greater than its limit). The simulation was run for various speeds and a parabola was fitted, with very little error, to a plot of wire angle at the AMF VACM v. surface current speed:-

$$\text{Angle (in degrees)} = 10 \times (\text{Surface current in m/s})^2 \qquad (1)$$

Assuming a cosine response to tilt for the AMF VACM rotor, its maximum speed error would have been 7%. However only 7% of the Aanderaa currents exceeded 1 m/s, with a corresponding AMF VACM speed error of 2%, and only 1% exceeded 1.2 m/s, with a corresponding error of 4%. This method will probably underestimate the correction since rotors do not have a perfect cosine response (SERKIN & KRONENGOLD, 1974). Again, suppose there is a sinusoidal oscillating tidal current, that the wire angle is proportional to the square of the speed and that a cosine speed correction is valid. Then the recorded amplitude at the frequency of oscillation will be reduced and odd harmonics generated. Unless otherwise stated neither of the meters have been corrected for rotor tilt (the correction for the Aanderaa would have been very small). How the vane is affected by the meter's tilt is uncertain but the error is likely to be small since the current speed is high when the tilt angle is large.

3. TIDAL CURRENTS

Scatter plots of the hourly currents recorded at rig B show that the ebb and flood were not precisely in opposite directions (Figure 4, note that the north components have been magnified by a factor of five.) Separate least squares fits to the ebb and flood currents gave a difference of 5.4^{o} for the AMF VACM and of 4.3^{o} for the Aanderaa. However, the AMF VACM plot has a step like pattern and so just the peak flood and ebb currents for each tidal cycle were studied. This time the difference for the Aanderaa record was 0.7^{o}, in the opposite sense, and for the AMF VACM record was 3.3^{o} at neaps and 1.2^{o} at springs. These differences are important since they imply residual currents perpendicular to the tidal flow and so it is important to determine whether they are real or whether they have been generated by the meters or their mooring.

GOULD (1973) has shown how a non-linear response in the compass will lead to erroneous residuals, as will be shown below, if the compasses are not correctly calibrated. The Aanderaa compass has a resolution of $1/3^{o}$ and was calibrated with the meter in its case, in the open air, away from the magnetic effect of buildings, every 10^{o} both before and after the cruise. The calibration before the cruise was applied to obtain the results in this paper and is shown in Figure 5. The differences between the two calibrations had zero mean, a standard deviation of 0.5^{o} and, in the directions of the tidal flow. the maximum difference was 0.7^{o}. The AMF VACM compass has a resolution of 2.8^{o} and can only be calibrated inside a building with the meter out of its case. Hence it is more likely that the calibrated AMF VACM compass was still non-linear than the Aanderaa compass.

There is scope for speculation as to how mooring interactions could contribute to the differences, both for the Aanderaa meter with its large vane aligned to the flow, and for the AMF VACM since it is an integral part of the meter wire. Perhaps, the pattern of the AMF VACM scatter diagram is caused by such an interaction, since the current direction changes for high speeds (above 1 m/s). It is more pronounced for the flood than the ebb since both meters recorded faster flood currents.

As to the differences being real; in the region where the measurements were taken the tides are subject to horizontal gradients. The region lies between a north/south flow in the western Irish Sea and an east/west flow in Liverpool Bay. At D and A the tidal directions were 10^{o} anti-clockwise relative to B and further south of B they have been measured clockwise relative to B. Differences in the directions of ebb and flood of between 2^{o} and 4^{o} in the same sense were calculated from the records from D for the same period. Hence, from the other observations and because the meters at B were similar overall it is probable that the ebb and flood currents were not in opposite directions and possible that the AMF VACM had some added instrumental non-linearities.

What will be the effect on the analysis of the records?

Consider a direction $\overrightarrow{AB}$ and a sinusoidal current with speed $S \sin \sigma t$. Suppose for $0 < t \leqslant \frac{\pi}{\sigma}$ the current direction is θ anticlockwise relative to $\overrightarrow{AB}$ and for $\frac{\pi}{\sigma} < t \leqslant \frac{2\pi}{\sigma}$ it is θ clockwise relative to $\overrightarrow{BA}$. Then the components of the current are

$u = S \sin \sigma t \cos \theta$ in the direction of $\overrightarrow{AB}$

$v = S |\sin \sigma t| \sin \theta$ in the direction perpendicular to $\overrightarrow{AB}$

v can be expanded as a Fourier series.

$$v = \frac{S \sin \theta}{\pi} \left[2 + \sum_{n=1}^{\infty} \frac{4}{1-4n^2} \cos 2n\sigma t \right]$$

Therefore, in the direction perpendicular to the principal axis of the current a mean current and even harmonics have been generated. For a tidal current of 1 m/s and a direction difference of 1° (it is difficult to calibrate the compass more accurately than this) the generated mean is 0.005 m/s - of the order of observed residuals. In general, if the tidal regime is approximately rectilinear, the record perpendicular to the principal axis will be sensitive to small differences and meter errors and may well be dominated by them.

Each component of the two 25 day records from rig B was harmonically analysed by a least squares method to find the amplitudes and phases of 27 major and 7 related constituents. (The relationships were derived from the average of analyses from three neighbouring coastal gauges of a year's elevation records). The results were then synthesized to give current ellipses for each constituent.

Table 2 contains some of the more important constituents from the Aanderaa's analysis, with standard errors estimated from the residual spectrum. The tide was semi-diurnal, with rectilinear flows in the east-west direction, parallel to the topography.

Comparison with the results from the pressure recorder at D showed a phase difference of between 80 & 100 degrees for all species from diurnal to sixth diurnal (apart from the third diurnal). Hence the tidal wave was standing and did not transmit energy. The ratios of current to elevation amplitude were similar for the constituents in each species but differed from species to species; the ratios would have been the same if the tidal wave was progressive, which was not the case here (ROBINSON, 1979).

Table 3 shows an excellent agreement in amplitude, phase and direction for the tidal analyses of the Aanderaa and AMF VACM data. Since all the constituents were nearly rectilinear it is not important that the two meters differed in the sense of rotation of some of the ellipses. The good agreement at MM and MSF (periods of a month and a fortnight) does not imply accurate determination of their amplitudes and phases, impossible in records of 25 days length, only that both meters recorded similar data at these low frequencies. The AMF VACM recorded slightly weaker semi-diurnals, particularly S2, consistent with the mooring motion referred to earlier. For the fourth diurnals the AMF VACM also recorded weaker currents. Agreement was least good for the sixth diurnals where the AMF VACM ellipses were fatter, eccentricities of the order of 0.3 compared with 0.06, and there were appreciable phase differences. (This AMF VACM analysis disagrees with that in BOOTH (1978) which showed some diurnals larger by a factor of five. The results are now more consistent with the analyses for the pressure recorder and for the meter at A).

The AMF VACM record was corrected for wire angle by equation 1, assuming a cosine response, and re-analysed. There was a 1%

increase in the semi-diurnal amplitudes and a 7^{o} increase in the phase of the sixth diurnals. So, as predicted, the alterations were in the odd harmonics of the dominant frequency and although with the right sign were insufficient to eradicate the differences with the Aanderaa meter. This shows the difficulty in correcting for wire angle once it has occurred, even though the meter recorded pressure.

The pattern described above was also indicated in the analyses of the meters at D and A although, because of the distances and gradients involved, close comparison was not possible. The differences at the fourth and sixth diurnals could have contributions from mechanisms already mentioned. For the fourth diurnals it was the difference in directions which also showed in the analysis of the north component of each meter relative to its east component. For the sixth it was the effect of mooring displacement.

The clockwise and anti-clockwise spectra were calculated for the residuals (hourly values of observations minus the calculated tide) for each meter. The total spectra are shown in Figure 6. As expected from previous comparisons there was less energy at high frequencies in the AMF VACM record (for periods less than 4 hours). There were peaks at the 8th and 10th diurnals since these were not considered in the analysis. The higher AMF VACM peak for the 8th diurnal could be related to the greater degree of AMF VACM direction distortion. The total residual variance of the AMF VACM was 0.00139 $(m/s)^2$ which was 20% less than the Aanderaa at 0.00168 $(m/s)^2$. This is demonstrated in Figure 4. where the AMF VACM plot is narrower, with less scatter.

4. RESIDUALS RECORDED BY THE METERS AT B

The data were reduced to 19 daily values for each meter at rig B by a low pass filter with cut-off between 0.0139 and 0.0347 cph and a cut-off frequency of 0.0241 cph. These values are plotted as progressive vector diagrams in Figure 7 and the velocity difference (Aanderaa minus AMF VACM) tabulated in Table 4. Both show that there was little difference between the two east components, but a large mean difference in the north components. The standard deviations of the differences of the two components were of the same order.

The difference in the overall residuals of 67° over a distance of 1.5 metres was unlikely to be real but probably stemmed from the operation of the meters. The main difference was in the component perpendicular to the tidal stream implying an error in the direction measurement spuriously transferrring energy from surface waves or tides into the residuals.

No direct measurements of waves were taken during the experiment but the wind data from Dublin, Ronaldsway, Squires Gate, Valley and Bidston have been inspected (Figure 3). These show that the period was fairly windy with three noticeable blows, 22-24 October, 29-30 October (both from the south) and 3-9 November from the south west. The AMF VACM unfortunately stopped recording during a bigger storm on 11-15 November. For each of the three windy periods the average wind speed was between 12 and 15 m/s with peaks up to 20 m/s. The first two blows were fetch limited at rig B but the third was not. It should have created waves of about 4m height, with orbital velocities of the order of 0.4 m/s at the meters and about twice this at the sub-surface buoy. (Wave height and period have been deduced from observations at the Morecambe Bay Light Vessel reported by DARBYSHIRE, 1958). The orbital velocities at the sub-surface buoy are important since the motion of the buoy is transmitted down the wire to the meters (HALPERN & PILLSBURY, 1976).

Confirmation of the times of wave action was obtained from the AMF VACM record by subtracting the vector mean speed over a sample interval from the scalar speed. In high tidal flows oscillating currents due to waves are important only near slack water. As expected the difference was zero for peak flow for the whole record but at slack water differences were recorded which correlated well with wind speed and direction, Figure 8. For the three stormy periods hourly differences of about 0.08 m/s were observed with a maximum difference of 0.15 m/s. The meter at A recorded a similar picture. The differences were somewhat less than expected (orbital speeds of 0.4 m/s with no mean current should return an average of 0.25 m/s) since the tidal current was never zero.

It is at the times of significant wave action that the differences between the Aanderaa and AMF VACM meters should be greatest, since the recording scheme of the AMF VACM is designed to record the mean current correctly in the present of wave oscillations whereas the Aanderaa should not. (See for instance BEARDSLEY, BOICOURT, HUFF & SCOTT (1977) where an Aanderaa recorded significantly higher residual speeds than an AMF VACM during wave action.) An indication that waves affected the Aanderaa is shown in the scatter plot of the 15 minute data, ALCOCK & HOWARTH (1978), where at the centre is a hole of radius 0.07 m/s, greater than the threshold speed of the meter. It should be noted that both meters measure speed with a rotor which is subject to errors in accelerating and decelerating flows (KARWEIT, 1974). However, the correlation between the wave indicators and the difference in residual flow was slight. In particular, for the stormy period 3-9 November when the biggest waves were generated, the differences were smallest.

Could the differences have a tidal origin? In studies of low frequency motion the most obvious tidal contribution will have the period of the spring/neap cycle - a fortnight. If the variations were proportional to the current speed, a conservative assumption for some of the errors, the magnitude variation over the cycle should be by a factor of two. No such variation is obvious in Table 4. Moreover, consider the neap tides on 21 October and 5 November, both windy periods, with peak currents about 0.7 m/s and 0.5 m/s respectively. The residual differences were about twice as large around the earlier date compared with the later. Hence, there is no clear correlation between either surface waves or tides and the difference in residual directions. The difference must be related to the direction differences noted in the section on tidal currents.

Another method of obtaining residuals is to calculate the tidal currents for the period, from the analyses, and subtract them from the observations, in this case giving 600 hourly values, from 19 October until 12 November. There were no significant differences between the residuals from the uncorrected AMF VACM record and that corrected for wire angle. The mean difference between the Aanderaa and the AMF VACM was again -0.016 for the north component and 0.001 for the east component, both for the 25 day period and the 19 day period for which filtered values were calculated.

Advantages of the tidal prediction method are that there are more estimates of residual current and also variations within a semi-diurnal cycle can be studied. A straight line was fitted to the residuals in m/s for each component, giving

East : AMF VACM = 0.93 x (Aanderaa) -0.002

North : AMF VACM = 0.37 x (Aanderaa) +0.005

The correlation coefficients were 0.94 for the east component and 0.48 for the north. This shows excellent agreement in the direction of tidal flow and poor agreement perpendicular to it, with the AMF VACM recording much smaller residual speeds. The east component residuals have a slightly greater standard deviation than the north (for the AMF VACM 0.032 and 0.020 m/s and for the Aanderaa 0.032 and 0.026 m/s), showing that the residuals were more variable parallel to the topography. The scatter in the north component differences was uniform throughout the tidal cycle (it was not greater at slack water or high currents) and also was not correlated with stormy periods.

So, for the residual currents recorded by the meters at B, there was excellent agreement in the direction of tidal flow and no agreement perpendicular to it.

4b. RESIDUALS RECORDED BY ALL THE METERS

The filtered residuals from all the meters for the period 22 October to 22 November form two distinct patterns. The first is, possibly, a clockwise gyre, a pattern consistent with depth mean currents computed from the September/October 1972 density field by a 3-dimensional numerical model, HEAPS & JONES (1977), and perhaps supported by the results from two drogue buoys, BOOTH (1978). This hypothesis is tentative. For the second pattern, however, the meters agreed very well on a residual westward flow. The spread in direction for all meters was 45° and for those at the same level was 25°. (The AMF VACM at B was by then not recording good data). The big difference occurred in the speeds, but with the AMF VACM at rig A giving an estimate between that from the Aanderaas at D and B, there is no clear difference between the meter types. The change from one pattern to the other is clearly defined for the meter at A and the top two meters at D, between 11 and 12 November, but for the bottom meter at D it took 3 days from 11 until 15 November and for the Aanderaa at B it was a gradual change from 10 to 17 November. The mean residuals for 22 October to 11 November and 12 to 22 November are in Table 5.

Storm surges occurred on November 11/12 and 14/15 and Figure 9 shows the filtered residuals for this. A 2 dimensional numerical model simulation for the period, HEAPS & JONES (1979), showed that the meters were situated where the surge currents were relatively weak (their Figure 26). This is confirmed by the observations, with a maximum daily speed of less than 0.1 m/s. The depth mean residuals from the model position closest to D have been plotted for comparison. The good agreement between meter types and between meters and model is apparent, though falling off on 16 and 17, when the winds were weaker. The surges were mainly in the east/west direction and the agreement in amplitude is shown by taking the difference between the eastward surge on 11 and westard surge on 15. This varied between 0.103 m/s at B and 0.085 m/s at A, with the meter at D and the model in close agreement with A. (The comparison between meters and numerical model is reported in more detail in HOWARTH & JONES, in preparation).

Considering the surges from the hourly, tidal, residuals all the meters agreed well on the timing of the peak flows - spot on on 11 and within two hours on 14/15. The currents for the first surge lasted less than 12 hours and the peak eastward flows agreed well - 0.140 m/s from the Aanderaa at B and 0.127 m/s from the AMF VACM at B, with the meter at A and the top meter at D lying in between. The north components were varied but considerably weaker. Similar comments apply to the westward surge on 14/15, where the currents were slightly faster.

The residual currents from all the meters agreed well for the second half of the experiment. The agreement between meters was also good for the variations during the surge period. This is encouraging since the surge currents were not very large and the weather was stormy. The biggest difference occurred in the component perpendicular to tide and surge, as was expected.

CONCLUSIONS

Month long records from 2 AMF VACM and 4 Aanderaa RCM4s were obtained in a shallow sea with strong rectilinear tidal currents. During this period there were also two storm surges with currents in the same direction as the tidal flow. The records from one AMF VACM and one Aanderaa RCM4, deployed 1.5m apart, were compared in detail for a 25 day period and it is a pity that, because of data loss, two other similar comparisons could not have been made. There was good agreement for tidal currents for the main constituents but small differences arose for the higher frequency constituents which were probably caused by meter and mooring malfunctions. Surge and overall residual currents from all the meters agreed well in general, apart from a difference between two meters 1.5m apart which implied a fault which would not have been obvious if only one meter had been deployed. For the two meters there was good agreement for residual currents measured in the direction of tide and surge propagation. However, in the direction perpendicular to tidal flow the residuals were not only more scattered, with the AMF VACM recording weaker residuals as expected, but there was a systematic difference which can, perhaps, be ascribed to the AMF VACM, either through a fault in its compass or because it was mounted directly into the wire and experienced significant wire angles. This shows the difficulty in measuring circulation since, for residuals in the direction perpendicular to rectilinear tidal flow, small errors can produce spurious residuals which will swamp the correct values, even when measured by more sophisticated meters.

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Rig	Latitude N	Longitude W	Water depth below chart datum (m)	Height of meter above sea floor (m)	Good data span (h)	Meter type	Date meter deployed	Date meter recovered
A	$53^{\circ}43.1'$	$4^{\circ}13.6'$	42	22.5	1371	AMF VACM	18/10/77	10/1/78
				21	0	Aanderaa	18/10/77	-
B	$53^{\circ}35.3'$	$4^{\circ}\ 5.5'$	44	23.5	620	AMF VACM	18/10/77	28/11/78
				22	983	Aanderaa	18/10/77	28/11/78
C	$53^{\circ}43.0'$	$3^{\circ}59.1'$	39	20.5	0	AMF VACM	18/10/77	25/11/78
						Aanderaa	18/10/77	25/11/78
D	$53^{\circ}45.8'$	$4^{\circ}\ 7.0'$	42	22	932	Aanderaa	17/10/77	25/11/78
				16	932	Aanderaa	17/10/77	25/11/78
				8	932	Aanderaa	17/10/77	25/11/78
				0	932	Pressure recorder	17/10/77	25/11/78

Table 1. Positions and times of the current meters records.

Constituent	Max. Amp M/S	Min. Amp M/S	s.e. of amp. M/S	Direction of max. current	Phase of max. current	s.e. of phase	Pressure at D Amplitude mb	Pressure at D Phase
MM	0.012	0.005		340.0	194.3			
MSF	0.013	0.004		97.2	174.2			
O1	0.017	0.001	0.003	90.3	323.4	9	10.7	46.4
K1	0.018	0.006	0.003	92.9	107.4	9	9.5	201.0
2N2	0.027	0.000	0.003	96.9	174.7	6	8.1	260.9
N2	0.149	0.002	0.003	96.8	211.4	1.0	44.5	294.2
M2	0.792	0.013	0.003	94.3	234.9	0.2	237.4	317.2
S2	0.264	0.003	0.003	94.6	278.1	0.6	74.5	356.0
M3	0.010	0.002	0.002	107.8	203.4	9	2.0	274.6
MN4	0.028	0.003	0.002	82.4	98.4	4	2.8	185.9
M4	0.060	0.005	0.002	80.5	112.2	2	6.3	200.9
MS4	0.035	0.004	0.002	79.9	147.2	3	3.7	235.3
2MN6	0.011	0.001	0.001	96.4	245.4	6	0.2	333.2
M6	0.013	0.001	0.001	102.1	248.3	5	0.6	354.0
2MS6	0.015	0.001	0.001	101.6	277.2	5	0.6	27.0

Table 2. Analysis of 25 days of Aanderaa record and of the pressure record from D
Standard errors have been calculated from the residual spectrum.

Constituent	Max amp Ratio	Min amp Ratio	Difference in direction of max currents	Difference in phase of max currents	Sense of Rotation
MM	1.0	1.0	-4.7	-13.5	A
MSF	1.2	1.3	0.3	- 1.1	A
O1	1.1	0.0	-0.4	- 1.7	D
K1	1.0	0.3	7.5	2.1	C
2N2	1.0		0.1	0.0	D
N2	0.97	1.5	0.2	0.0	D
M2	0.98	1.0	1.5	- 0.6	C
S2	0.95	1.7	2.9	- 0.2	C
M3	1.1	1.5	-0.3	- 2.1	A
MN4	0.89	0.7	-4.3	5.2	A
M4	0.93	0.8	-1.3	0.2	C
MS4	0.86	1.0	1.9	1.3	C
2MN6	0.6	2.0	7.5	-29.3	C
M6	1.1	4.0	5.9	-24.2	D
2MS6	1.1	5.0	-7.6	-40.3	D

Table 3. Comparison of AMF VACM and Aanderaa tidal current analyses. Ratios are AMF VACM ÷ Aanderaa; differences are AMF VACM - Aanderaa.
A = Anticlockwise; C = Clockwise;
D = Differerent senses of rotation.

Date	North Component m/s	East Component m/s
22/10/77	-0.021	-0.001
23	-0.026	-0.005
24	-0.018	0.005
25	-0.021	0.008
26	-0.016	0.006
27	-0.019	-0.001
28	-0.017	0.011
29	-0.010	0.004
30	-0.019	0.006
31	-0.014	0.001
1/11/77	-0.021	0.000
2	-0.013	-0.001
3	-0.013	-0.002
4	-0.010	-0.001
5	-0.012	0.000
6	-0.009	0.001
7	-0.014	-0.001
8	-0.024	-0.001
9	-0.011	0.003
Mean	-0.016	0.002
Standard Deviation	0.005	0.004
Aanderaa Mean	-0.011	-0.011
AMF VACM Mean	0.005	-0.012

Table 4. Difference between Aanderaa and AMF VACM low pass filtered values.

Rig	Meter type	Speed m/s	Direction
Period I			
A	AMF VACM	0.026	30
D top	Aanderaa	0.013	108
D middle	"	0.010	101
D bottom	"	0.018	145
B	AMF VACM *	0.013	293
B	Aanderaa	0.016	220
	* (22 October to 9 November)		
Period II			
A	AMF VACM	0.034	295
D top	Aanderaa	0.018	269
D middle	"	0.013	288
D bottom	"	0.012	250
B	"	0.051	280

Table 5. Overall means for 22 October to 11 November (Period I) and 12 November to 22 November (Period II)

Figure 1. Map of rig positions.

Figure 2. Mooring configuration of rig B.

Figure 3. Wind record from Valley, Anglesey for October and November, 1977.

Figure 4. Scatter plots of hourly values of current from rig B from 00.00 on 19 October to 23.00 on 12 November. a) AMF VACM : b) Aanderaa

Figure 5. Deviation from linear of pre-cruise compass calibrations for Aanderaa on rig B.

Figure 6. Power density spectra for residual currents from meters on rig B - AMF VACM: -- Aanderaa.

Figure 7. Progressive vector diagram of low pass filtered currents from meters on rig B.
—— AMF VACM: -- Aanderaa

Figure 8. Difference between hourly values of scalar and vector speeds recorded by the AMF VACM on rig B.

Figure 9. Low pass filtered residuals from 8 - 17 November, each relative to its mean for the period.
a) East component : b) North component.

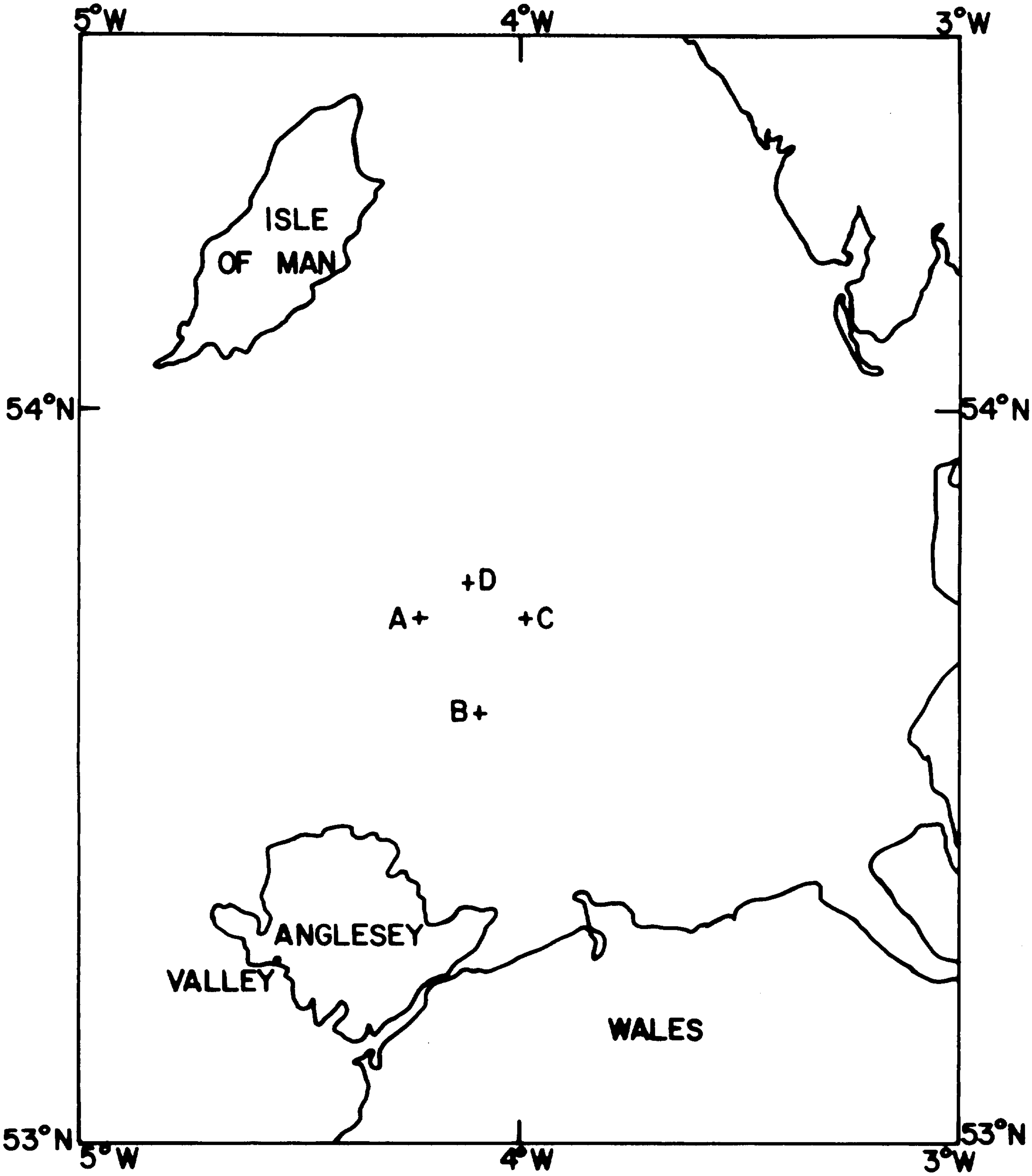

5°W
4°W
3°W
ISLE
OF MAN
54°N
54°N
+D
A+
+C
B+
ANGLESEY
VALLEY
WALES
53°N
53°N
5°W
4°W
3°W

FIGURE 1

MOORING CONFIGURATION

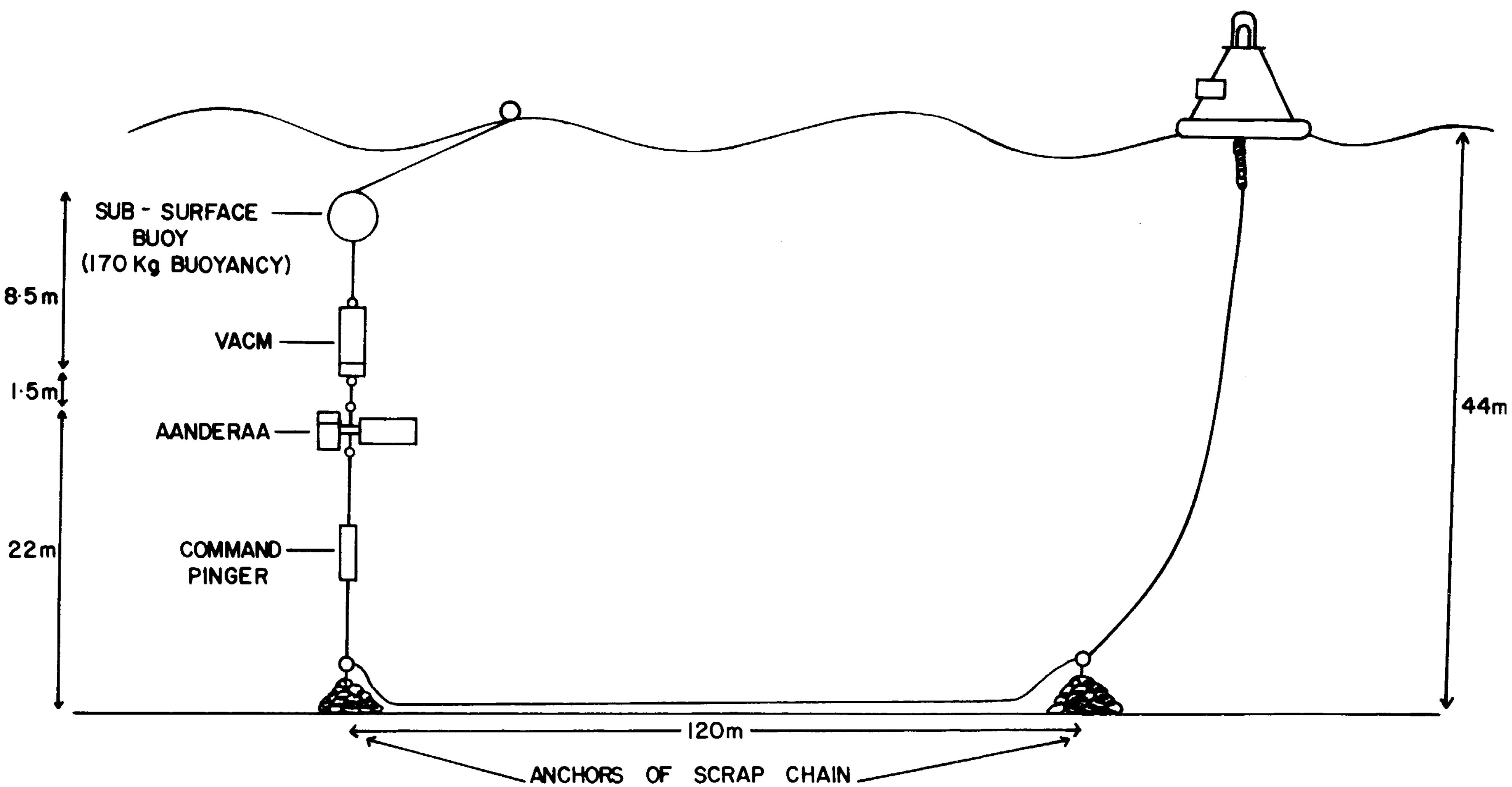


FIGURE 2

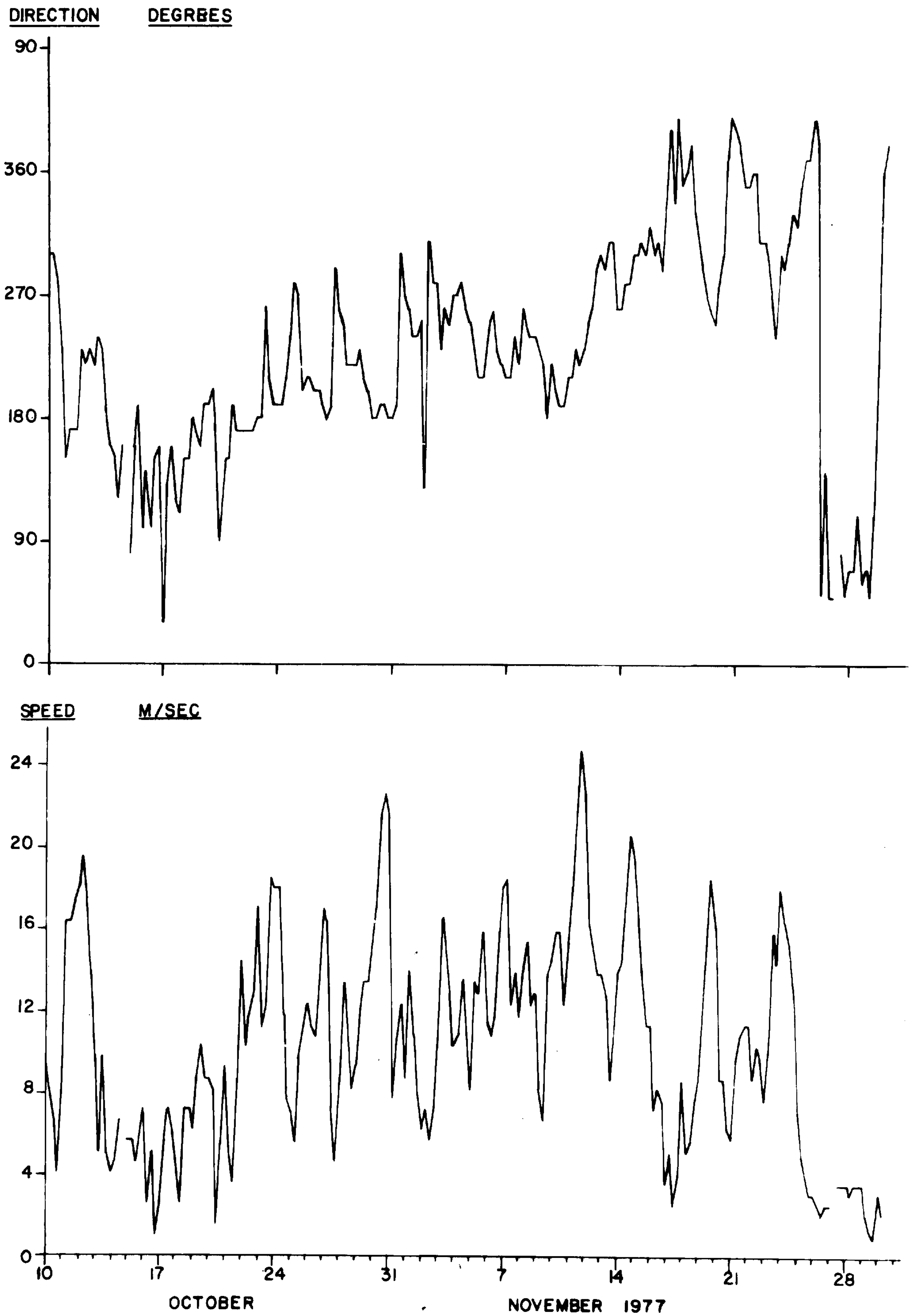

DIRECTION DEGRBES
90
360
270
180
90
0
SPEED M/SEC
24
20
16
12
8
4
0
10
17
24
31
7
14
21
28
OCTOBER
NOVEMBER 1977

FIGURE 3

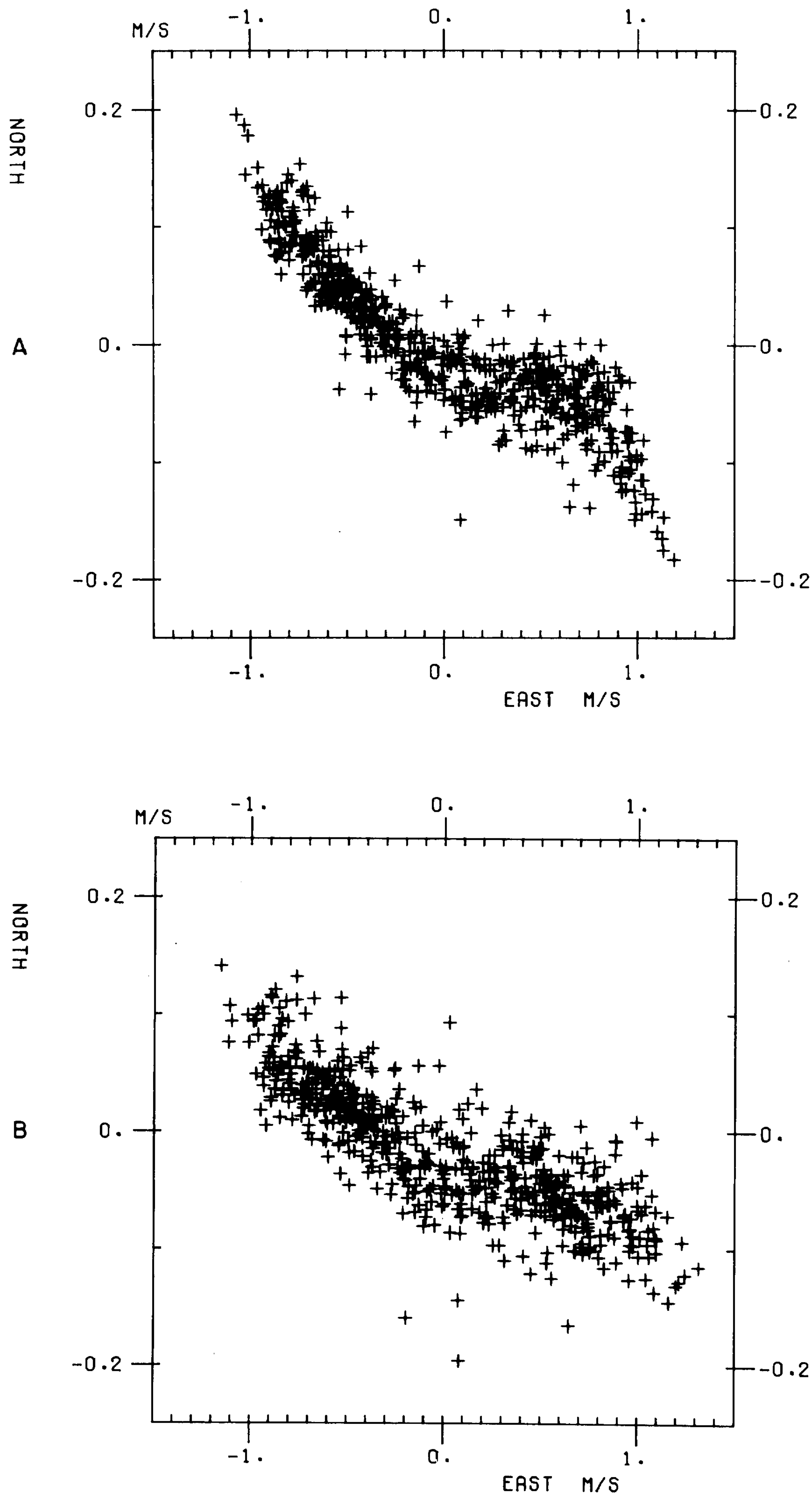


FIGURE 4

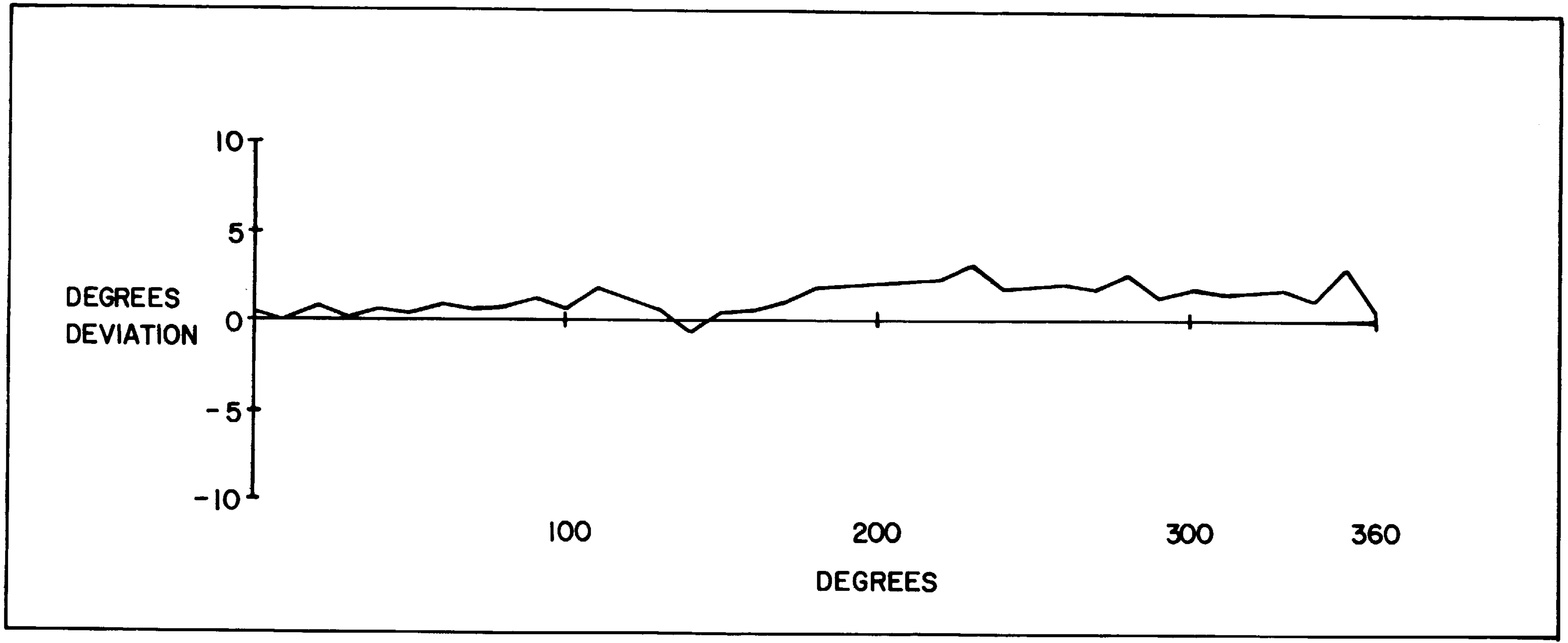
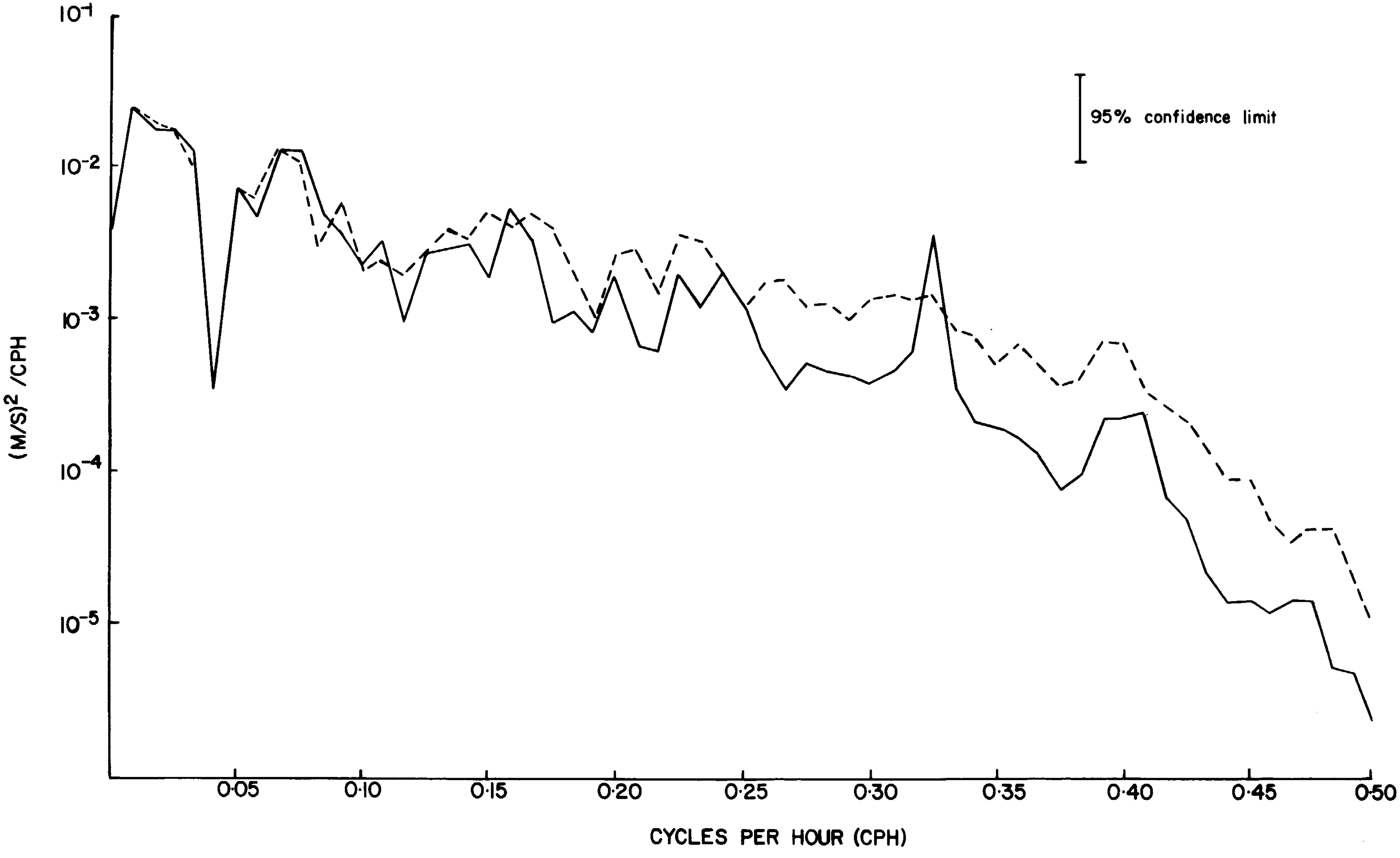


FIGURE 5



95% confidence limit
(M/S)^2 /CPH
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0·05
0·10
0·15
0·20
0·25
0·30
0·35
0·40
0·45
0·50
CYCLES PER HOUR (CPH)

FIGURE 6

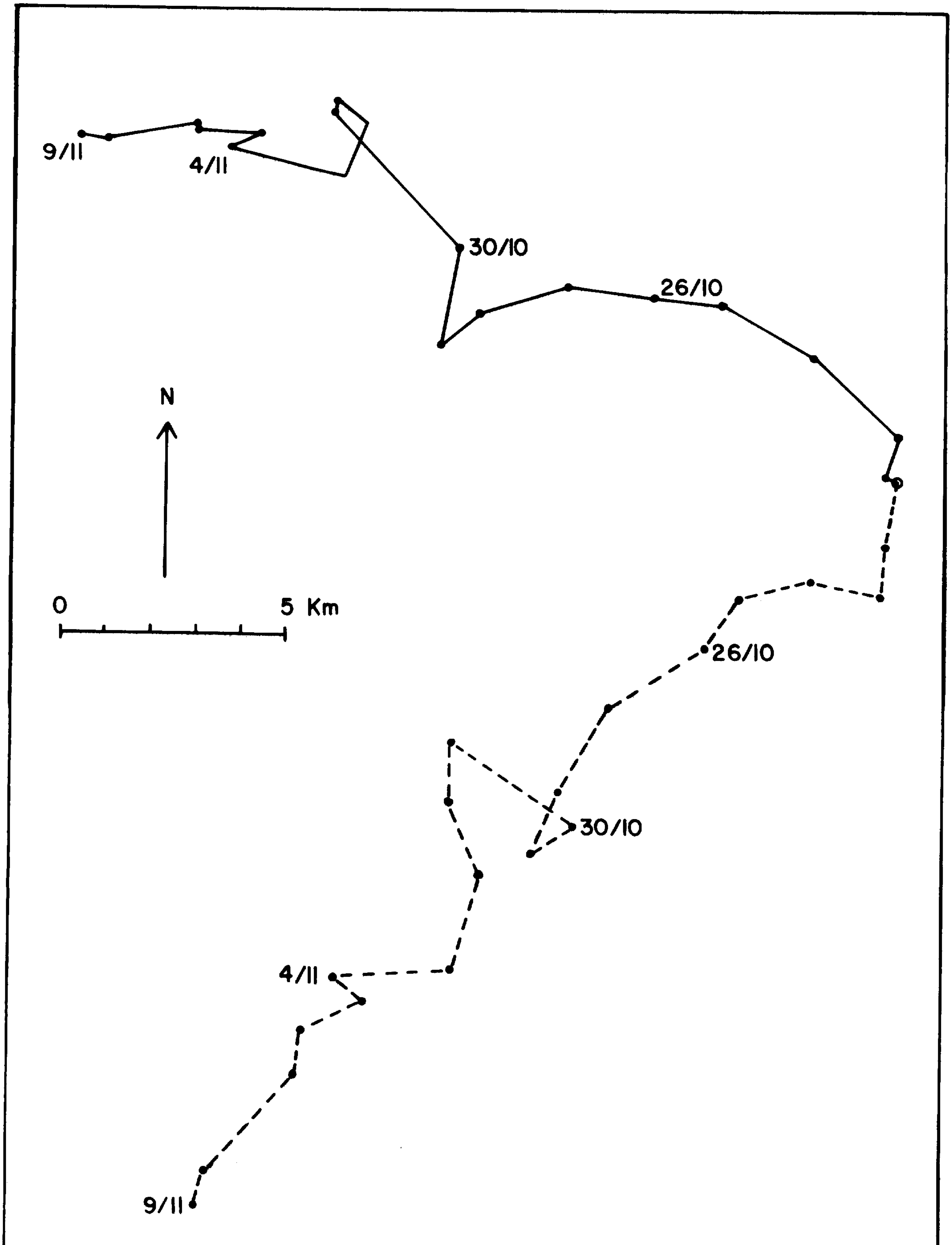


FIGURE 7

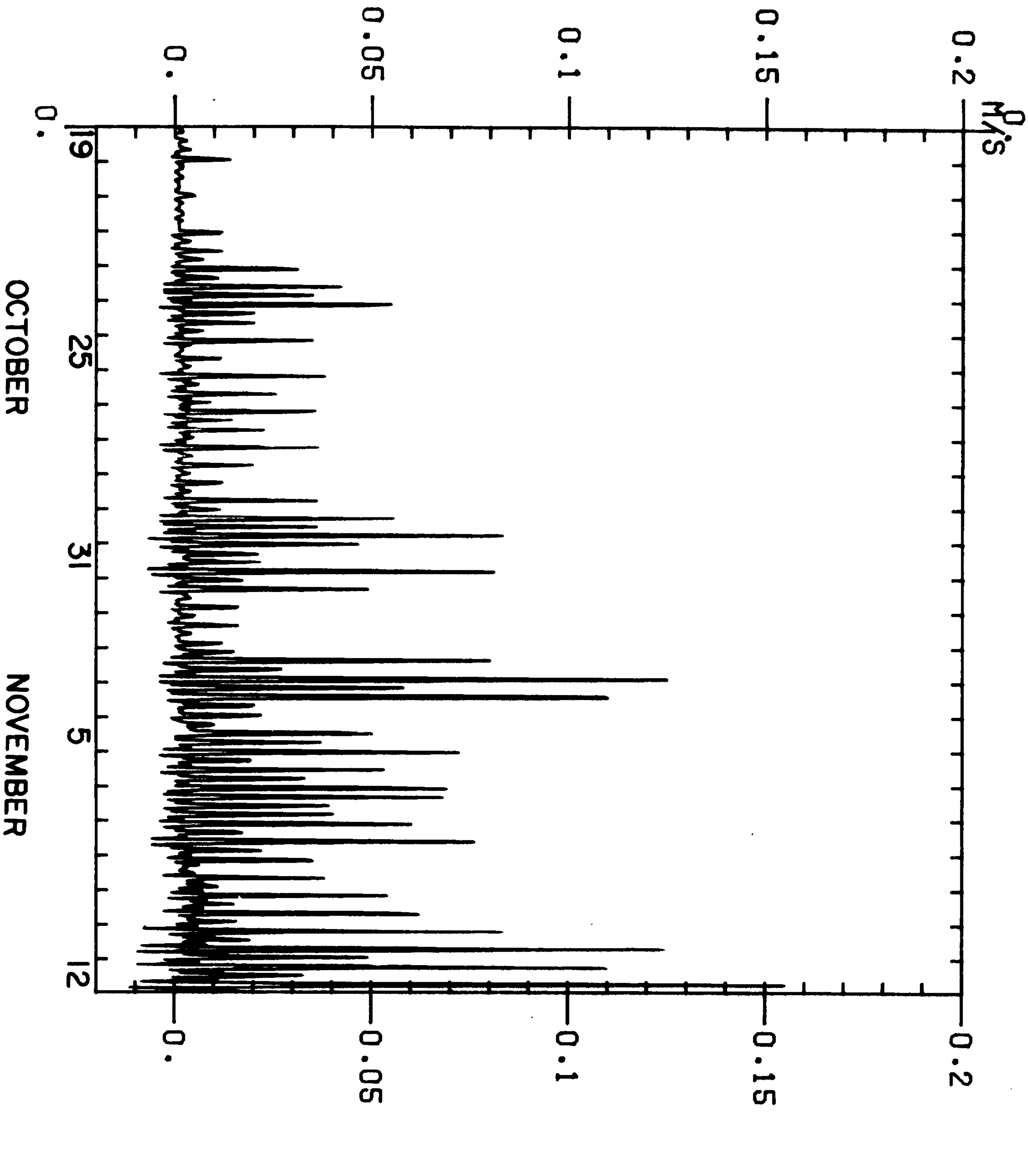


FIGURE 8

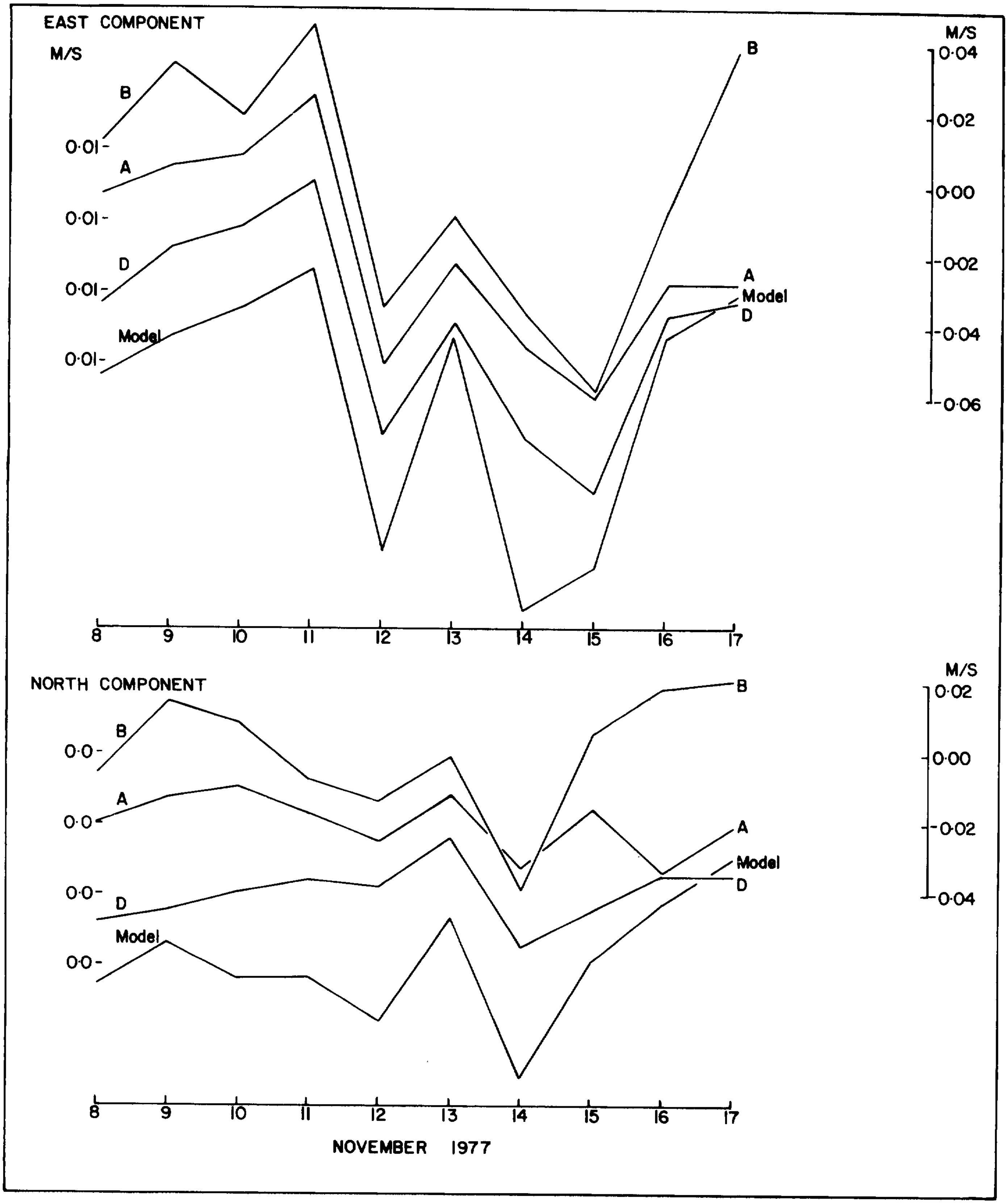

EAST COMPONENT
M/S
B
A
D
Model
0·01-
0·01-
0·01-
0·01-
B
A
Model
D
M/S
0·04
0·02
0·00
-0·02
-0·04
-0·06
8
9
10
11
12
13
14
15
16
17
NORTH COMPONENT
B
A
D
Model
0·0-
0·0
0·0-
0·0-
B
A
Model
D
M/S
0·02
0·00
-0·02
-0·04
8
9
10
11
12
13
14
15
16
17
NOVEMBER 1977

FIGURE 9