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SOME NOTES ON FLOAT-CURRENT METER INTERCOMPARISONS NEAR THE DB1 SITE

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INTRODUCTION

The long term measurement of mean near-surface currents by moored sensors and assessment of the accuracy of the observations presents considerable difficulty. In the past, the lack of linear sensors with sufficiently fast response which could average correctly weak horizontal components of flow in the presence of complex oscillatory flow has been a major handicap. With the development in the past few years of new and improved sensors this has perhaps assumed a lesser importance than the problems of mooring the sensor in the surface wave field. A truly fixed-point (Eulerian) measurement cannot be achieved using a conventional mooring, and the motion of the sensor in the spatial and time dependent near-surface velocity gradients may result in substantial errors. Pollard (1973), for example, has estimated that for some types of mooring errors exceeding 20 cm/s may obtain in severe wave conditions.

For observations in the uppermost metre or two, Collar, Carson and Griffiths (1983) proposed that the sensor might be attached to a wave slope follower, and showed that in regular Stokes waves the errors of measurement can be modelled in a reasonably simple manner. The work described in this interim report has sought to explore the possibilities of using the technique in the open sea to determine the near-surface current profile.

In the primary experiment described below current sensors were mounted immediately beneath small moored surface following buoys and comparisons were made between the outputs from these sensors and the rate of displacement of acoustically tracked Lagrangian drifters. This was thought to offer the best independent means of assessing the measurements made by the current meters, though such a comparison is not straightforward in spatially non-uniform flow. On the other hand, any contribution that arises from Stokes Drift in gravity waves is included in both measurements, even if in practice this may be inexact.

The experiment was conducted within about 50 km of the continental shelf edge at the site of the data buoy, DB1, partly because DB1 could provide concurrent wind and wave data series. Furthermore the work is complementary to present and past studies of the current data obtained from this buoy (which also is a wave slope follower and carries a long path acoustic current meter 3 metres below the surface - DBCM). Previous analyses of DB1 data had shown surface tidal streams to be rotary and not to exceed 0.5 m/s; the major axis of the tidal ellipse is aligned in an approximately northeasterly direction.

Data were obtained from current meter moorings at the site during two periods, 8th December 1979 - 27th January 1980 and 10th - 15th June 1980. During the first period the experiment with drifting floats was abandoned owing to severe weather conditions, although intercomparisons were possible between data sets obtained from moored current sensors and the DB1 sensor. During the second period in June 1980 weather conditions (fig. 6) were more favourable and the experiment was completed.

EXPERIMENTAL DETAILS

Two vector averaging electromagnetic current meters (VAECM) were mounted on a thin annular float of the type used for directional wave measurement. The sensor heads were annular in form and were mounted rigidly at selected distances beneath the surface. These heads have a linear output, good directional response, and laboratory experiments have indicated (Griffiths and Collar, 1980) that errors in measuring mean current in turbulent conditions should be small. However, the data return from these buoys was poor due to a combination of instrumental problems and the flooding of an instrument housing. One complete, and two incomplete, records were obtained from a total of three moorings - one in the first period, two in the second period.

Details of the moorings are shown in Fig. 1 and Table 1. Wave-tank experiments with models had demonstrated the importance of good wave-slope following; the mooring compliance was therefore provided by a 'Waverider' shock cord connected to the surface buoy via a 4 m stiffened bridle. The remainder of the mooring was conventional; a subsurface buoyancy sphere supported three mid-water current meters, an acoustic release and a 6 kHz transponder beacon.

In the first period (December 8th 1979 - January 27th 1980) an AMF Vector Averaging Current Meter (VACM) type 610C and an Aanderaa type RCM5 current meter were included in the mooring at 50m depth in order to provide data for comparison with surface measurements and to permit assessment of the effects on these different instruments of wave motion transmitted down through the mooring. The VACM provided a record of 47 days duration. Approximately 1% of the data were lost due to internal malfunction, but the clock maintained a correct sequence throughout. The losses were distributed randomly through the data and missing values were interpolated where necessary. The tape in the Aanderaa current meter filled in 10 days and it was not possible to check timing thereafter. However, the instrument was operating correctly on retrieval and the data set appeared to be of excellent quality. Twelve hours of good data were obtained from the VAECM at 0.5 metres depth before the surface buoy overturned in heavy seas.

In the second period (June 8th - 12th 1980), two moorings were set (CM1 and CM2), each containing 3 current meters in addition to the surface VAECMs. These comprised a VACM (610C) and an Aanderaa type RCM5; on one mooring the third current meter was a Plessey type 9021, in the other a Simrad UCM2 ultrasonic current sensor was included so as to afford some basic testing of this new instrument.

The sampling schemes of the instruments, which all gave complete records of good quality, are given in Table 1a. For the UCM2, burst sampling was adopted - in which 10 samples were taken in 30 seconds every four minutes - and a vector averaged current was computed during processing.

One nearly complete record was obtained from a depth of 0.5 m, VAECM1; a short record of only a few hours duration was obtained for the same depth from the second mooring 500 metres distant, VAECM2. This was limited by damage sustained when the instrument towed under.

Data were available from the data buoy, DB1, for both periods. The current data were generally of good quality, although intermittent loss of the 2^5 bit (32 cm/s) in the vector averaged East binary data word was a recurring problem. Detection of these anomalies could at times prove difficult although comparison with the predicted tide greatly improved this.

VARIABILITY IN MOORED CURRENT METER RECORDS (JUNE 1980)

Coherence spectra were calculated for pairs of current meter data sets. Data were handled in 3 sections of 1024 records and east and north components were treated separately. Fig. 2 shows a high degree of coherence between the 50 m depth current data from the same mooring (A and B), with a coherence exceeding 0.9 at about 1 cph. The coherence is generally low between surface and 50 m currents (D). For instruments at the same depth, but separated horizontally by 0.5 km (C), the coherence again falls rapidly to 0.9 at about 0.47 cph. The reason for this is evident in progressive vector diagrams of high-pass filtered currents, which reveal periodic but uncorrelated variations with scales of ~300 m and rms amplitude 2-5 cm/s.

Temperature changes recorded at each mooring by the 50 m VACM and Aanderaa instruments show a high degree of correlation. For most of the time the records (Fig. 3) indicate a temperature of 10.9±0.1°C, but sudden

Table 1 Characteristics of Moored Instruments

(a) Period 1 - Dec 1979 - Jan 1980
(b) Period 2 - June 1980

Table 1(a)

Instrument	Depth	Other Sensors	Vector Avg.	Sample Interval (secs)	Record Length (days)
VAECM	0.5 m	-	Yes	112.5	0.5
VACM 610C	47 m	Temp.	Yes	112.5	46.8
Aanderaa RCM5	48 m	Temp., Press.	No	120	10.1

Table 1(b)

Instrument	Mooring	Depth	Other Sensors	Vector Avg.	Sample Interval (secs)	Record Length (days)
VAECM2	CM1	0.5 m		Yes	112.5	0.25
VACM 610C	CM1	54 m	Temp.	Yes	112.5	5
Aanderaa RCM5	CM1	55 m	Temp., Press.	No	120	5
Plessey 9021	CM1	56 m		No	120	5
VAECM1		0.5 m		Yes	112.5	5
VACM 610C	CM2	53 m	Temp.	Yes	112.5	5
Aanderaa RCM5	CM2	54 m	Temp., Press.	No	120	5
UCM2	CM2	55 m	Temp., W Axis	Yes (by software)	10 samples spaced 3 s every 240 s	5
Ultrasonic CM (DBCM)	DB1	3 m		Yes	300 s each hour	Continuing, but 2 months in this instance

*Data buoy provides a number of other parameters including wind speed, direction, wave directional information, sea surface temperature on a continuing basis.

increases to as much as 13^{o} occurred at approximately 12 hour intervals at the start of the record: later, a dominant period of ~6 hours was evident.

The temperature changes were associated in both surface VAECM and 53 m VACM records with a maximum in the variance at frequencies above 4 cpd (fig. 4). The maximum consistently appeared within the range 70^{o}-170^{o} of the phase of the M_2 tide, and at times seemed to result from bursts of coherent high frequency motion at the two levels.

Pressure changes recorded by the Aanderaa meter at each mooring - of amplitude <5 m - also had a well defined six hour period arising mainly from changes in instrument depth due to drag forces on the mooring. The more prominent temperature changes were generally manifest in weaker currents. Overall, the evidence available implies vertical movement of the thermocline, but it is insufficient to permit the conclusion that this is periodic.

The current record obtained from the 0.5 m level at CM1 shows marked variability over timescales from a few minutes to ~2 hours. Although lack of a complete record from the corresponding surface VAECM at CM2 has prevented detailed coherence estimates being made, comparisons can be made between the short records obtained prior to the surface buoys submerging. Current magnitudes at the 0.5 m level at CM1 and CM2 are plotted in Fig. 5. Currents obtained from DB1 at 3 m depth are also shown; note that the hourly sampling scheme provides completely inadequate resolution of the near-surface variability. Strong similarities are evident between the 0.5 m currents, with short periods of strongly enhanced or diminished current being experienced at CM2 approximately 10-15 minutes before being recorded at CM1. When allowance has been made for the tidal magnitude and direction the delays appear consistent with a roughly northwesterly propagation of these short period motions.

The foregoing observations are all consistent with the presence of internal waves during the summer months (current records taken during the winter period, though noisy, do not show this variability at higher frequencies and it is absent from concurrent temperature records). Possible generating mechanisms for internal waves at the shelf break have been reviewed by Huthnance (1980); evidence for their existence has been presented by Pingree and Mardell (1981), whose midwater current meter records show very similar features to those in Fig. 3. Previous observations had not been made close to the surface, however.

In a two layer system the phase velocity of linear internal waves, of wavelength much greater than the depth of the mixed layers is given by:

$$c^2 = \frac{ghh'}{h+h'} \cdot \left(\frac{\rho-\rho'}{\rho}\right)$$

where h = lower layer depth ≃ 120 m
h'= upper layer depth ~ 50 m
ρ = lower density
ρ'= upper density
g = gravity

For a typical value of $\rho-\rho' \sim 0.4$ kg.m^{-3}, c is 40 cm/s. Assuming a wavelength of 1.5 km (Pingree, 1981), this gives a period of about 1 hour, consistent with high frequency fluctuations observed in our current meter records. A phase velocity of ~0.5 m/s is consistent, also, with the order of the propagation delay noted in our surface current records. Horizontal water particle peak velocity can be obtained from:

$$v = c\,\frac{\partial\eta}{\partial z}$$

where η = wave amplitude.

η decays linearly from the boundary to zero at the sea floor and to $\eta' = -Z(\rho-\rho')/\rho$ at the surface. Hence the horizontal particle velocities within both layers are uniform but of opposite phase. If we assume a peak internal wave amplitude Z, of 20 m, then v upper = 16 cm s^{-1} rms, v lower = 7 cm s^{-1}, in a ratio ~2.4:1. This is of the same order as the ratio of the rms high frequency component of the VAECM and VACM records (figs. 4(a) and (b)) ~2.0:1.

FLOAT TRACKING EXPERIMENT (JUNE 8TH - 12TH 1980)

Comparisons were made between the outputs of the data buoy acoustic current meter, the VAECM (0.5 m depth) and the rates of displacement of floats carrying canvas cruciform drogues centred at 3 and 0.5 m respectively. Surface winds during the experiment were generally light, reaching a maximum of about 10 m/s (fig. 6). Significant wave height derived from data supplied by the wave statistics package on DB1 was correlated with wind speed and attained a maximum of 2.4 m, although the duration of the float tracking also included two very calm periods.

Each acoustic transponder float was contained in a plastic cylindrical tube which floated with its axis vertical. A canvas cruciform drogue was attached to the tube, centred at the comparison depth. Dimensions of floats and drogues are given in Table 2.

Table 2 Float and Drogue Dimensions

Float length	1.7 m
Diameter	0.1 m
Freeboard	0.1 m
Float drag coeff.	1.2
Drogue drag coeff.[1]	1.2
Drogue width	1.8 m
Drogue depth	1.8 m (0.76)*
Frontal area	3.24 m^2 (1.37)*
Vertical drag coeff.[1]	0.06

[1] Ref. Booth (1978)

*½ m float

The float tracking system is described in Swallow, McCartney et al., 1974, and its present application is similar to that described by Collar, 1978. The range of a float from the ship was determined by direct acoustic interrogation. A subsequent transmission from a moored remote interrogator, triggered from the ship, permitted calculation of a second range which then determined the float position relative to the ship-remote interrogator baseline. The ship position was obtained at each transmission time by measuring ranges to two transponding beacons located in the current meter moorings CM1 and CM2 whose separations from each other and from the remote interrogator were known from acoustic ranging measurements at the time of laying. The directional orientation of the network was established relative to true North to within an estimated $\pm 2^{\circ}$ by making many visual bearing observations at different phases of the tide with any two of the surface buoys in transit from the ship. Float position ambiguity arising from the two-range determination was quickly resolved by reference to adjacent fixes and to the known launch and retrieval positions.

Errors in determining float position arise from uncertainty in the measured acoustic travel times, which can be read with a resolution of 10 ms (corresponding to 7.5 m). The effect of a travel time error is dependent on the geometry of the triangulation, range errors being magnified when the included angle at the float approaches 0° or 180°. The uncertainty from these causes is thought to have been generally <30 m, corresponding to a few cm/s in speed between adjacent fixes.

Lagrangian currents were computed between adjacent float position fix times, typically 15-20 minutes. The corresponding VAECM currents were averaged over the duration of the float track. Data buoy currents were obtained by interpolation between hourly values using cubic splines, prior to averaging.

At times, comparisons produced substantial (~20 cm/s) differences between Lagrangian currents and corresponding current meter observations. These differences did not correlate with either wind speed or wave height. Neither was there any obvious correlation between individual speed differences and float-current meter separation, which might be attributable to a time invariant gradient in the flow. Differences of this order cannot be accounted for solely by uncertainties in float positions. Rather, it is consistent with the variability in surface currents remarked earlier. There is other supporting evidence, for example in the comparisons of float tracks with VAECM progressive vectors: at times very close agreement is obtained (fig. 7(a)) but abrupt changes are then often manifest (fig. 7(b)). During the experiment, groups of floats, identically drogued, were deployed at intervals in order to test for variability at scales within the range 10^2-10^3 m. Over a period of several hours the tracks show a correlation between the speed of dispersion of members of the group and their initial separations at deployment (fig. 8). This coherence in the Lagrangian reference frame could indicate the presence of Langmuir circulations, but we have insufficient observational data to test this possibility.

Comparison of the float velocities with VAECM currents showed that while directions are in generally good agreement a speed-dependent difference exists in the magnitudes, the VAECM under-reading at speeds above ~0.25 m/s. This is almost certainly a systematic error in the VAECM output, arising as a consequence of flow obstruction by the surface buoyancy*. In the single point mooring arrangement the current meter was maintained at a constant distance 3.5 m downstream of the surface buoyant floats (fig. 1a). The order of magnitude of the flow obstruction has subsequently been confirmed by observations made in the laboratory tow tank.

At speeds below about 0.25 m/s there is a tendency for the VAECM to overread compared with the floats. The reason for this is not clear.

*The original mooring design called for a small buoyant float at the surface. Additional buoyancy was added during the experiment when the surface buoy towed under in unexpectedly high tidal currents.

Orbital rectification by the current meter - or the influence of surface wind on the floats - is unlikely, in view of the lack of a clear dependence of the effect on windspeed (fig. 9).

The corresponding comparisons for the DBCM with 3 m floats are shown in fig. 10. In this case trends are less evident: the scatter is somewhat larger, possibly due to the inadequate sampling rate of the DBCM. Negative values of the (float-DBCM) speed difference are scattered throughout the speed range, and there appears to be no particular trend at the lower speeds. However, the largest positive values appear to be biassed towards higher speeds. For several reasons we do not believe that this distribution is significant. It would imply a gross under-reading by the DBCM at the higher speeds, and substantial non-linearity over the speed range as a whole. It is known from earlier comparisons in fast tidal streams that the DBCM output is essentially correct between 0.8 and 1.2 m/s. In present analyses (see later sections) values of M_4 and M_6 constituents, which are sensitive to instrumental non-linearity, are characteristically very small. Furthermore for the closest floats the mean DBCM-float difference is also small. Table 3 contains differences in current magnitude and direction, sorted according to the mean float-DBCM separation, R, between adjacent fixes. A mean has then been calculated within each of two range intervals.

For current magnitude, the effect of changing the range interval is small for $R < 2$ km. At ranges $R > 2$ km the mean of a group of 19 points shows floats to be moving more quickly than predicted by the DBCM. Uncertainty in the assumed velocity of sound, or in position fixing geometry, does not account for this, and topographic effects are very unlikely. If the comparison is restricted to the 3 m floats within ~1 km of the buoy, a zero value for $\overline{V_{cm} - V_f}$ lies well within the 95% confidence interval (± 0.025 m s^{-1}) for the measured value, 0.008 m s^{-1}. Systematic mean differences in direction - clearly visible in fig. 10 - are to be expected; they arise from uncertainties in compass calibration and also in the determination of the fixed transponder orientation. Taken over all 3 m float comparisons, $\overline{\theta_{cm} - \theta_f} = 4.1 \pm 3.9^{\circ}$. In the corresponding comparison of closest 0.5 m floats with the VAECM, $\overline{V_f - V_{cm}} = 0.045$ m s^{-1} and $\overline{\theta_{cm} - \theta_f} = 6.8^{\circ}$.

Table 3 Comparison of magnitudes and directions of currents as measured by floats and DBCM

Range (km)	No. of obs.	$\overline{V_{cm}-V_f}$ $cm.s^{-1}$	σ_V $cm.s^{-1}$	$\overline{\theta_{cm}-\theta_f}$ (deg)	σ_θ (deg)
<0.75	20	-0.8	7.3	3.9	11.1
>0.75	64	-2.5	9.1	5.0	11.5
<1.0	33	-0.9	7.3	4.1	11.1
>1.0	51	-2.9	9.6	5.3	11.5
<1.5	54	-1.4	7.7	5.4	11.5
>1.5	30	-3.4	10.3	3.6	11.1
<2.0	65	-1.03	8.0	5.4	11.2
>2.0	19	-5.8	10.1	2.8	11.8

σ_V, σ_θ are the standard deviations of values of $(V_{cm}-V_f)$, $(\theta_{cm}-\theta_f)$ from their respective means. Range is defined as the separation of float and DBCM midway between two adjacent position fixes. Mean current during the comparison $\overline{V}_{cm} = 34.9\ cm.s^{-1}$.

MEASUREMENT OF NEAR-SURFACE SHEAR

There is now in existence a large set of current observations made by DB1 at 3 metres depth. The short sections of record that we have examined, when low pass filtered, show the 3 m current and 8 m wind to be well correlated. The data in Fig. 11, for example, were obtained during December 1979, when winds were particularly strong. A coherence analysis has not been made for these data but the correspondence between current and wind is clearly of the same order (current at 3 m ≃ 1% of wind speed at 8 m) as that found at a previous site in the southern North Sea (Collar & Vassie, 1978). Note, however, the consistent Ekman-like angular offset obtaining between wind and current vectors, which seems physically plausible at this open sea site. It was not observed in the very limited records obtained in the North Sea, maybe as a result of topographic constraints close to the coast.

As well as seeking to establish the accuracy of measurement of these wind induced currents, a further objective of the present work is to see whether near-surface shear can be determined from simultaneous observations at more than one level relative to the instantaneous surface. As yet very limited observations have been made. The results are sufficiently encouraging to justify further investigation - although interpretation of such differences may not be as straightforward as initially thought.

During the period shown in Fig. 11 a simultaneous 12 hour series of current data was obtained from a VAECM moored at 0.5 m depth in strong wind conditions. These data have been compared with the 3 metre currents.

In the 24 hours prior to the deployment of the VAECM the wind had decreased from 14 m/s to 6 m/s; within the span of the data set it increased steadily from 9 m/s to 19 m/s. Fig. 12 shows the East and North components of the current measured by the VAECM, the data being averaged over 112.5 seconds. Hourly values of the DB1 currents, averaged over 5 minutes, are included for comparison.

Although the VAECM records are noisy, it is nevertheless possible to extract from them a well defined mean current by taking, say, a five minute mean. This has been done in Fig. 13 in which hourly vectors of current and wind are plotted. The predicted tide is also shown (hatched), based on an analysis of 2 months of DB1 data which includes this period. The consistent vector difference between 0.5 m and 3 m currents and its close correlation with wind direction, is now apparent: the 0.5 m current is significantly enhanced beyond both the predicted tide and 3 m current in downwind directions, and reduced when current and wind have components in opposite directions. The effect is dramatic in the final comparison at 01.30, when the resultant current at 0.5 m is reduced to nearly zero by the wind. The effect of the wind on the 3 m current is less easily estimated. Comparison of observed and predicted tides shows remarkable agreement at times when the tidal current is effectively downwind. Thereafter a clear difference emerges as the tidal current rotates into the wind. However, this comparison may be partly obscured by shortcomings in the tidal analysis, which can generate periodicities in the residuals of the order of this record length. Furthermore the residuals may contain non wind-related currents. Thus, while there is evidence for wind related differences of ~0.6% of wind speed in current between 0.5 and 3 m, we need to examine longer sections of record to establish this in an absolute sense.

Evidence of vertical shear in mean current was also sought during the float tracking experiment. A difference was observed between currents at 0.5 and 3 m. This has been plotted, together with the wind vector in fig. 14. The data have been smoothed with a 12-hour time constant in order to minimize small differences in the tidal signals and to eliminate the short term variability. Differences of similar magnitude were observed (Fig. 15) in the corresponding rates of displacement of floats drogued at 0.5 and 3 metres depth. These were closely coupled to wind direction, but the magnitudes are thought to be too large to be due to direct wind forcing of the float or to float dynamics in waves. Nevertheless the evidence for shear is not conclusive.

Even if differences in currents at different levels are well estabished, their interpretation may not be simple, because the apparent current recorded by a sensor in the surface wave zone may depend upon the nature of the surface waves and upon the type of mooring employed. Pollard (1973) estimated the effect of suspending a current meter beneath a surface follower and concluded that in stormy conditions errors of several cm/s could occur. Collar, Carson and Griffiths (1983) showed that in monochromatic two dimensional Stokes waves a wave slope follower includes the surface Stokes drift in its measurement, but cannot resolve the vertical shear in Stokes drift if mounted rigidly beneath the buoy. Buoy diameter (D), too, is found to attenuate the measurement at shorter normalised wavelengths, $^D/\lambda$. Whether these simple error models are applicable in the open sea is not yet evident. Further experiments using different types of near-surface mooring which can be expected to have differing error characteristics are clearly necessary. At the same time independent observations must be made, such as those provided by Lagrangian drifters. In this way it may be possible to establish the order of errors incurred at any depth in the wave zone.

INSTRUMENTAL COMPARISONS AT 50 M DEPTH

Current meters were attached to the moorings during both periods at approximately 50 metres depth in order to provide background data and also to see whether surface mooring motion transmitted downwards would contaminate the data. Initial tests were also made of a Simrad Ultrasonic Current Meter type UCM2. Details of the moorings and instruments are given in fig. 1 and Table 1. The types of current meter used differ in a number of respects. The Aanderaa instrument counts the number of revolutions of a Savonius rotor over a preset sampling interval and records this together with a single measurement of direction. The Plessey meter has an identical sampling scheme, but uses an impeller and has a smaller alignment vane. Although the mooring attachment methods differ, both meters are gimballed and should therefore measure the horizontal flow within certain limits of the mooring wire angle (±12° Aanderaa; ±30° Plessey). The VACM, also, senses the polar components of the flow but does not rely on a large vane for orientation of the instrument. Furthermore, it computes a vector average of the current over the sampling interval, obtaining a direction sample from a light vane eight times per rotor revolution, and sums resolved East and North components independently. It differs from the other instruments, also, in that it is coupled directly into the mooring line and has no gimballing arrangements. The fourth type of instrument, the ultrasonic current meter, UCM2, measures independently three orthogonal components of flow using the travel time difference method. Vertical orientation of the instrument and stability in horizontal direction are achieved by using an Aanderaa gimballing arrangement and large vane. The instrument had several sampling options, but at the time these did not include internal vector averaging. A recorded burst of ten samples at a 0.33 Hz rate, repeated at 4 minute intervals was selected since this permitted subsequent computation of a vector average. The 3 second intervals between samples is a disadvantage due to the possibility of aliassing, but it was dictated by the relatively poor response of the compass.

(a) VACM and Aanderaa

The steadiness, S, of the flow is given by the ratio of the modulus of the velocity vector, $|\vec{V}|$ to the scalar speed, V, derived from the Savonius rotor count. Values lie between 0 (oscillatory flow with zero mean) and 1 (unidirectional flow). This ratio, plotted against time for the first period (December 1979)(fig. 16) showed the unexpected dependence on the M_2 tidal magnitude and was substantially reduced when neap tides and stormy conditions occurred simultaneously. In higher tidal currents (Days 353-359, 364-373 and 382-386; also throughout the summer deployment) the steadiness was unaffected by the surface conditions; winds in these periods were generally below 10 m/s. At such times the steadiness is close to unity, but it does show a periodic modulation at 4 cpd due to the M_2 tide and a completely unexpected inverse dependence of steadiness on speed (fig. 17). This behaviour appears at a well defined current threshold, ~35 cm/s, and persists until currents are weaker, some hysteresis being present. The most likely cause is an oscillation or 'strumming' of the mooring, possibly excited by vortex shedding from the subsurface buoyancy or instrument cases. The rôle of the compliant mooring section in supporting such oscillations is not clear, and the effect clearly needs further investigation, particularly as it causes over-reading by the Aanderaa meter of several percent (fig. 18). It is disturbing to find such errors in calm conditions in which they would not normally be expected.

Comparison was made between the output of the Aanderaa meter and the scalar speed of the VACM. These had been expected to show under-reading of the VACM by a few percent due to lack of gimballing arrangements for this instrument. The IOS mooring design program, SHAPE, had predicted a mooring wire inclination at the instruments of 13° and a depression of the instrument by 7 dbar. This value was approximately correct because the pressure transducer in the Aanderaa meter recorded maximum pressure changes of ±5 dbar. Thus, given the VACM tilt response measured by us in steady flow in the tow tank (fig. 19), it was surprising to find no systematic differences between the rotor counts of the two instruments. We conclude that vertical cosine responses determined in laminar flow are probably not applicable to situations in which oscillatory flow is also present.

In the winter period substantial Aanderaa errors were to be expected in view of surface wave conditions. The correlation between Aanderaa-VACM difference and significant wave height is shown in fig. 20. The extent of downward transmission of surface buoy motion is difficult to estimate. In Table 4 we calculate the variance to be expected at 50 m depth from the heave spectrum of DB1. The times were chosen to coincide with comparative shipborne wave recorder measurements. Agreement between these and the DB1 measurements was reasonably good (J.A. Ewing, pers. comm.). Mean currents are also shown in Table 4, together with corresponding values of steadiness, S. It is clear that, during the later measurements at least, variance in the current measurements can be accounted for by reversing orbital flow at the depth of the instruments.

(b) Plessey 9021 and CMI UCM2

The Plessey 9021 and Simrad UCM2 instruments were deployed during the summer period only. Reasonably good agreement in magnitude was obtained between the Plessey instrument and VACM (fig. 21), with an absence of the over-reading at the higher speeds noted in the case of the Aanderaa. Noticeably less scatter was also observed between these instruments than either the VACM-Aanderaa comparison - or the VACM-UCM2. This presumably reflects the ability of the Plessey impeller to record reverse flow, unlike the Savonius rotor. Though using a necessarily restricted sampling scheme, which resulted in increased scatter, the UCM2 also produced apparently good agreement with the VACM in mean magnitude (fig. 22). However, agreement in direction was poor: systematic differences of 15° were found over the range 150°-360°. This may have resulted from the supply by the manufacturer of the UCM2 of batteries with ferromagnetic cases (Tadiran Lithium cells). Although a post-deployment calibration was carried out with the battery pack in place, the systematic differences remained.

Table 4 Estimates of orbital motion at 50 metres depth, December 1979

Time/Day	8 m wind speed (m/s)	rms surface wave ampl. (m)	rms wave ampl. at 50 m	rms orbital speed 50 m (m/s)	mean current speed (m/s)	S observed
0900/343	17	1.15	0.27	0.14	0.30	0.84
1800/343	19	1.44	0.38	0.19	0.27	0.80
1800/348	22	1.73	0.46	0.21	0.29	0.82
1500/349	18	1.92	0.63	0.27	0.27	0.81

Each of the direction sensor comparisons showed increased scatter in the 90°-180° sector, and to a lesser extent between 270° and 360°, though it was most pronounced in the Aanderaa-VACM comparison. This is clearly related to the previously-remarked maximum in the high frequency (>4 cpd) variance of current measured at both 0.5 and 50 metres (fig. 4).

The vertical axis of the UCM2 mounted on the upstream side of the instrument case registered unexpectedly large currents, ±4 cm/s. These were coherent with the horizontal component, u, - the v component was very small since the instrument was gimballed in a standard Aanderaa mounting and aligned along the u direction by a large vane. Tilt angles of $\pm 4^{\circ}$ would have been required to produce these values. In steady flow this would not be consistent with the expected operation of the gimballing arrangement. Conclusions based on performance in steady flow seem to be inapplicable when oscillation of the mooring takes place.

RELATIONSHIP BETWEEN MIDWATER AND NEAR-SURFACE CURRENTS

Two comparisons have been made between currents measured by DB1 and currents measured at nominally 50 metres depth by moored VACMs. The first (December 1979/January 1980) yielded 47 days of data; harmonic analyses provided the principal constituents shown in Table 5. While values of diurnal constituents and of S_2 are in good agreement, there is a clear difference between M_2 values recorded by the two instruments. This is probably too large to be accounted for by the standard error of the measurement (estimated to be <5%). Of the much smaller higher order constituents M_4 is included, since it is sensitive to any distortions introduced by non-linearity in the current meter or its mooring system. The values of M_4 are, in fact, small and are representative of values obtained near the shelf break on other occasions (J.M. Vassie - pers. comm.).

There is no obvious instrumental explanation for the discrepancy, which, however, has been observed also when using a current meter string elsewhere in the Celtic Sea. The combined evidence of present and previous float comparisons does not support systematic under-reading by DB1 throughout its speed range. It is possible that some degree of overreading by the VACM took place, caused by pumping of the Savonius rotor. Certainly significant orbital motion was experienced at times at the depth of the current meter. However, rotor pumping should result also in an enhanced value for S_2 - and this does not occur.

The summer period produced evidence of a rather unusual tidal regime. The float tracking experiment showed near surface currents to be, on average, ~10 cm/s lower than those at 50 m*. This is clearly shown by the comparison of VACM speeds with surface (0.5, 1 and 3 m) float speeds in fig. 23. Furthermore, harmonic analysis of a section of DBCM record spanning June and July shows intermittent loss of coherence in the tidal signal. Two short sections of DBCM data and the predicted tide are shown in fig. 24 for the winter and summer periods. The poorer fit of the predicted tide during early June (fig. 24a) is evident, particularly between Days 155 and 158. At other times - including the float tracking period - the fit was good. Overall, values of M_2 and S_2 were reduced in comparison with those in the earlier period (Table 6), for which a short section of typical record is shown in fig. 24(b). The greatest departures from the predicted tide occur in this record at times of strong surface winds: on Day 349, for example, winds of ~30 m/s from the S.W. were recorded.

We do not believe that the unusual currents observed in June 1980 were symptomatic of any instrumental malfunction. Recent work by Cutler (pers. comm.) has shown that large inertial currents existed at this time, and the existence of an internal tide is also a possibility. More detailed investigation of the complete DB1 data set should help in developing an understanding of the complex current regime at the site, although surface observations alone are clearly insufficient.

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*This may explain some experiences of divers inspecting moorings at the site, who on occasion have reported greater difficulty in coping with currents at depths of a few tens of metres than with currents at the surface.

Table 5 VACM/DB1 Comparison December 1979/January 1980

Constituent	DB1 Amp (cm/s)	DB1 Phase (°)	VACM Amp (cm/s)	VACM Phase (°)
East component				
O1	1.3	269	1.4	279
K1	1.6	15	1.3	28
M2	27.2	114	30.2	112
S2	10.4	156	10.5	154
M4	1.1	195	0.4	38
North component				
O1	1.2	216	0.6	148
K1	1.3	293	1.1	279
M2	31.8	50	34.4	46
S2	11.8	92	11.1	88
M4	0.07	332	0.4	177

Table 6 DB1 Comparison December/January and June/July 1980

Constituent	Winter Amp (cm/s)	Winter Phase (°)	Summer Amp (cm/s)	Summer Phase (°)
East component				
O1	1.1	260	1.1	280
K1	1.6	17	1.4	42
M2	27.4	115	25.0	116
S2	10.4	157	9.4	166
M4	1.1	195	0.017	261
North component				
O1	0.9	207	0.9	172
K1	1.2	299	1.3	287
M2	31.8	50	29.4	53
S2	12.2	95	11.0	101
M4			0.01	223

CONCLUSION

Each of the measurement techniques applied during the summer experiment have shown the presence of considerable near-surface variability over time-scales of a few minutes to a few hours. This has added greatly to the difficulties of making instrumental comparisons. In particular it has limited the extent to which Eulerian and Lagrangian observations may be related.

The comparison with the DB1 data has been further handicapped by the hourly sampling scheme, which fails to resolve many of the scales present during the summer months. A sampling interval not exceeding a few minutes would be more appropriate at this, and similar, locations. Nevertheless an average over the closest float-current meter comparisons suggests that the accuracy of the present current meter observations in light to moderate sea conditions (wind <10 m/s) is of order 1-2 cm/s. This reinforces the conclusion of a previous experiment carried out in much higher mean currents. These results conflict with two tank tests carried out on a $\frac{1}{24}$ and a $\frac{1}{10}$ scale model, which had predicted underreading of nearly 10% due to flow interference by the hull. We can only attribute this discrepancy to inability to achieve in the tow tank the correct Reynolds number scaling.

The float comparisons have also been valuable in exposing deficiencies in the system for mooring current meters within a metre of the sea surface. More work is evidently needed both to surmount the flow obstruction introduced by surface buoyancy and to ensure stability of the surface buoy in extreme conditions. But, though limited by instrumental problems, the results obtained so far from the VAECMs provide incentive to persevere with the technique to the point where its accuracy can be properly assessed. It is encouraging that by averaging a current meter output over, say, five minutes it is possible to obtain a smooth record within the uppermost 0.5 m in storm conditions. It seems likely, also, that measurements of tidal or inertial currents close to the surface are quite feasible with an accuracy similar to that achieved below the wave zone. Wind-related currents present a much more difficult problem: we cannot say whether the depth dependence of the near-surface currents we have observed is real or simply caused by rectification of orbital motion. The measurements made so far tend to exclude the latter cause, but as yet we lack any convincing proof. If the measurement is accurate then a problem of interpretation exists: any contribution from Stokes drift must be identified. At present only two techniques appear to offer any possibility of progress in the problem: the first is to try to model the effects of different types of moorings in waves and to test them comparatively. The second technique is to make further comparisons with independent Lagrangian techniques. Experience with the present work suggests that a site for a further experiment should ideally have the following qualities:-

(a) well mixed surface layer
(b) absence of shipping/fishing activity
(c) good exposure to waves
(d) uniformity of bottom topography
(e) minimum tidal currents consistent with (a),

i.e. the experiment would probably have to be conducted in the winter months before the onset of stratification, and should, if possible, span a period of neap tides.

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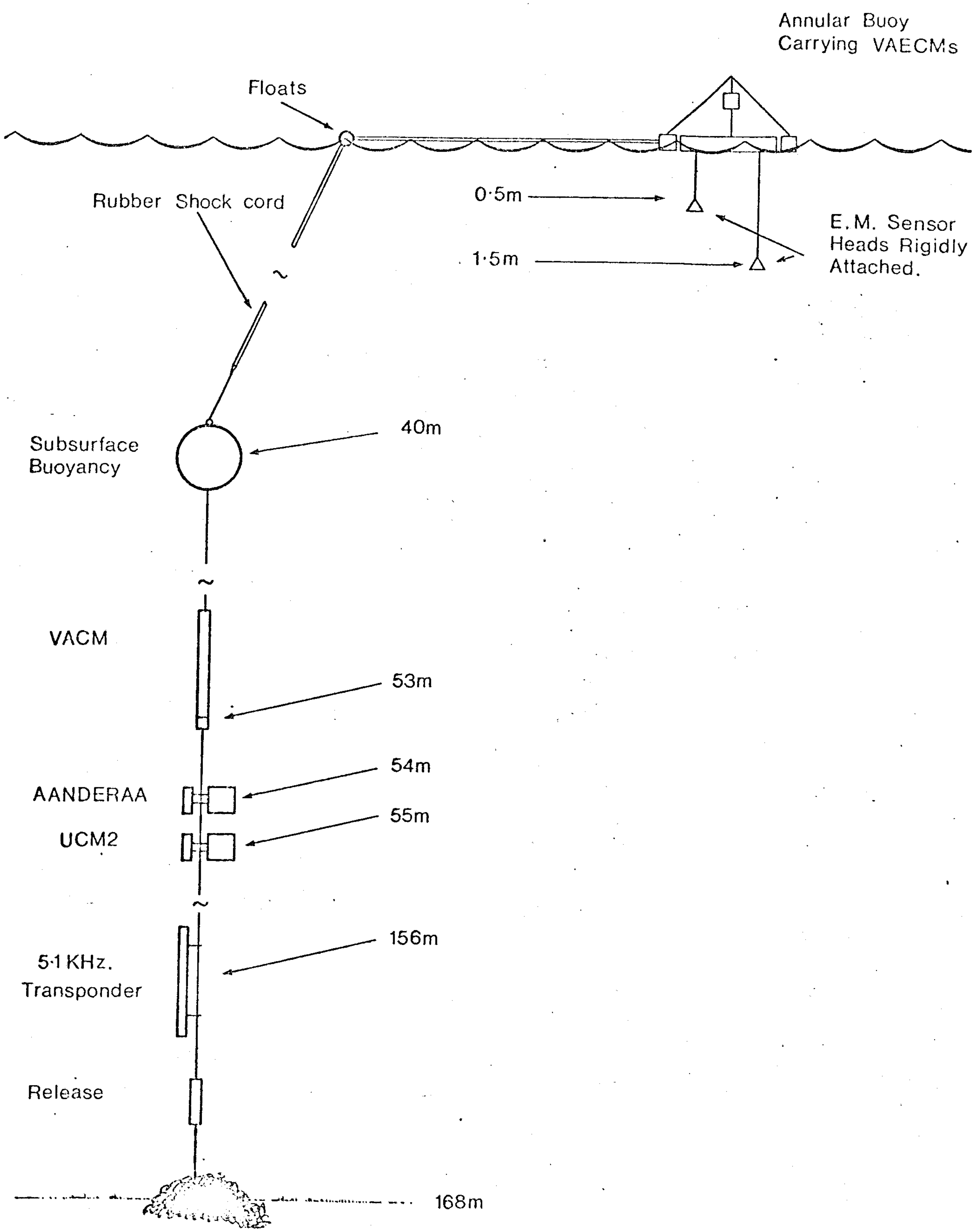


Fig. 1(a)

Figure 1. Near-surface current moorings (a) and their disposition (b).

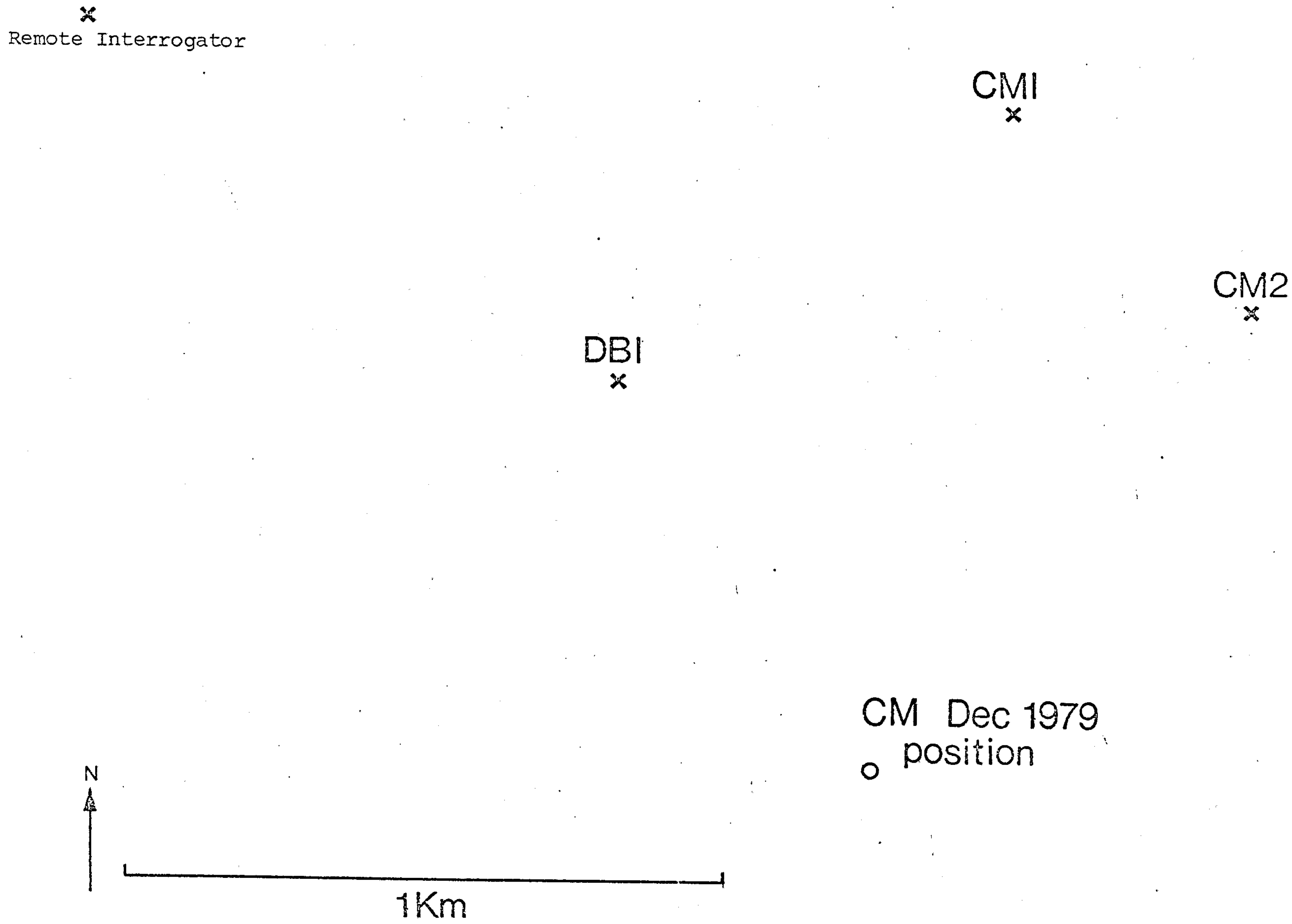


Fig. 1(b)

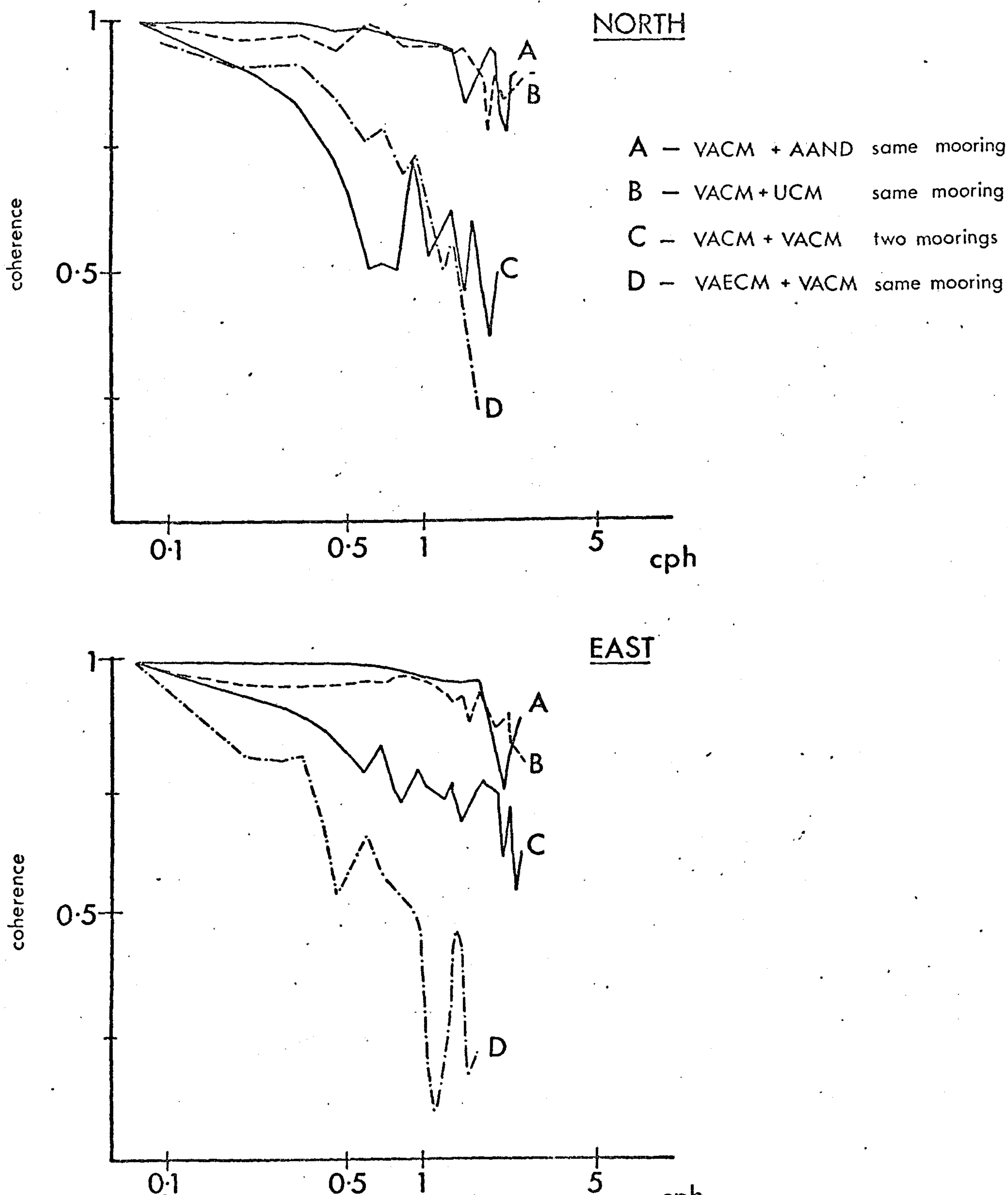


Figure 2. Coherence between currents observed at 50 m depth.

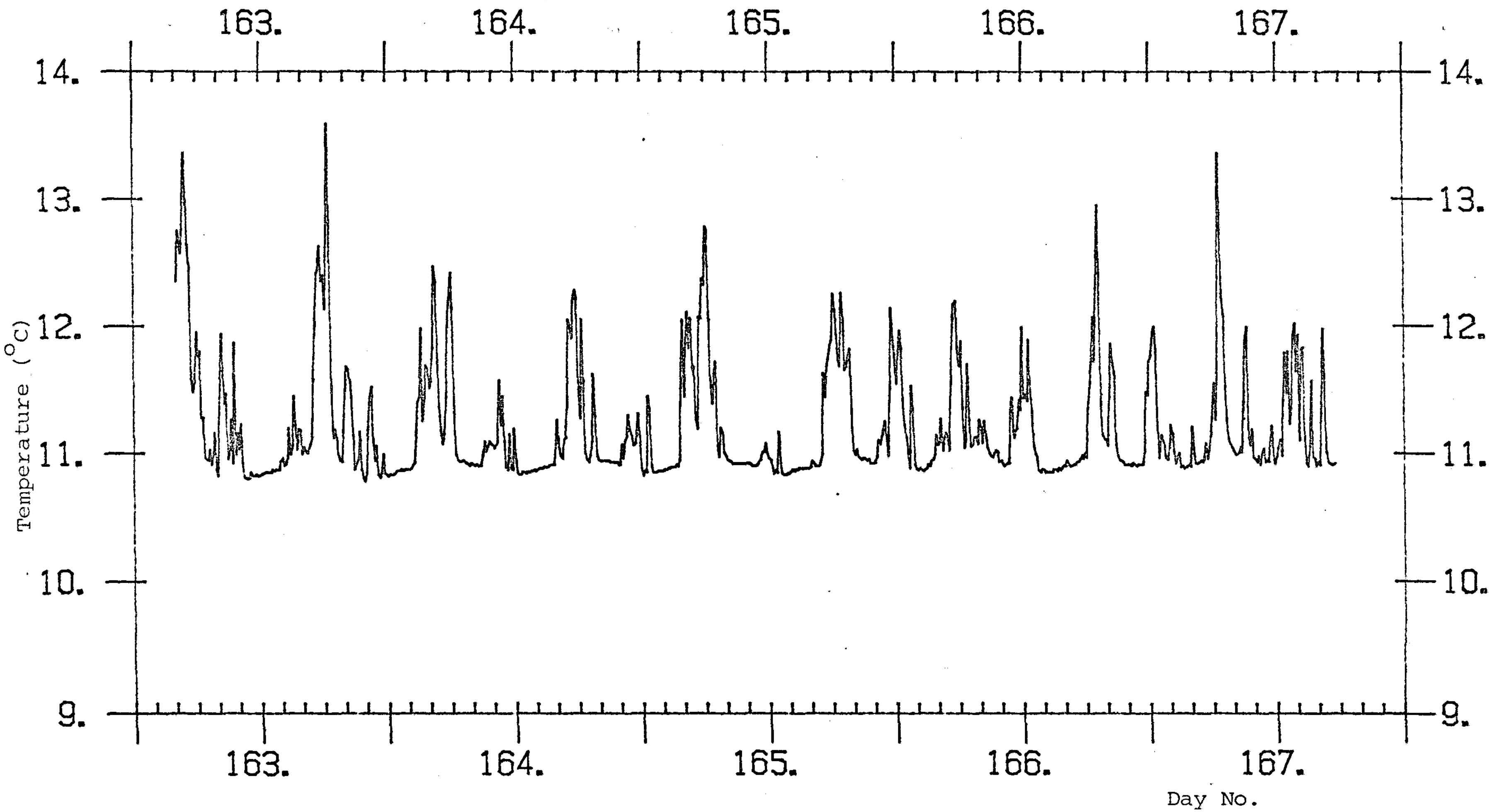
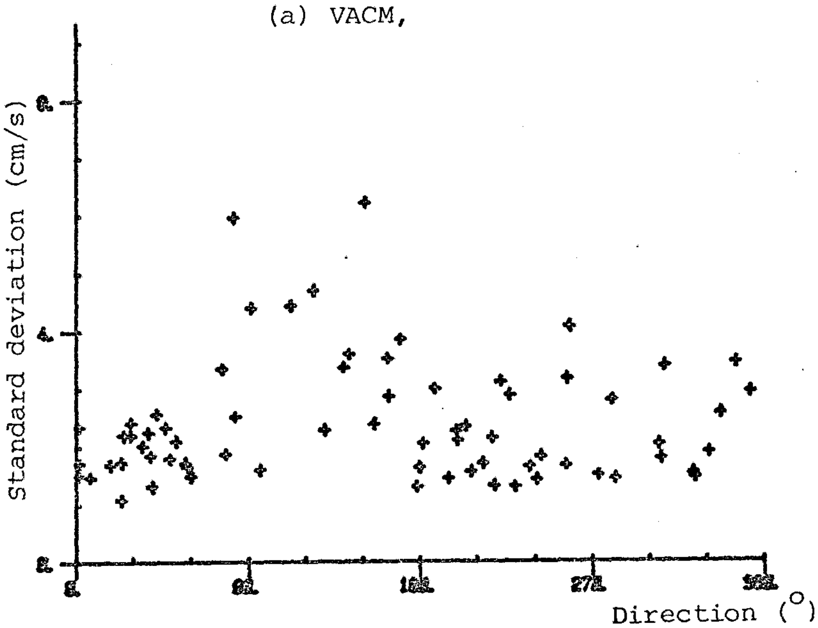


Figure 3. Temperature record obtained at 53 m depth.

Figure 4. Angular dependence of variance in high pass filtered currents (f > 4 cpd) for
(a) VACM,



(b) VAECM, computed over 1 hr periods.

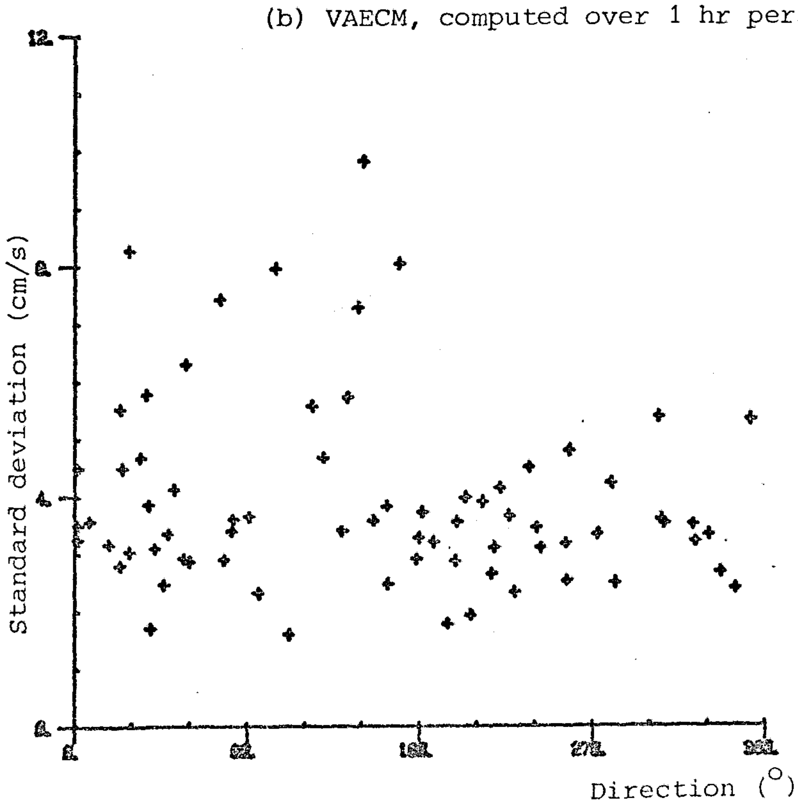
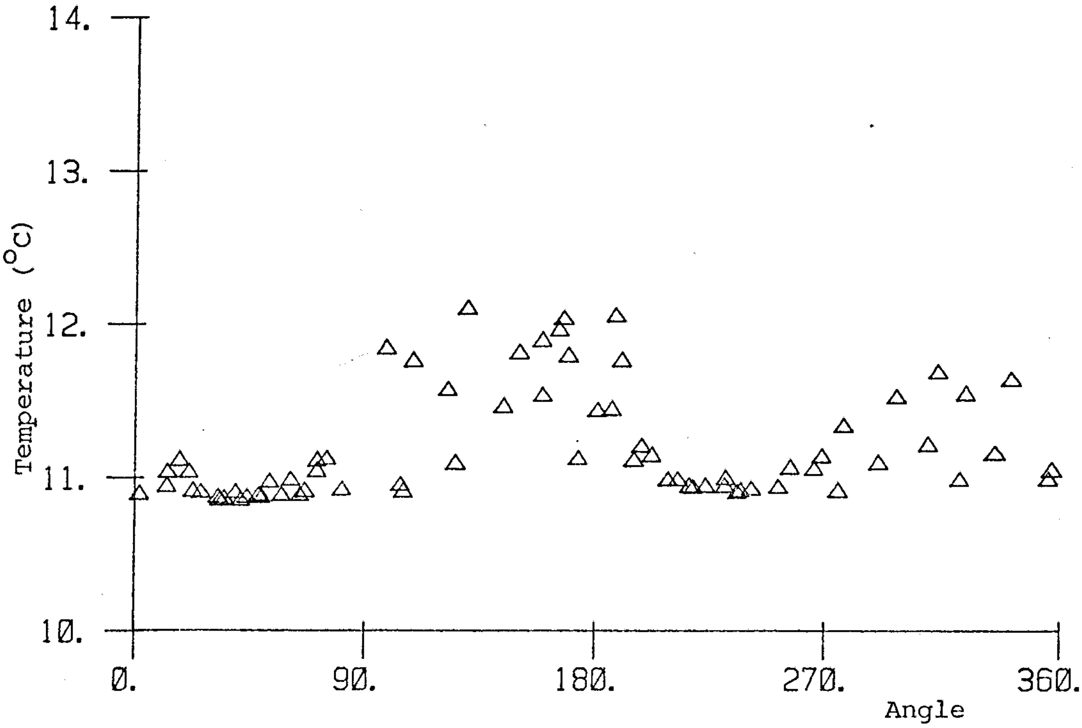


Figure 4(c) Angular dependence of variance in temperature (f > 4 cpd).



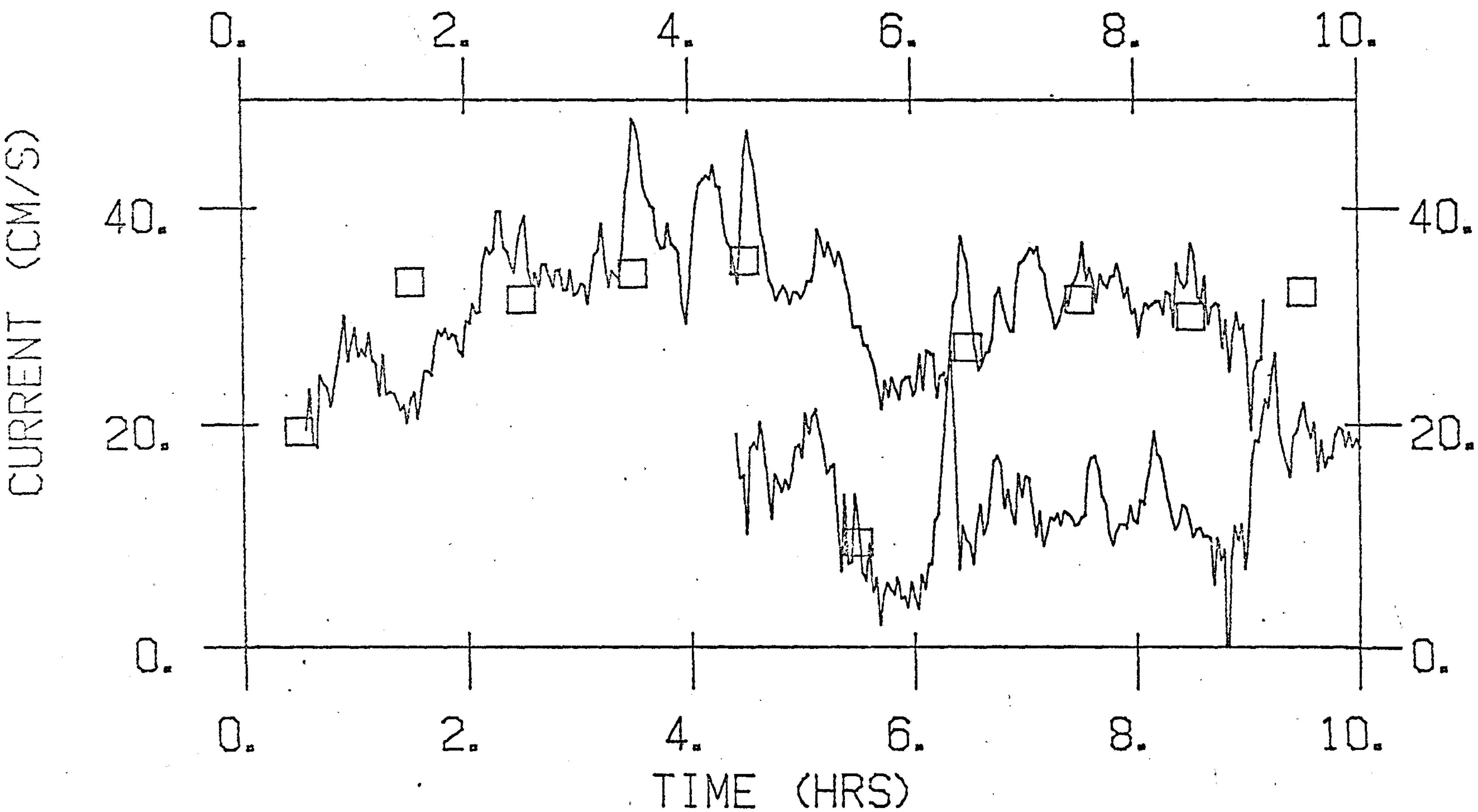


Figure 5. Current records obtained from two VAECMs at 0.5 m depth independently moored and separated by 0.5 km. Lower trace reduced by 20 cm/s. Symbols are hourly DB1 (5 mins mean) currents measured at 3 m depth; horizontal separation from VAECM 0.8 m.

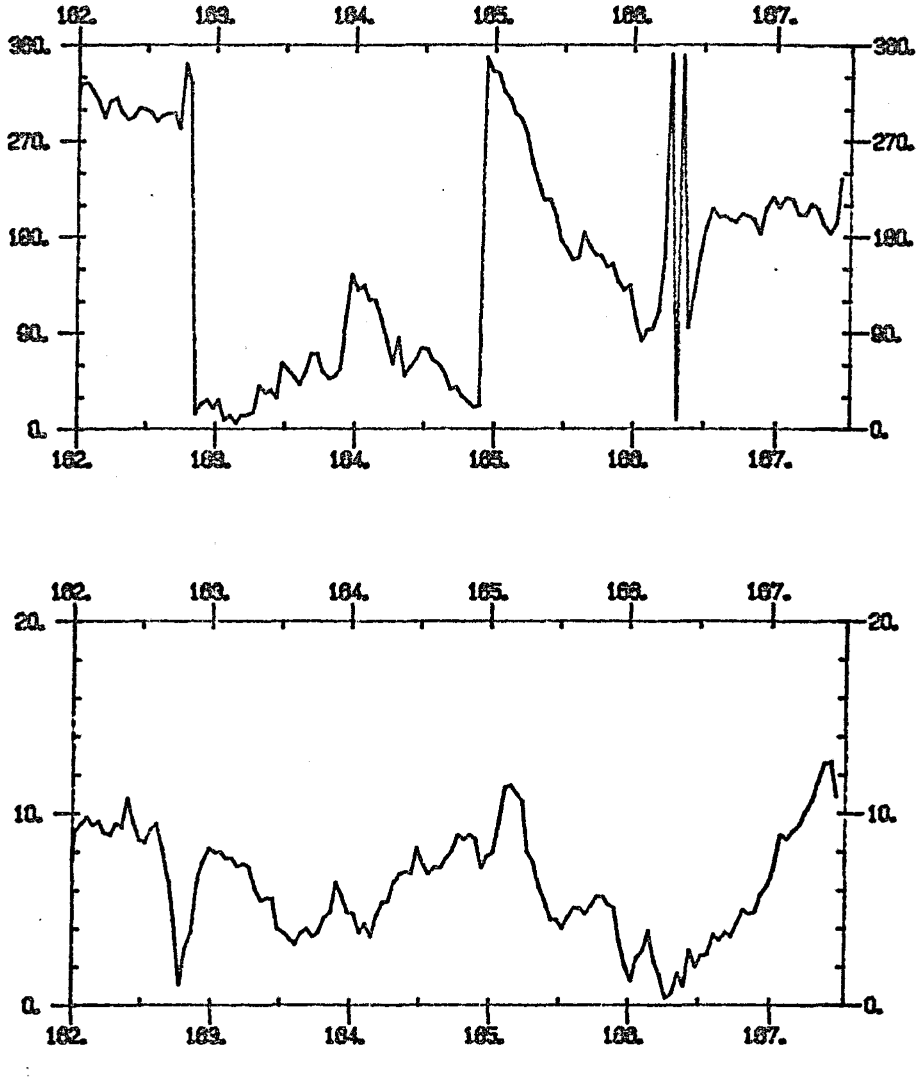


Figure 6. Surface winds (8 m) at DB1 site (June 10th-17th 1980) during float tracking experiment.

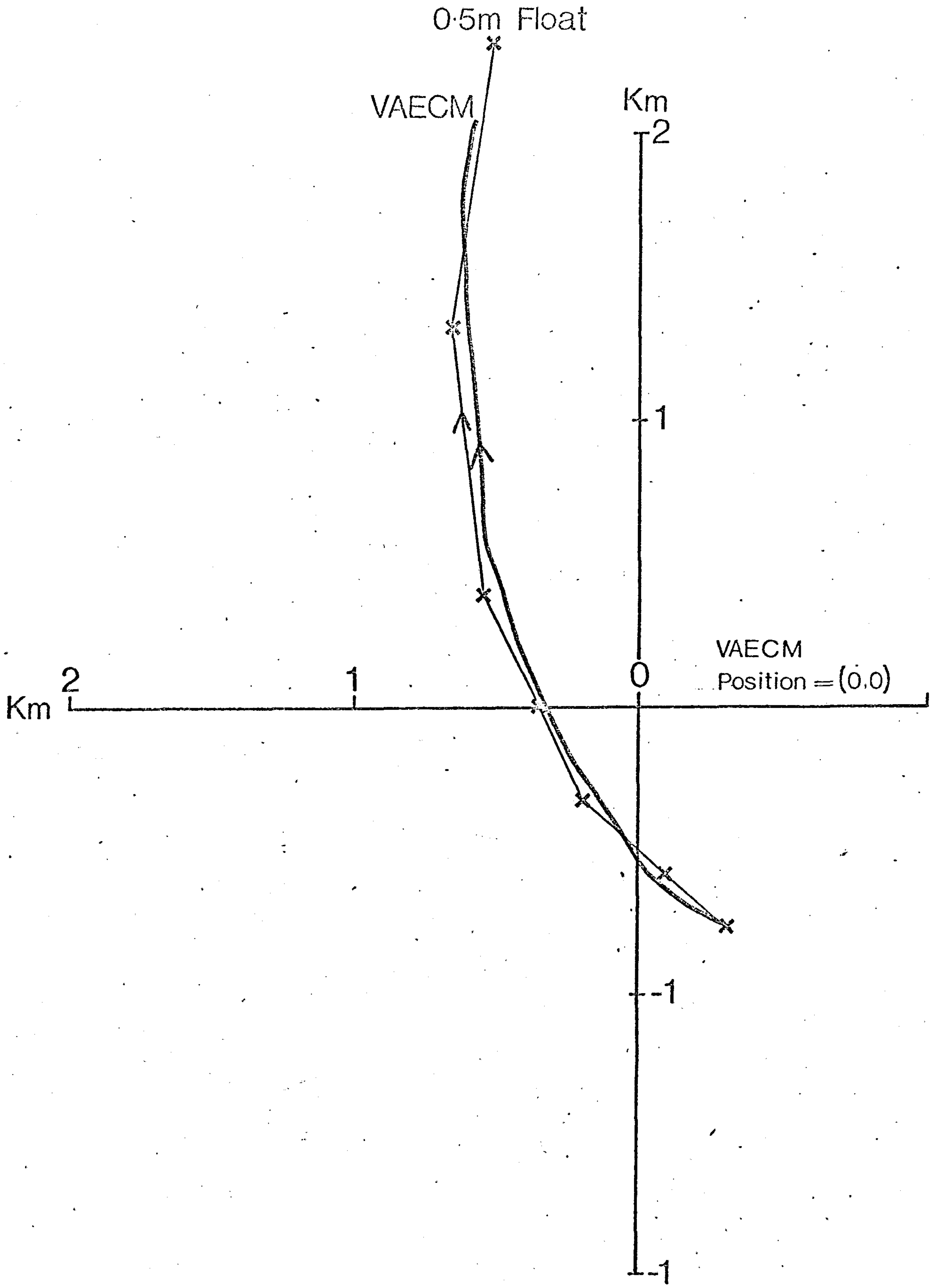


Figure 7(a). Comparison of VAECM progressive velocity vectors with Lagrangian float tracks. Note VAECM origin has been transformed in each case so as to coincide with the float track.

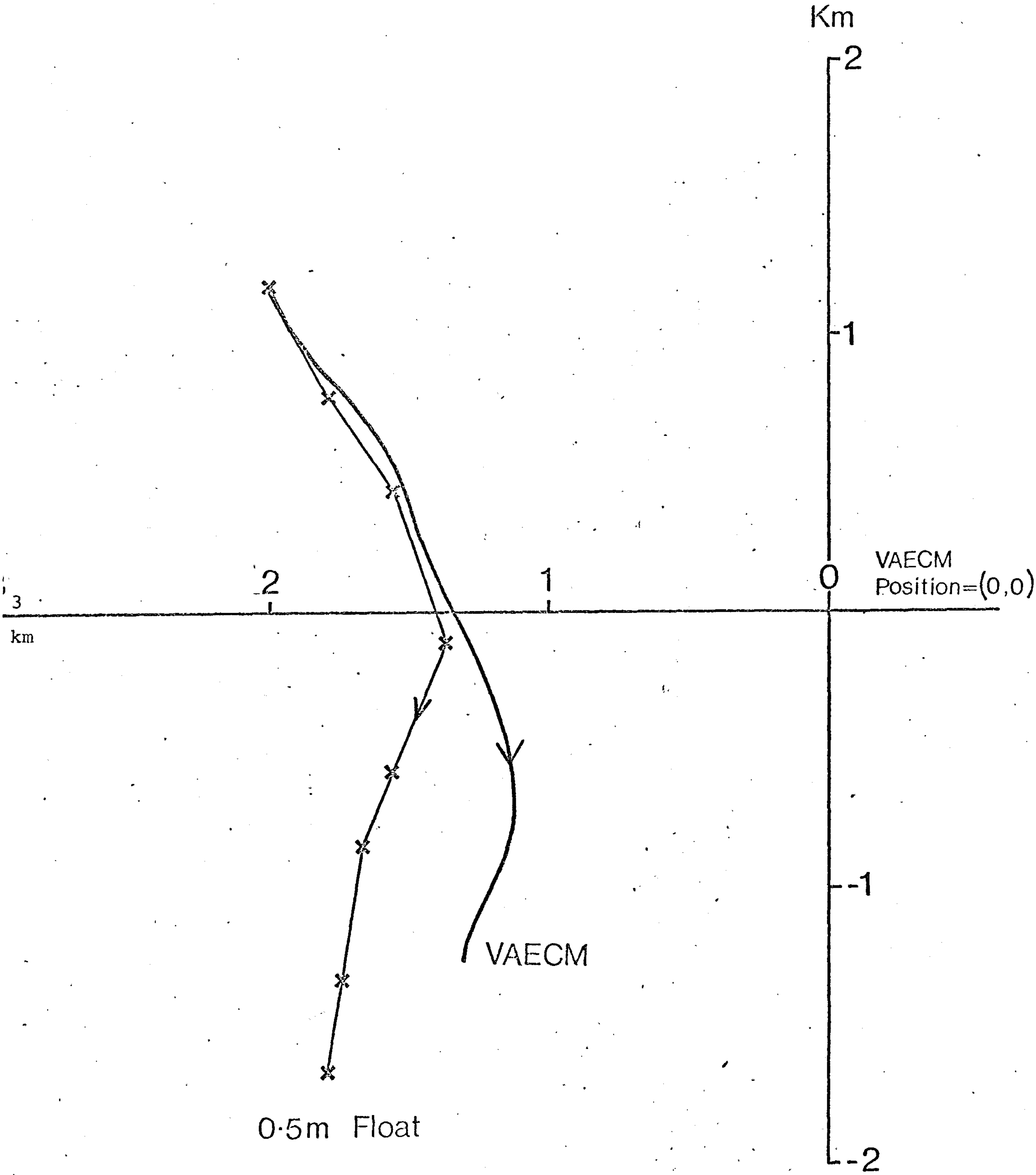


Figure 7(b). Comparison of VAECM progressive velocity vectors with Lagrangian float tracks. A nominal correction for flow obstruction has been applied to the VAECM records.

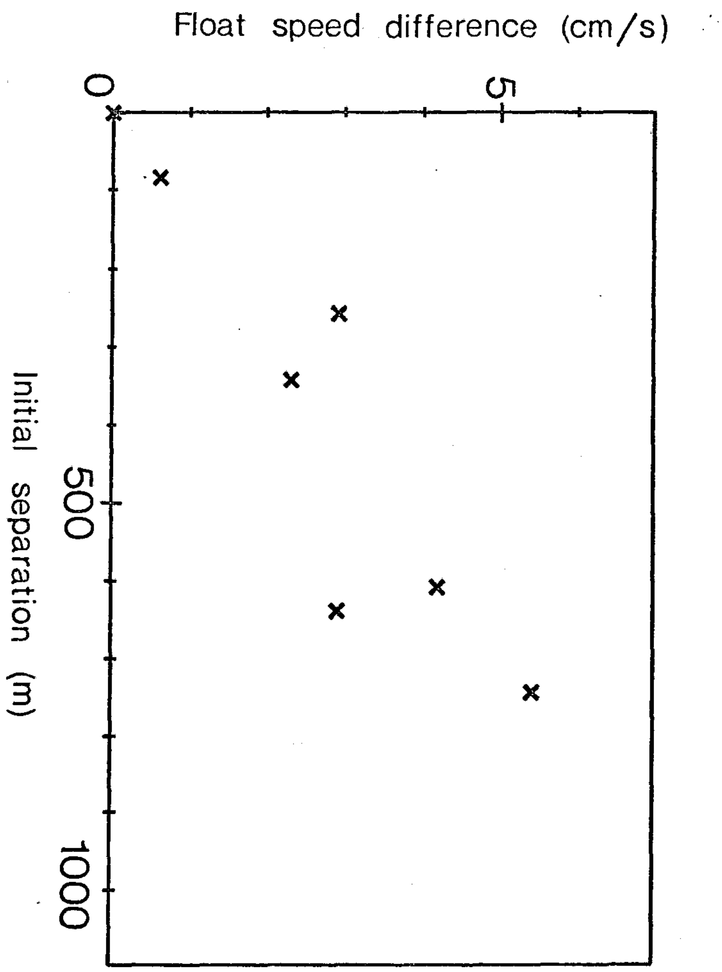


Figure 8. Difference in speed between identical floats, averaged over complete tracks, as a function of their initial separation.

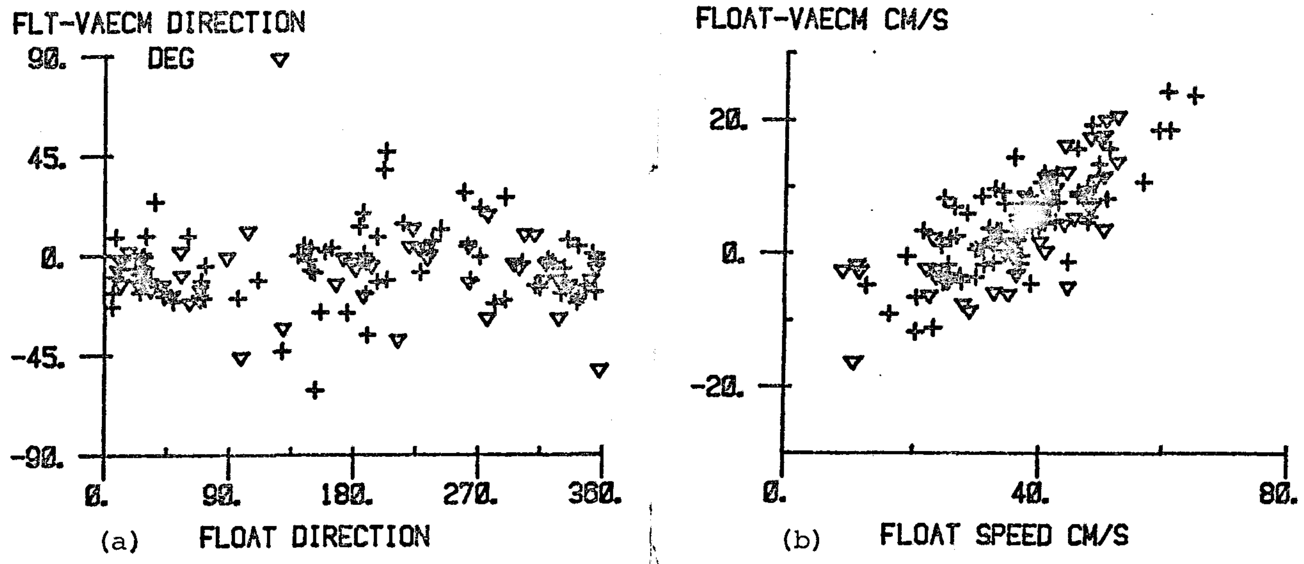
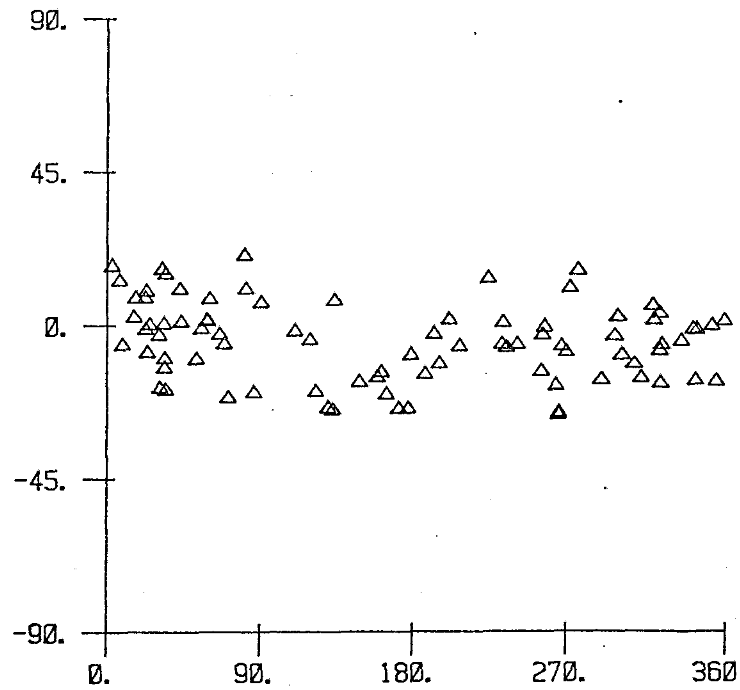


Figure 9. Differences in current direction (a) and speed (b) between individual 0.5 m float and VAECM observations over 15-minute intervals, plotted against float direction and speed, respectively. Points are classified according to prevailing wind speed.

+ Windspeed <5 m/s

∇ Windspeed >5 m/s



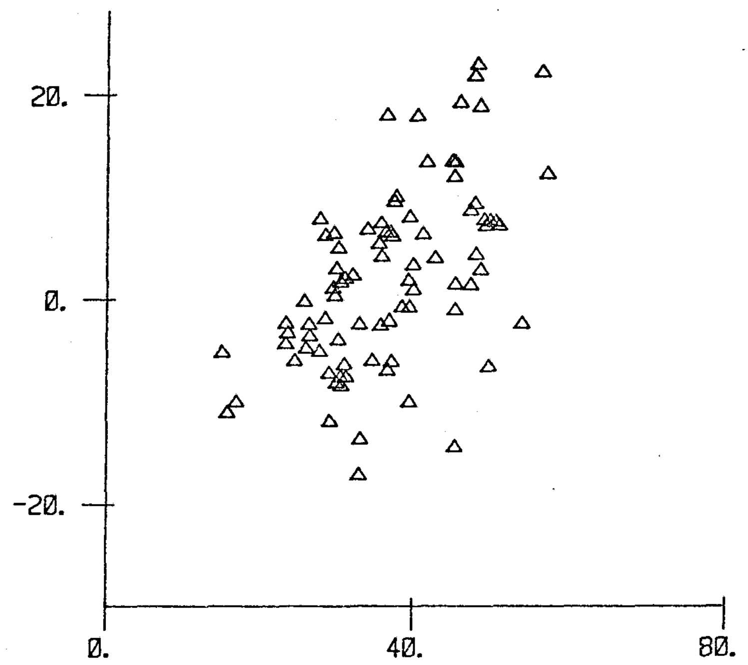


Figure 10. Differences in current direction and speed between individual 3 m float and DBCM observations over 15 minute intervals, plotted against float direction and speed, respectively.

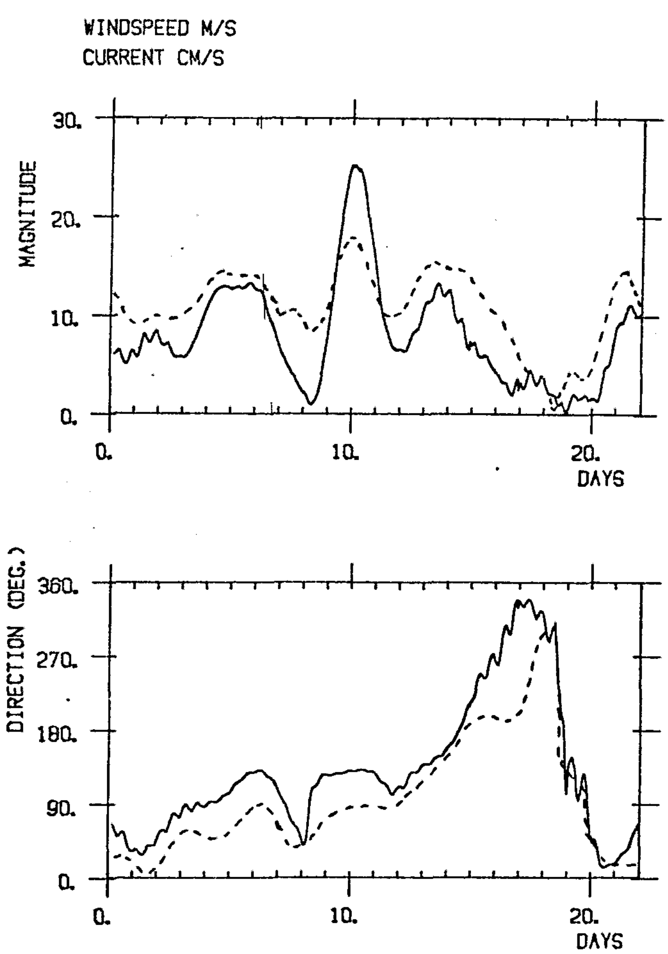
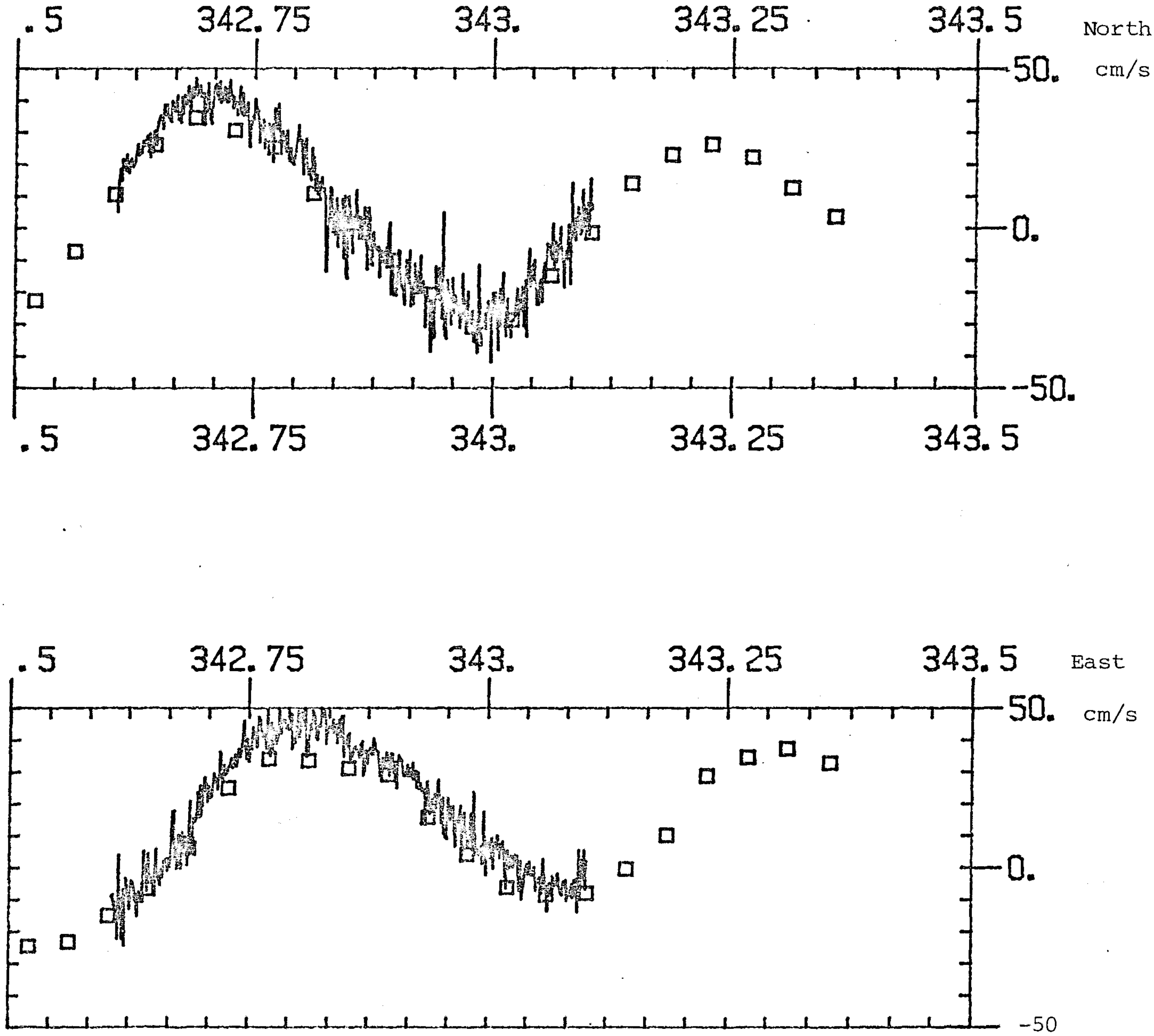


Figure 11. Low pass filtered output from DBCM at 3 m depth (solid line) and wind data at 8 m (broken line) December 1979. Filter cut off at 25 hrs.

Figure 12. East and North components of currents measured by VAECM at 0.5 m depth, December 1979 (112.5 second averages). Symbols - 5 min averaged DBCM currents. Windspeed increased from 9 m/s-18 m/s through the duration of the record.



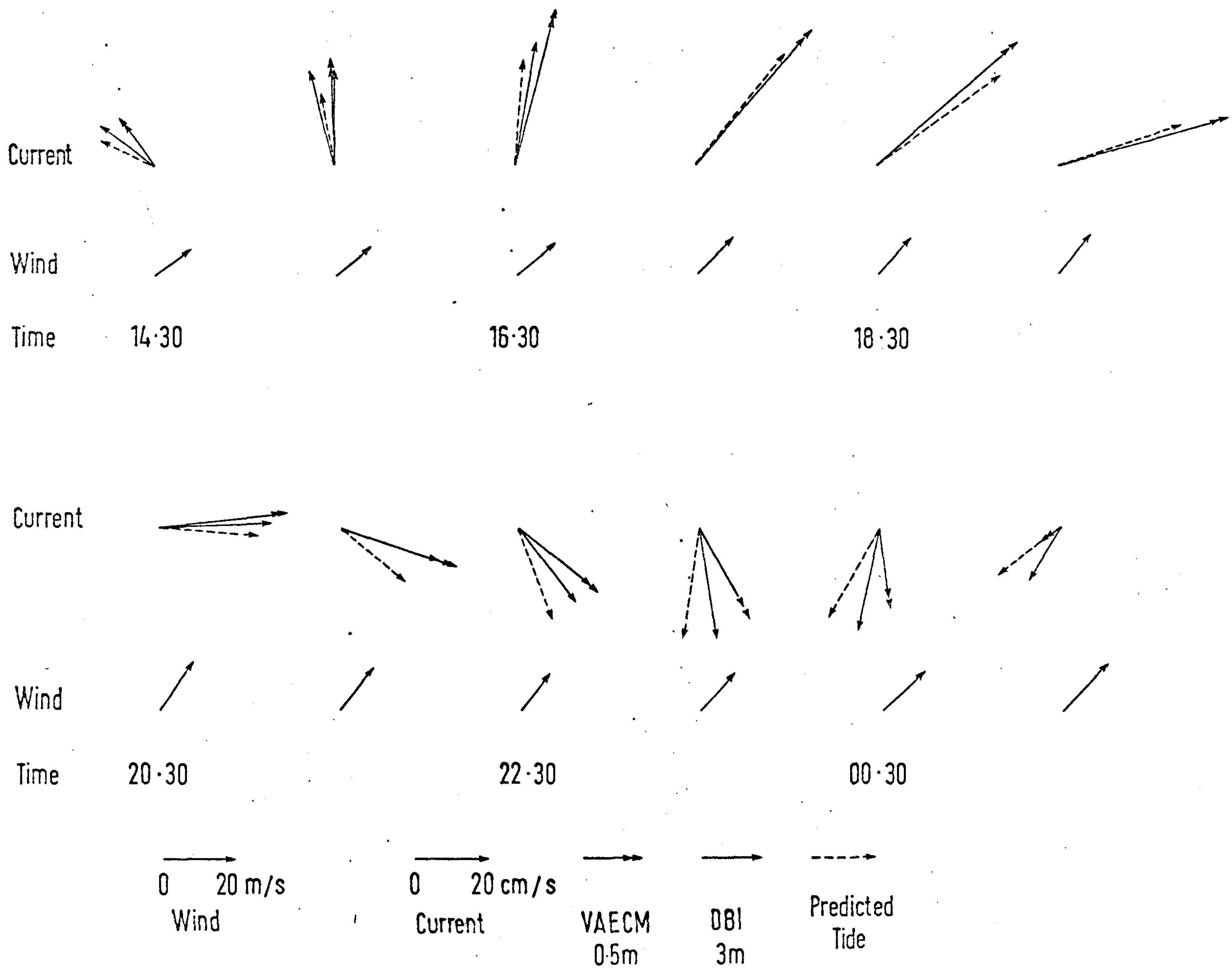
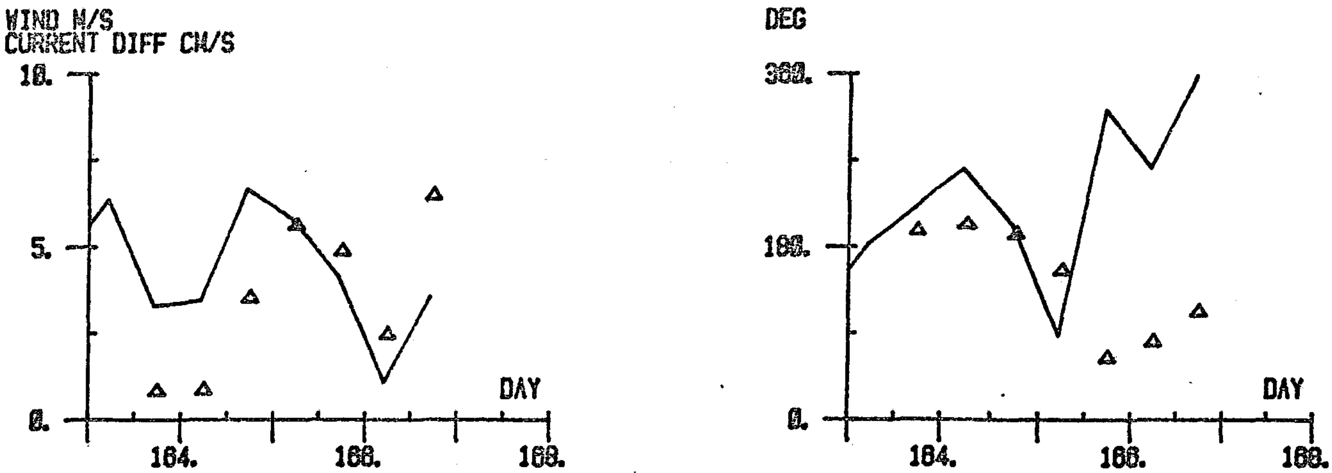
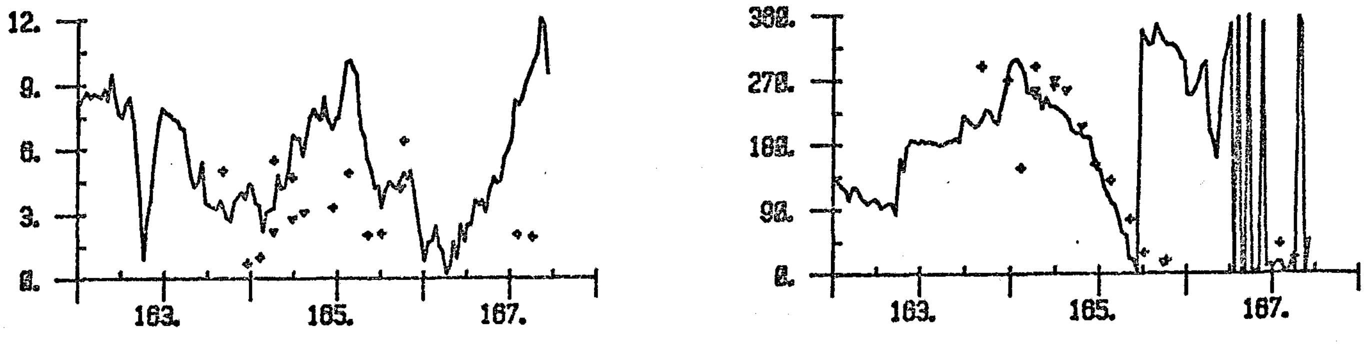


Fig. 13 Vector comparisons over 12 hours of VAECM (0.5 m) and DBCM (3 m) currents with wind and predicted tides, December 1979.



(a) (b)

Figure 14. Difference in vector speed (a) and direction (b) from true north (b) of 12-hr mean currents measured at 0.5 m (VAECM) and 3 m (DBCM). Solid line: 12-hr mean wind.



(a) (b)

Figure 15. Difference in vector speed (a) and direction (b) relative to true north of 0.5 m and 3 m drogued floats. Solid line - wind.

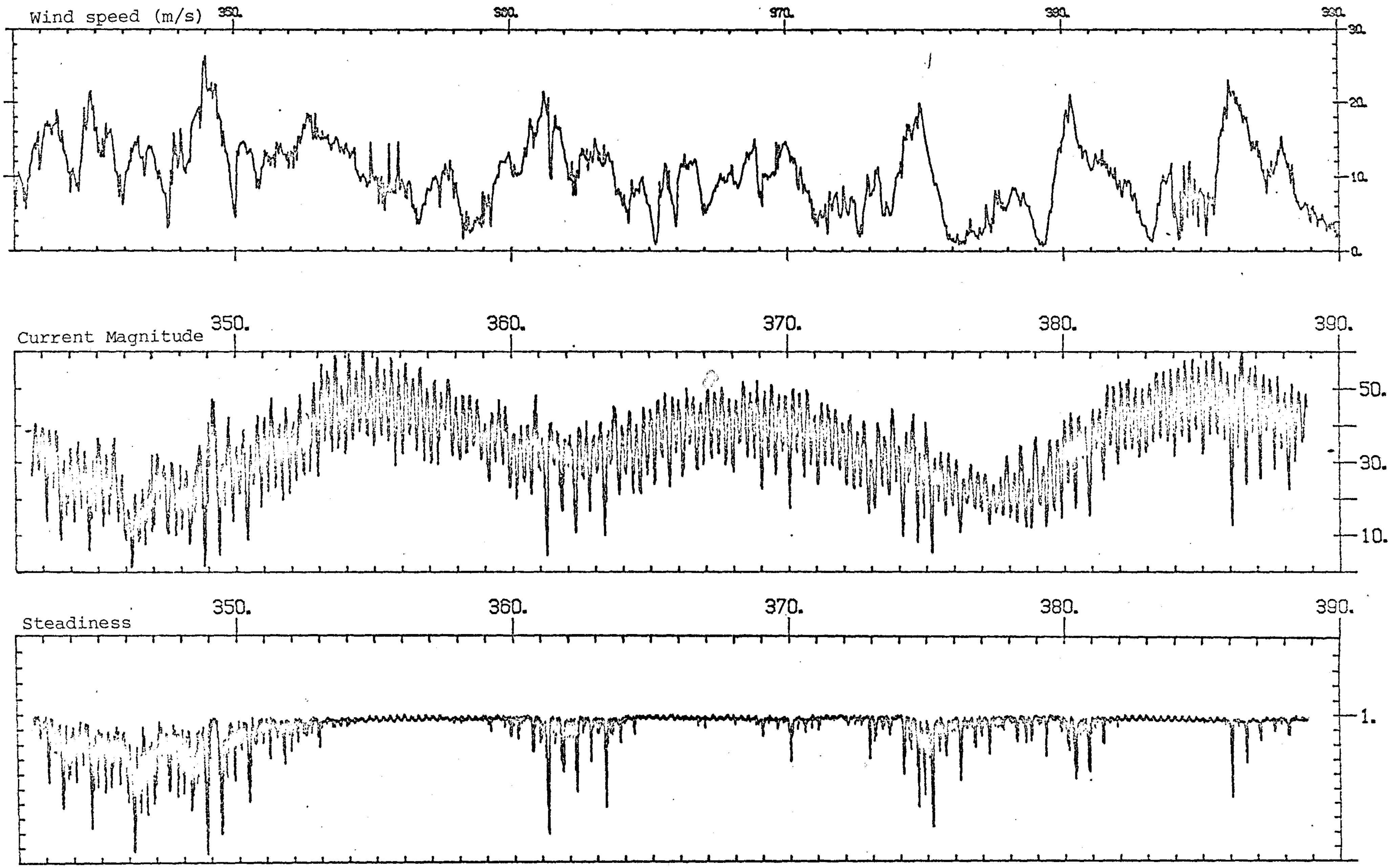
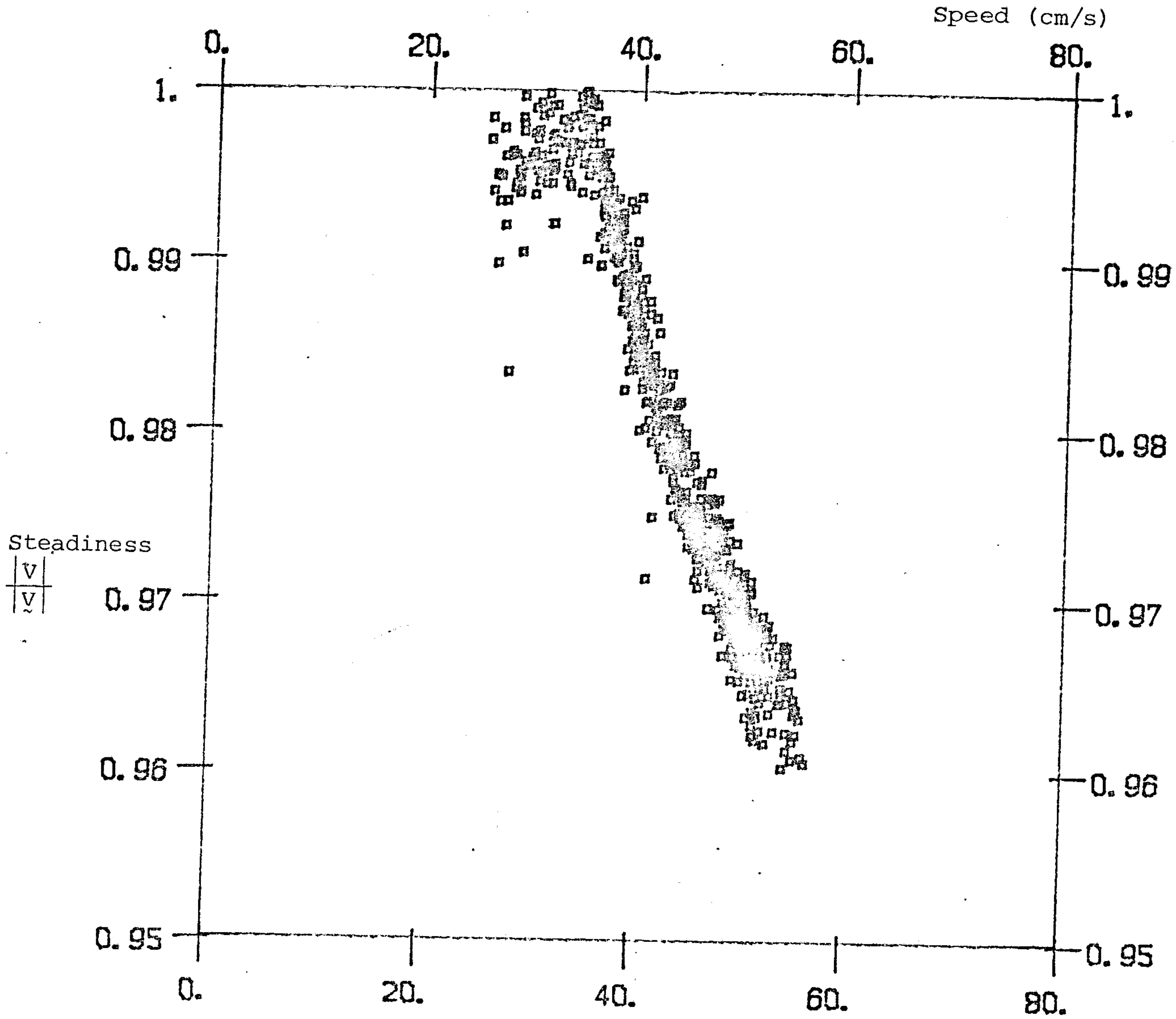


Fig. 16 Steadiness, S, current magnitude and windspeed during first deployment period (December 1979-January 1980). Note reductions in S during neap tides and at high wind speeds.

Figure 17. Steadiness, S, plotted against speed (VACM at 53 m, June 1980), showing reduction in S at higher currents.



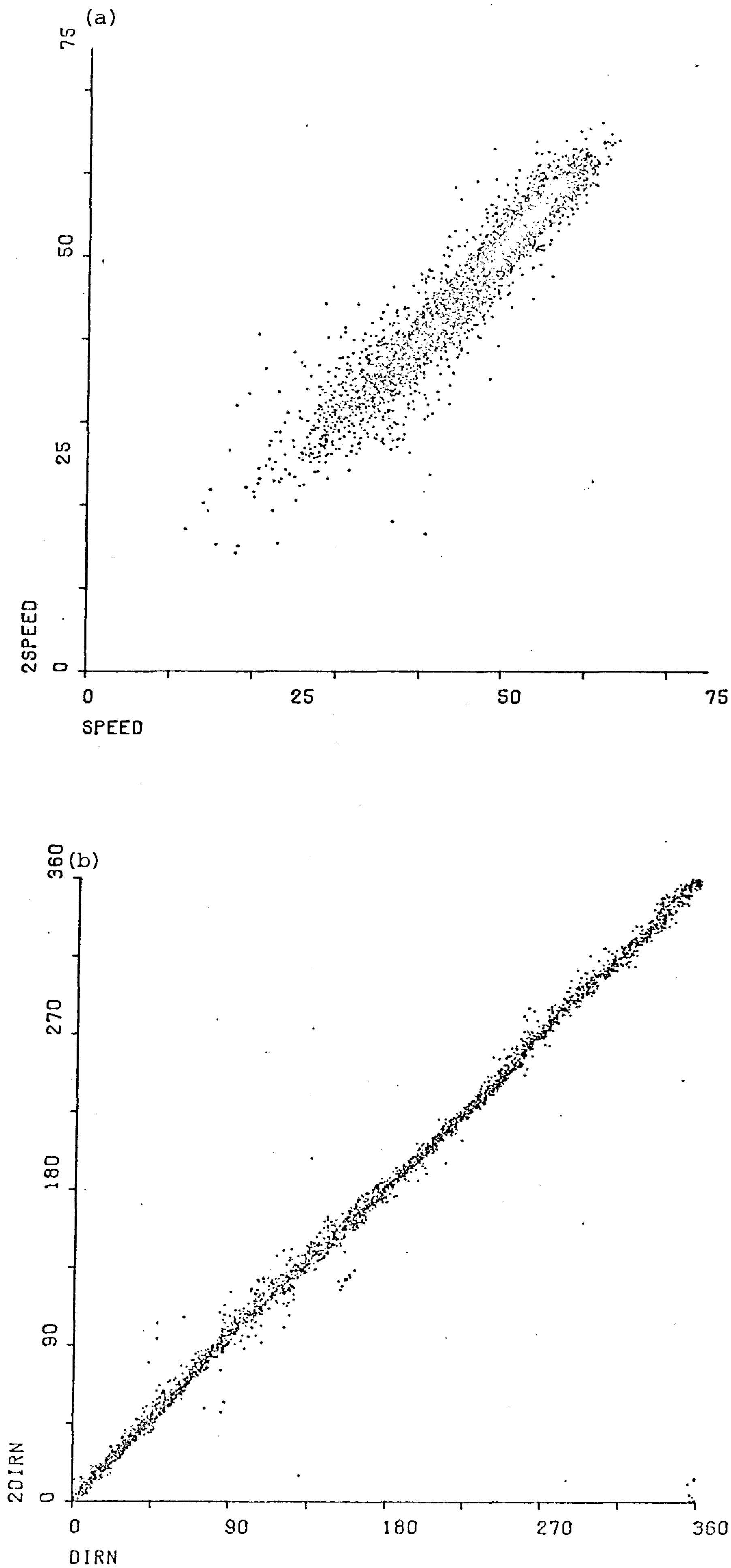


Figure 18. Scatter plot (a) speed (b) direction at 53 m depth of Aanderaa against VACM (June 1980). Note overreading of Aanderaa at higher speeds, believed to be caused by mooring oscillation.

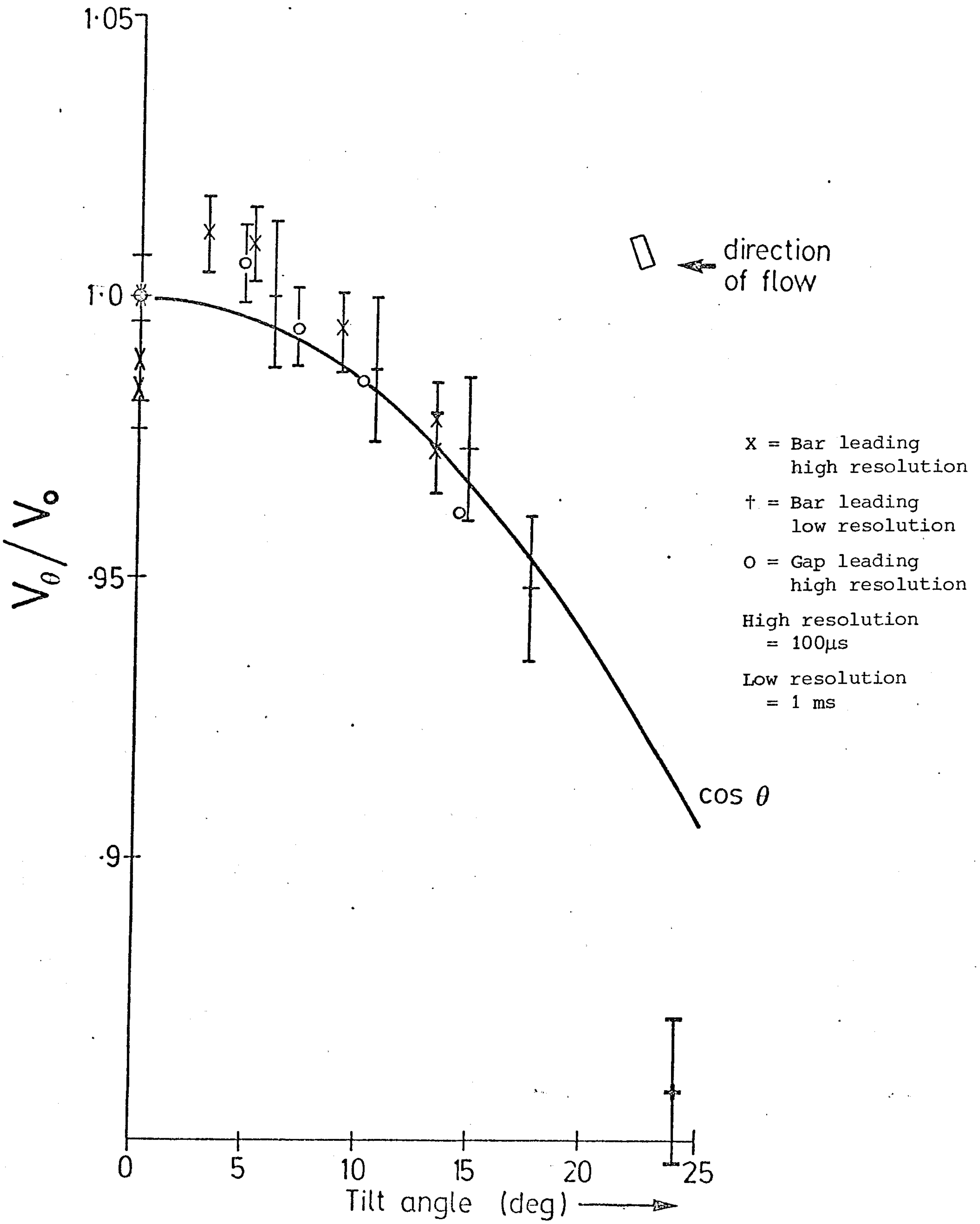


Fig. 19 Tilt response of VACM measured in tow tank.

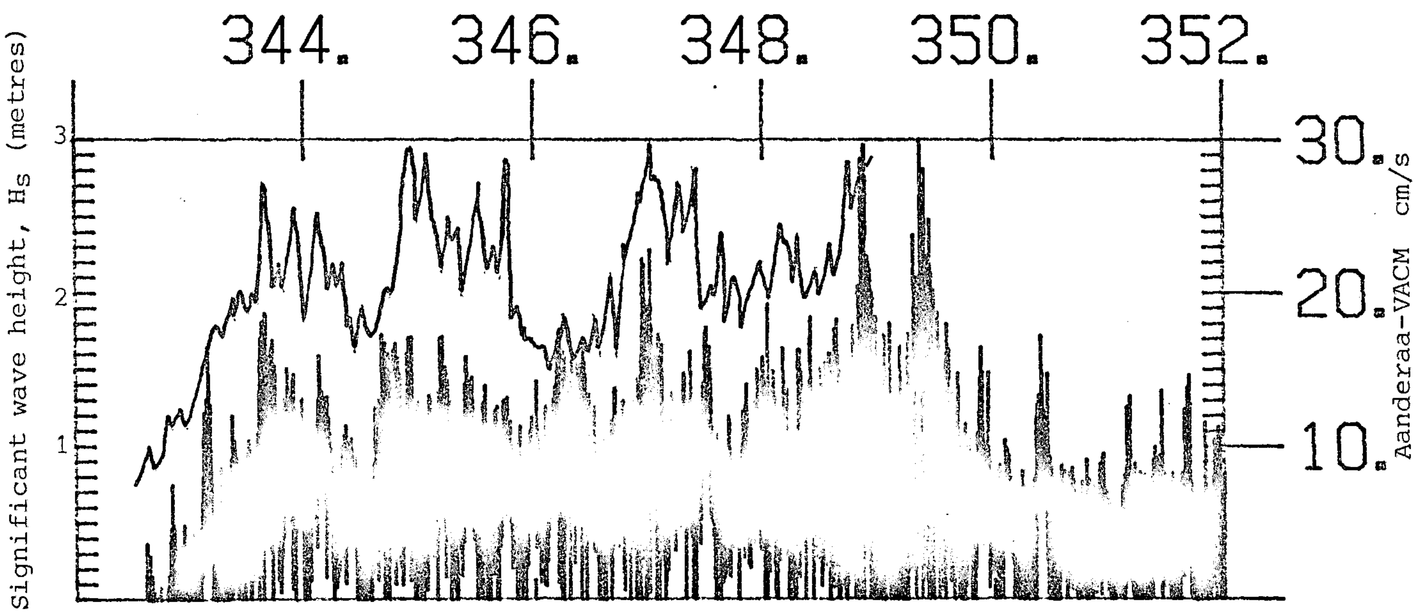


Figure 20. Relationship between difference in current magnitudes measured by Aanderaa and VACM (53 m depth, December 1979) and significant waveheight as given by wave statistics package on DB1.
(N.B. A fault existed on the wave statistics package after Day 349, resulting in loss of data).

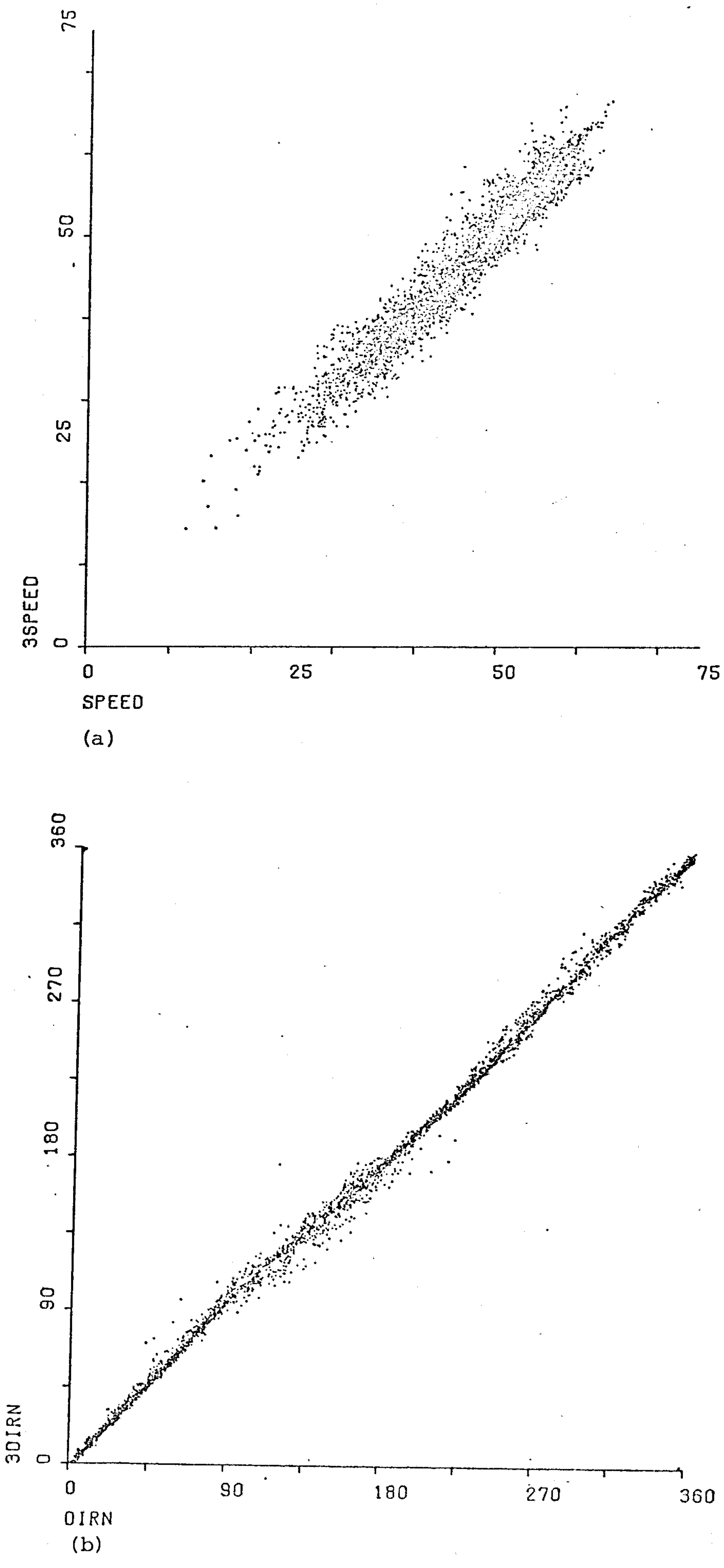


Figure 21. Scatter plot VACM - Plessey 9021 (June 1980).
(a) Magnitude (b) direction.

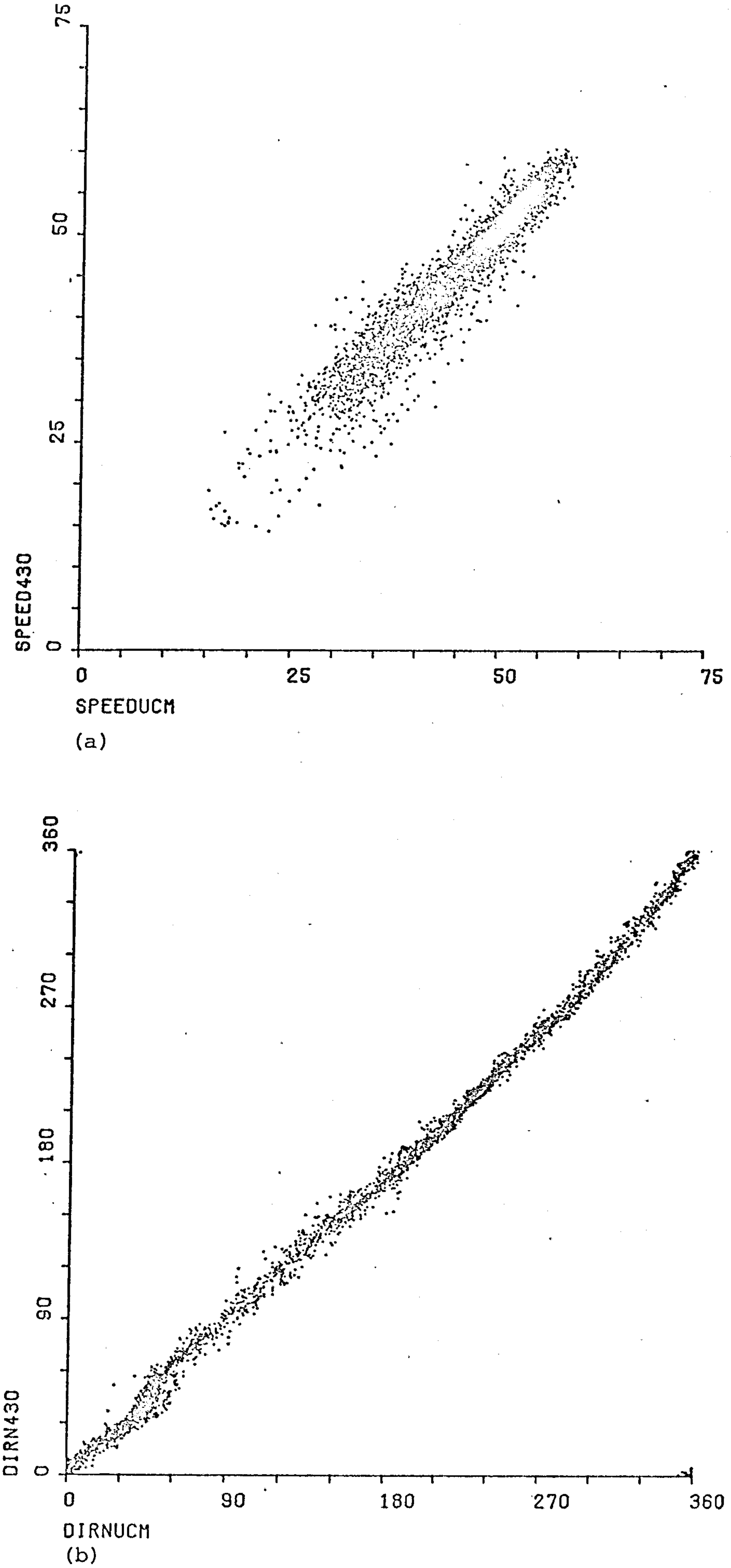


Figure 22. Scatter plot VACM - Simrad UCM2 (June 1980).
(a) Magnitude (b) direction.

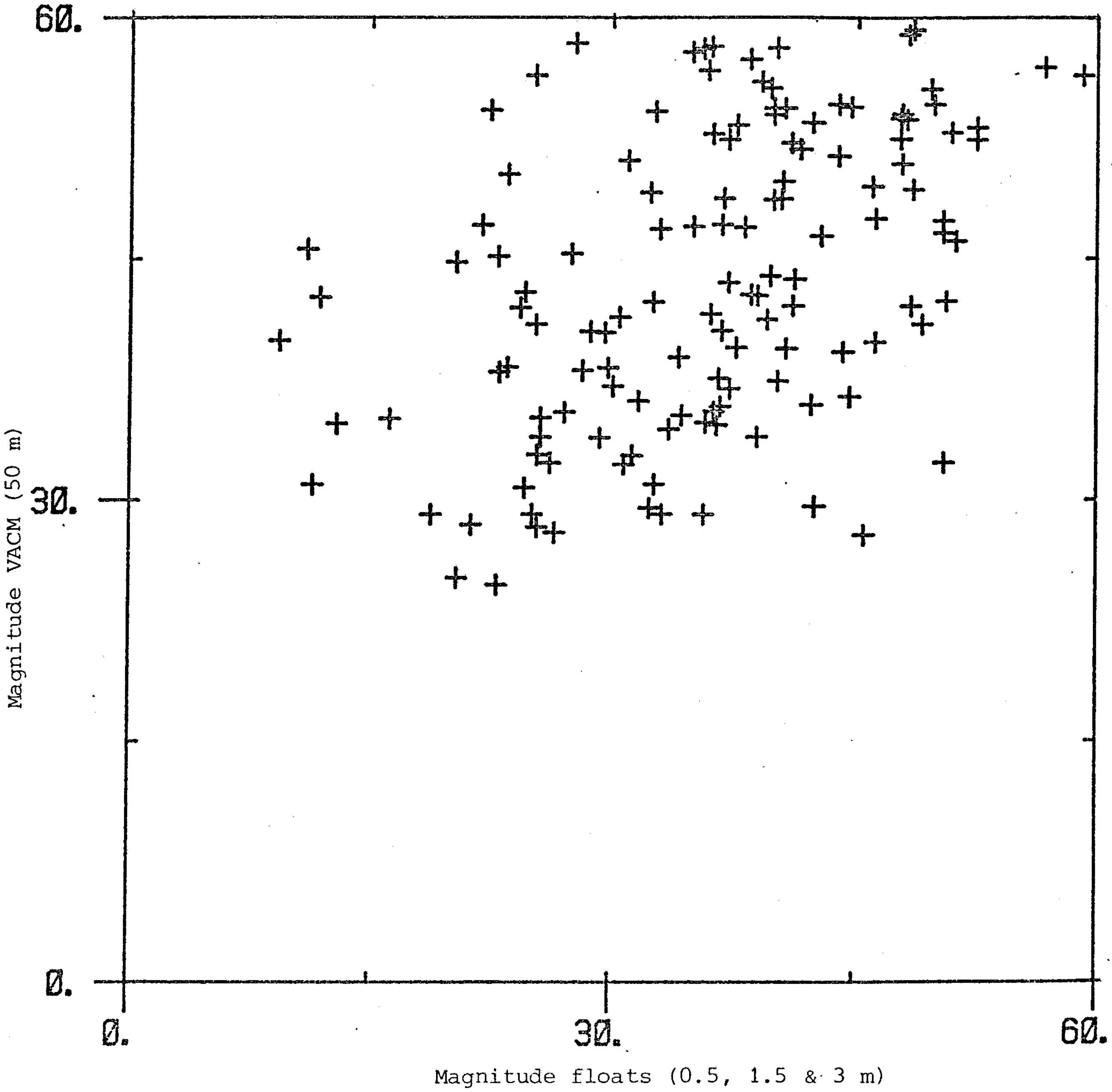


Figure 23. Scatter plot VACM (~50 m depth) speeds - near surface (0.5, 1, 3 m) float speeds, showing enhanced midwater currents.

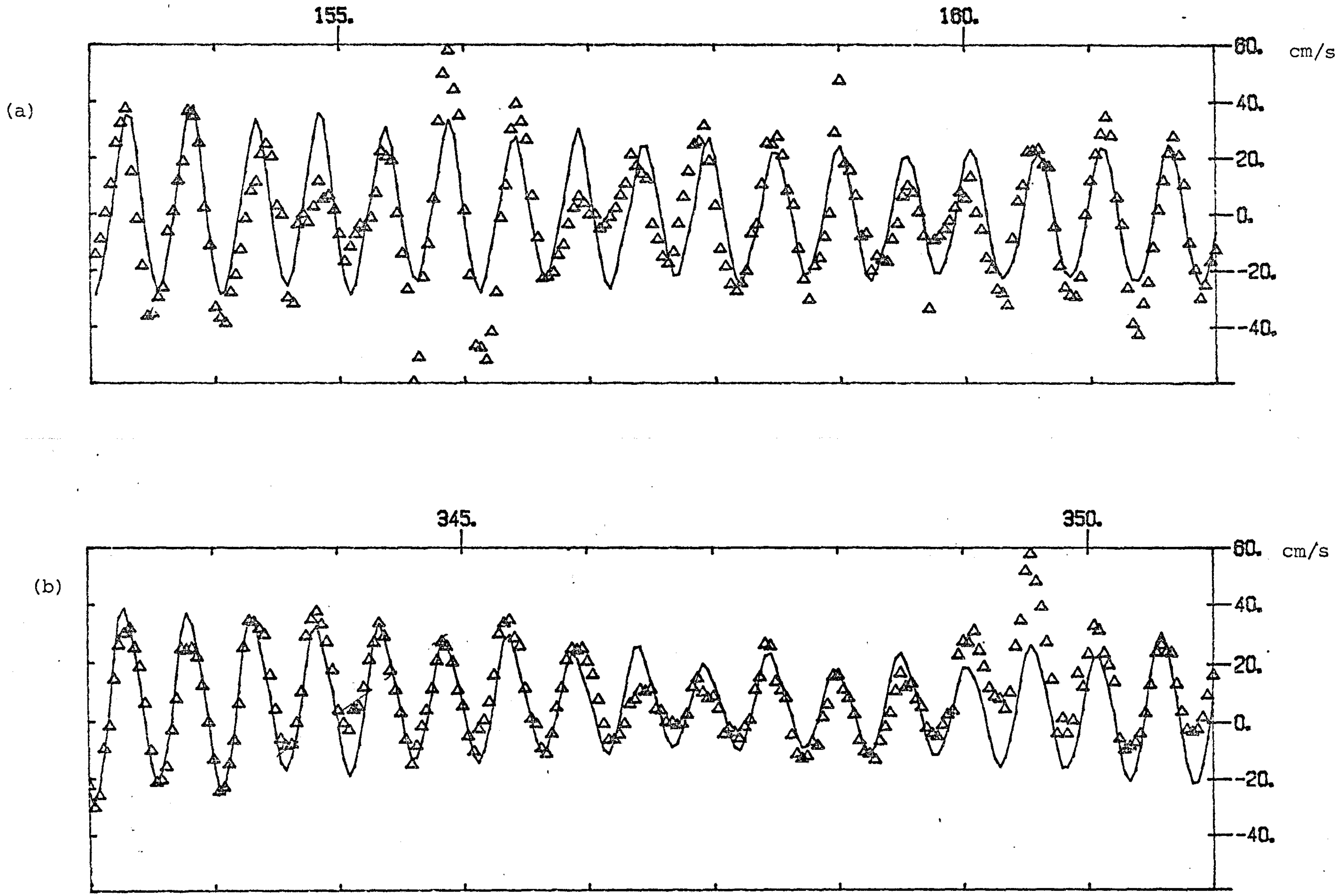


Figure 24. Observed DBCM currents (symbols) and predicted tide (line).
(a) June 1980 - East component.
(b) December 1979 - East component.