CHAPTER 30

FIELD MEASUREMENTS OF NEARSHORE VELOCITIES

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Abstract

Two component electromagnetic flowmeters are being used as the basis of an apparatus to measure nearshore velocities on natural beaches. The flowmeters are mounted on free standing tripods, 1 m. base side and 0.3 m. high, to measure the two components of horizontal flow, and have been used in depths of up to 4 m. and up to 150 m. from the shoreline. The apparatus has proved both flexible and reliable on beaches ranging from steep shingle (slope $\sim$ 0.13) to very shallow sand (slope $\sim$ 0.01) and under a wide variety of wave conditions, including full storm waves on a beach of intermediate slope ($\sim$ 0.04).

Results show that a single flowmeter can be used on a tidal beach to measure the variation of the flow field along a line perpendicular to the shoreline. In this way edge waves and steady nearshore circulation patterns have been detected. If several flowmeters are placed on a line perpendicular to the shoreline, the progress of individual waves can be followed as they pass over each flowmeter in turn, and hence propagation speeds, changes of wave form and the development of lower frequency wave motion close to the shoreline can be studied.

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Introduction

In recent years there has been a considerable increase in the theoretical understanding of modes of water motion trapped or generated in the narrow region bordering the coastline. Steady longshore currents, rip currents and wave set-up and set-down have all been explained in terms of the transfer of momentum from the incoming, breaking waves. Edge waves have been shown to be a possible cause of rip currents and of various sedimentary features which exhibit a regular, longshore rhythmical pattern. A number of recent theories have been concerned with the process of wave breaking, and the importance of the resulting turbulent velocity field and intensive vertical and horizontal mixing to many nearshore processes has also been highlighted.

Despite the fundamental importance of these phenomena to coastal engineering, reliable field observations of the velocity field close to the shore are at present relatively rare, particularly in the surf zone. However such measurements are needed urgently to evaluate the validity of the new theoretical ideas, and to suggest where these ideas are inadequate and need further improvement.

This paper describes a research programme to measure nearshore velocity fields, based on electromagnetic flowmeters. Some preliminary results using a single flowmeter and a line of three flowmeters perpendicular to the shoreline are discussed.

Electromagnetic Current Meters.

The two-component electromagnetic flowmeters originally developed by Tucker and co-workers (1970) at the National Institute of Oceanography, and now marketed by Colnbrook Instrument Development Limited, Poyle Road, Colnbrook, Buckinghamshire, England, were chosen for the present research programme since they are well suited to the violent nearshore environment, being rugged and compact, with no moving parts and a relatively fast response time. The measuring head itself, discus shaped, 11.4 cms. in diameter and 3.8 cms. deep, contains a circular solenoid developing an alternating magnetic field of about ± 60 guass perpendicular to the circular plane of the discus. Dissipation is about 8 watts. Water flowing through this field in the plane of the discus produces, by electromagnetic induction, a potential gradient perpendicular to the flow. Two pairs of electrodes mounted on the discus detect the two components of the electric field and hence measure the two components of the flow. The electrode sensitivity is about 200 $\mu V/ms^{-1}$, and calibration experiments have confirmed that this remains constant to about 1% for currents up to at least 3 ms^{-1}.

The directional properties of the flowmeter have been described by Tucker (1972). In the plane of the discus, the measured current amplitude is accurate to better than 5% for any direction of flow, though there is a small systematic variation in the error as the flow direction changes relative to the electrode alignment. The response to flow out of the plane is more complex, but is approximately correct for tilt in the range $\pm 30^{\circ}$ out of the discus plane. The time constant and noise level of the flowmeters depend on the waveform and frequency of the alternating current driving the magnetic field. In the present instrument an alternating square wave drive of 40Hz. results in a time constant of about 0.1 sec. (3 dB point ≈10 Hz.), and a noise level equivalent to a rms current of 5 mm s^{-1} was achieved in the field experiments; these characteristics have been considerably improved in more recent instruments (Tucker- private communication). The long-term stability of these flowmeters has allowed them to be used as ships' logs, and our experiments confirm that they can be used to measure the mean flow patterns in the nearshore zone at least over a period of several hours.

Figure 1 shows the mounts which were used to hold the heads, aligned to measure the horizontal flow field, on beaches in water of depth varying from 10 cms. to more than 4 m.. Non-magnetic materials were used throughout to prevent distortion of the flowmeter field. The spars holding the heads were of stainless steel, and supported the heads from below so that turbulence generated by the mounts would not pass over the heads themselves; calibration of the instruments in steady flows confirmed that the turbulence from the spars did not contribute significantly to the overall noise level. At the opposite end of the spars demountable underwater plugs were used, so that different lengths of electrical cable could be used, depending upon the distance of the instruments from the shore-based electronics units. The tripods themselves were constructed of aluminium alloy angle, with a base triangle of 1 m. sides and standing about 0.3 m. high. Lead weights at the corners of the base could be added to counteract the torque due to violent flow around the head. For very shallow water, simple triangular bases of aluminium angle were used to hold the flowmeter heads as little as 10 cms. from the sea-bed.

The larger tripods could also hold capacitance pressure sensors below the flowmeters; measurements of the two horizontal components of flow and the vertical displacement of the water surface at a point allow an approximate directional spectrum of the surface waves to be calculated.

This apparatus was designed for use on tidal beaches. The tripods were placed in situ above the low water mark at low water, and were then covered for several hours spanning high water as the tide rose and fell. The instruments were placed at known positions relative to a fixed origin above the high water mark, with the flowmeter electrodes aligned by eye to within 2° of the offshore and longshore directions.

This simple method of mounting the flowmeters has proved both flexible and reliable on beaches ranging from a steep shingle beach (slope $\sim$ 0.13) to a very shallow sandy beach (slope $\sim$ 0.01), and under a variety of wave conditions, including full storm waves on a beach of intermediate slope ($\sim$ 0.04); experiments have not yet been conducted under storm conditions on the steepest beaches. Position and orientation changes of the tripods could be checked at each low water. When the triangular tripod bases were dug into the beach to a depth of about 10 cms., and the electric cable to the flowmeter similarly dug in, no lateral movement was detected on any of the beaches and tilt of the heads out of the horizontal plane was at most a few degrees.

The chief problems in the field experiments occurred in making a satisfactory connection between the flowmeter spar and the electric cable connecting it to the shore-based instruments. The low voltage signal from the electrodes is very susceptible to being swamped by spurious voltages due to leakage from the current leads driving the magnetic field solenoid; impedances less than 1000 $M\Omega$ between the drive and the electrode leads cause appreciable deterioration in the signal to noise ratio. Although co-axial leads were used throughout in order to minimize the pick-up between the electrode and solenoid drive circuits, connections to the spars were particularly prone to damage when the tripods were dug up and moved to other locations, and the instruments could become unworkably noisy unless care was taken in making the demountable connections.

The shore-based instruments driving the flowmeters were housed in a Land Rover vehicle parked as close to the shoreline as possible, to obtain maximum offshore distance to the flowmeters with the minimum length of cable. Experiments have now been conducted with up to 150 m. of cable to the spars and, with suitable calibration adjustments, this length could probably be considerably increased without significant decrease in the signal to noise ratio. The Land Rover contained the flowmeter electronics and both analogue and digital logging apparatus. The digital logger was a battery driven magnetic tape machine able to record up to 10 analogue and 1 digital channels every 1/3 second; signals from five flowmeters could be recorded every 1/3 second continuously for a period of up to 2 hours.

A single flowmeter on tidal beaches

On tidal beaches, a single fixed flowmeter can be used to measure the variation of the velocity field along a line perpendicular to the shore, by making use of the change of shoreline position during a tidal cycle. We have used this technique to measure nearshore drift currents, incident gravity waves, edge waves and high frequency motion close to the shore.

An implicit assumption is that the velocity field is quasi-stationary as the shoreline moves. The validity of this assumption can be checked by comparing measurements made at the same distance from the shore on the rising and falling tide. As an example, figure 2 shows measurements of steady longshore currents in a wide surf zone on a shallow beach, where the point at 93m. and the lower point at 115m. were measured on the rising tide and the remaining points on the falling tide. The consistency of these results confirms that, at least for the steady longshore currents, the velocity field remained reasonably stationary over a 4 hour period. Also plotted in figure 2 are drift velocities obtained by measuring the longshore displacements of floats over periods of order 2 minutes at different distances from the shoreline; the results are seen to be in good agreement with the flowmeter data.

Since the flowmeters measure both onshore and longshore components of the mean flow as functions of offshore distance, they can also be used to detect nearshore circulation cells. For example measurements on a steep beach gave onshore and longshore drift currents which varied with offshore distance as shown in figure 3b. These currents have been interpreted as measurements along a line A in a nearshore circulation cell system shown schemmatically in figure 3a.

In addition to the mean flow, average properties of the fluctuating motion can also be measured at different distances from the shoreline using a single flowmeter. The measured velocity fluctuations in any chosen frequency band may be due to gravity waves or edge waves, and both may be either standing or progressive waves. Edge waves are modes of wave motion trapped to a shoaling coastline by refraction; their amplitude varies sinusoidally along the shore and decays rapidly seaward from the shoreline. By measuring the r.m.s. amplitudes of both onshore and longshore flow at different distances from the shoreline with a single flowmeter, it is possible to distinguish between gravity and edge waves, and standing and progressive wave motion.

The relative phase of the onshore and longshore components of velocity measured simultaneously by a single flowmeter assists in distinguishing these wave components. If we define the offshore and longshore co-ordinates as the x and y directions respectively, then it is readily shown that the velocity potentials ϕ for a gravity wave of frequency σ can be written

$\phi \sim \sin k_1 x \cos (k_2 y - \sigma t)$ for a standing wave formed by reflection at the shoreline

and $\phi \sim \cos (k_1 x + k_2 y - \sigma t)$ for a progressive wave,

where k_1, k_2 are the onshore and longshore wave numbers. The onshore and longshore velocities are $u = \frac{\partial \phi}{\partial x}$ and $v = \frac{\partial \phi}{\partial y}$ respectively, and hence these velocity components are in quadrature for standing gravity waves and in phase or antiphase for progressive gravity waves. Similarly the velocity potentials for edge waves of frequency σ and longshore wave number λ can be written

$\phi \sim f(x) \cos \lambda y \cos \sigma t$ for standing waves

and $\phi \sim f(x) \cos (\lambda y - \sigma t)$ for progressive waves, where $f(x)$ is a function which decays rapidly offshore (Eckart 1951; see also Bowen and Inman, 1969). Once again $u = \frac{\partial \phi}{\partial x}$ and $v = \frac{\partial \phi}{\partial y}$; in this case therefore the onshore and longshore velocities are in phase or antiphase for standing edge waves and in quadrature for progressive edge waves.

These considerations have enabled us to distinguish short period standing edge waves in the velocity field on a steep beach (Huntley and Bowen, 1973).

An array of 3 flowmeters at different distances from the shoreline.

Although useful data can be obtained using a single flowmeter, arrays of flowmeters, measuring simultaneously at different positions in the nearshore zone, provide considerably more information. The condition of a statistically stationary velocity field can be relaxed or even dropped, relative phases at different positions can be measured, and progressive movement of individual waves can be followed.

A closely spaced array of flowmeters on a line at right-angles to the shoreline can be used to study the horizontal turbulence in the nearshore zone and, in principle, could provide a measurement of the horizontal eddy viscosity as a function of distance across and seawards of the surf zone. Simultaneous measurements of turbulence and incident wave orbital velocities provide an estimate of the total "radiation stress" at different distances from the shoreline. Since the flowmeters measure not only the fluctuating components but also the steady flow at a point, this technique could provide a direct test of the theories of longshore current generation based on radiation stress and horizontal eddy viscosity (Bowen, 1969, Longuet-Higgins, 1970a,b).

With an array perpendicular to shore it is also possible to follow the progress of individual waves as they pass over each flowmeter in turn, and hence wave propagation speeds, changes of wave form and the development of lower frequency wave motion close to the shoreline can be studied. Figure 4 shows some preliminary results from simultaneous measurements of onshore-offshore horizontal velocities at three different distances from the shoreline. The right hand side of the diagram shows the beach profile, with offshore distance from the shoreline plotted upwards and the offshore distance axis itself representing approximately the mean sea level; the positions of the three flowmeters relative to this profile are shown as dots A,B and C.

The left hand side of the diagram shows a short example of the onshore velocity time series measured with these flowmeters. In each case negative velocities represent flow towards the shoreline; flowmeter C was uncalibrated during this experiment. Oblique lines have been drawn to join the peak onshore velocities of chosen waves at each of the flowmeters.

The breaking regime for the incident waves during the time of these measurements was complex, though typical of many beaches when an offshore bar is present. The incident swell waves, with a period of about 8 seconds and average height of about 0.5 m., broke on the offshore bar on the shoreward side of flowmeter C, but reformed and ceased to break as they passed over the crest of the bar and approached flowmeter B. The waves then broke a second time shorewards of flowmeter A, with a surf zone about 10m. wide. The time series of onshore-offshore velocities reveal details of this wave behaviour. At flowmeter C the time series of velocities under the unbroken swell waves has the form of an amplitude modulated sine wave, but the re-formed waves in much shallower water at flowmeters B and A show the rapid acceleration and deceleration about the peak onshore velocities characteristic of peaked solitary-wave motion. The increase in onshore currents as the waves steepen between B and A is also clear.

The average phase velocities of individual wavecrests can be found from the time lag between the passage of the waves over successive flowmeters, and in figure 4 these phase velocities are represented by the slopes of the straight lines joining crests in each of the flowmeter records. As expected, the phase velocity between flowmeters B and A is less than between C and B as the waves travel more slowly in the shallower water. There is also a marked dependence of the phase velocity of a wave on the amplitude of onshore velocity under its crest. Thus in figure 5 an enlargement of a portion of the onshore velocity time series from the three flowmeters shows, in the top record, a low wave followed by a much higher wave. As the waves progress over flowmeters B and A, the higher wave travels more quickly than the low wave, causing the two waves to merge together in record A. A similar effect can be seen at the beginning of the record in figure 4 and, towards the end of this figure the opposite effect can also be seen where a high wave begins to leave a smaller wave behind. Such merging and splitting of wave crests must be very significant in forming the frequency spectrum of wave energy in the nearshore region.

When the reciprocal of the time lags, for example between A and B, are plotted against water particle velocities under crests, as in figure 6, the dependence of the phase velocity, c, on the particle velocities, u, is clearly seen. The approximate straight-line fit to these data is in good agreement with the characteristic equation for finite amplitude shallow water waves. Investigation of the propagation of these waves is continuing.

As the shoreline receded on this tidal beach, the effect of the outer bar became more pronounced and the onshore array of flowmeters was able to detect further changes in the waveforms of the incident waves (figure 7). In particular, the inner flowmeters show that the re-formed waves on the shoreward side of the bar became bore-like, with rapid acceleration to peak onshore velocities, and were frequently split, with a train of waves following the forward face of the bore. Splitting of the wave crests in this way is characteristic of the formation of undular bores and has been observed on other beaches (Gallagher, 1972, Huntley and Bowen (in press)). In this case the undulations were formed as a result of a weakening of the breakers as they passed over the crest of the bar and into the deeper water beyond (cf. Gallagher, 1972).

Figures 8 and 9 show examples of the complete range of parameters measured with the array in this field experiment; the longshore component of the middle flowmeter was not operating. As expected for refracted incident waves, the longshore flow components are small in figure 8, but closer to the shoreline, in figure 9, the longshore flow is comparable to the onshore flow, and a low frequency component is very marked. The period of this low frequency motion is approximately

24 seconds, and is thus in good agreement with the measurements made by Emery and Gale (1951) of swash period on beaches of comparable slope.

There are indications that the onshore and longshore components of this low frequency motion are in antiphase, which would be consistent with standing edge wave motion. An edge wave of this period would have wavelengths of about 15 m. and 45 m. for a zero and first order mode respectively, and either of these values could account for the fact that the motion is observed only with the nearshore flowmeter, since the amplitude of edge wave motion decays rapidly offshore and becomes negligible at a distance from the shoreline comparable with the edge wave wavelength. Possible non-linear mechanisms for generating low frequency edge waves include interaction between two incident wave trains (Gallagher 1971), or growth of edge waves from standing waves formed by reflection at the shoreline (Guza and Davis 1974). Huntley and Bowen (in press) have also suggested that edge waves may be formed on steep beaches, by strong interaction between incident waves and a natural low frequency swash motion characteristic of the beach slope and surf zone width. It is possible that a similar interaction occurred on this beach.

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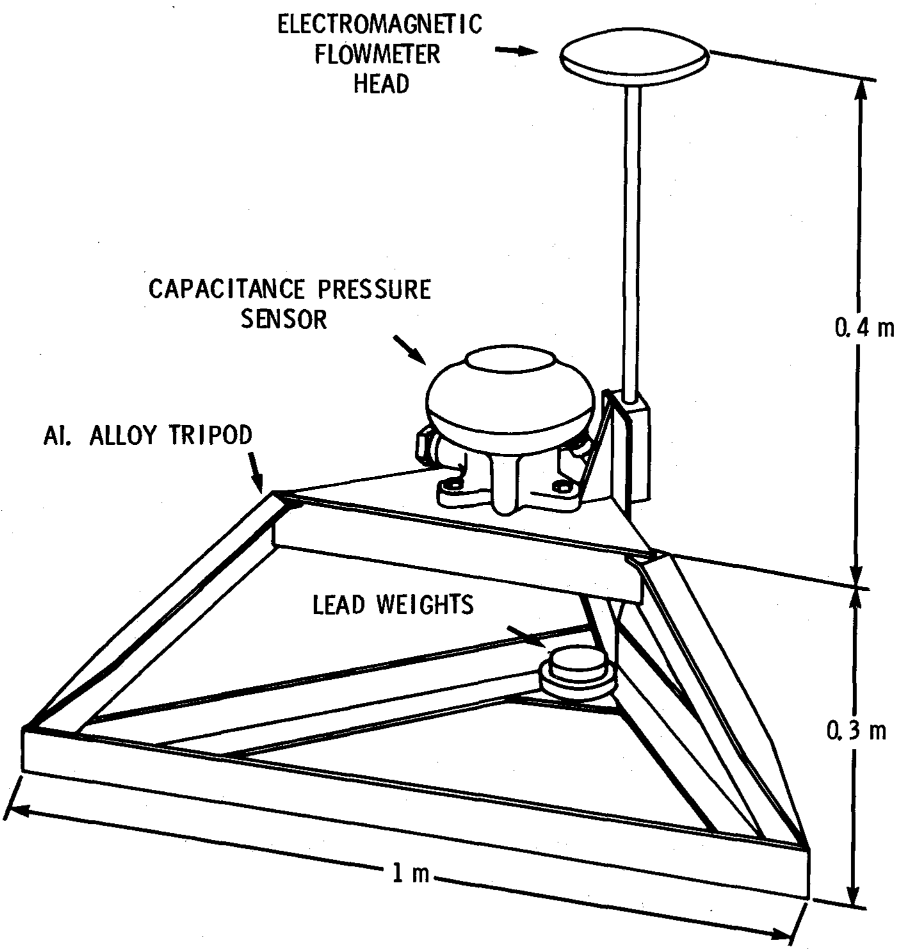

Figure 1. Schemmatic diagram of the flowmeter mount.

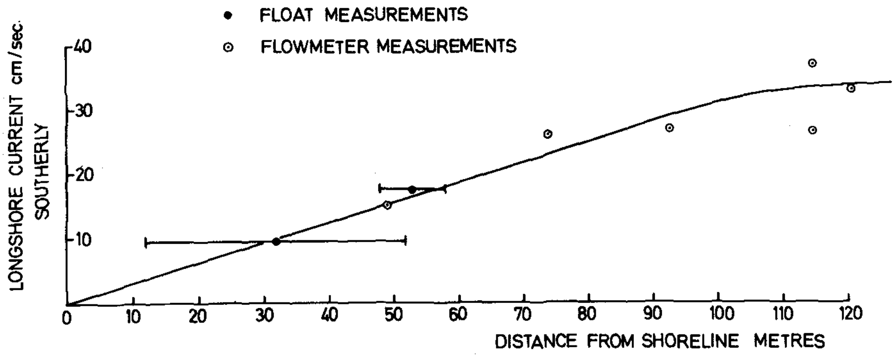

Figure 2. Longshore drift currents on a shallow (slope 0.01) beach. The surf zone was about 250 m wide. (From a forthcoming book to be published by John Wiley and Sons Ltd. - HAILS/CARR: Nearshore Sediment Dynamics and Sedimentation).

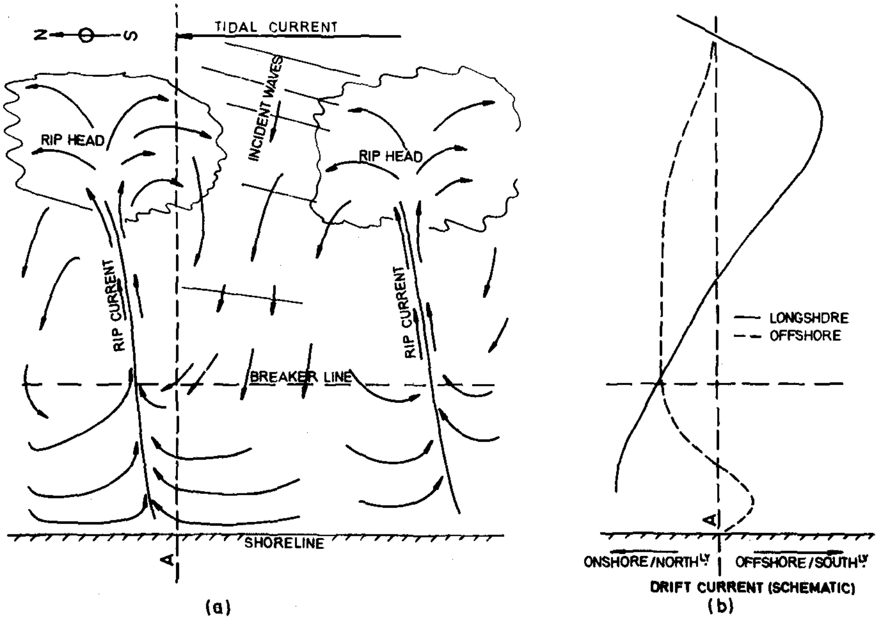

Figure 3. (a) Schemmatic diagram of a nearshore circulation system detected on a steep beach.

(b) The measured variation of longshore and on/offshore current amplitude with distance from the shoreline. These measurements are consistent with measurements along a line A in figure 3a.

(From a forthcoming book to be published by John Wiley and Sons Ltd. - HAILS/CARR: Nearshore Sediment Dynamics and Sedimentation).

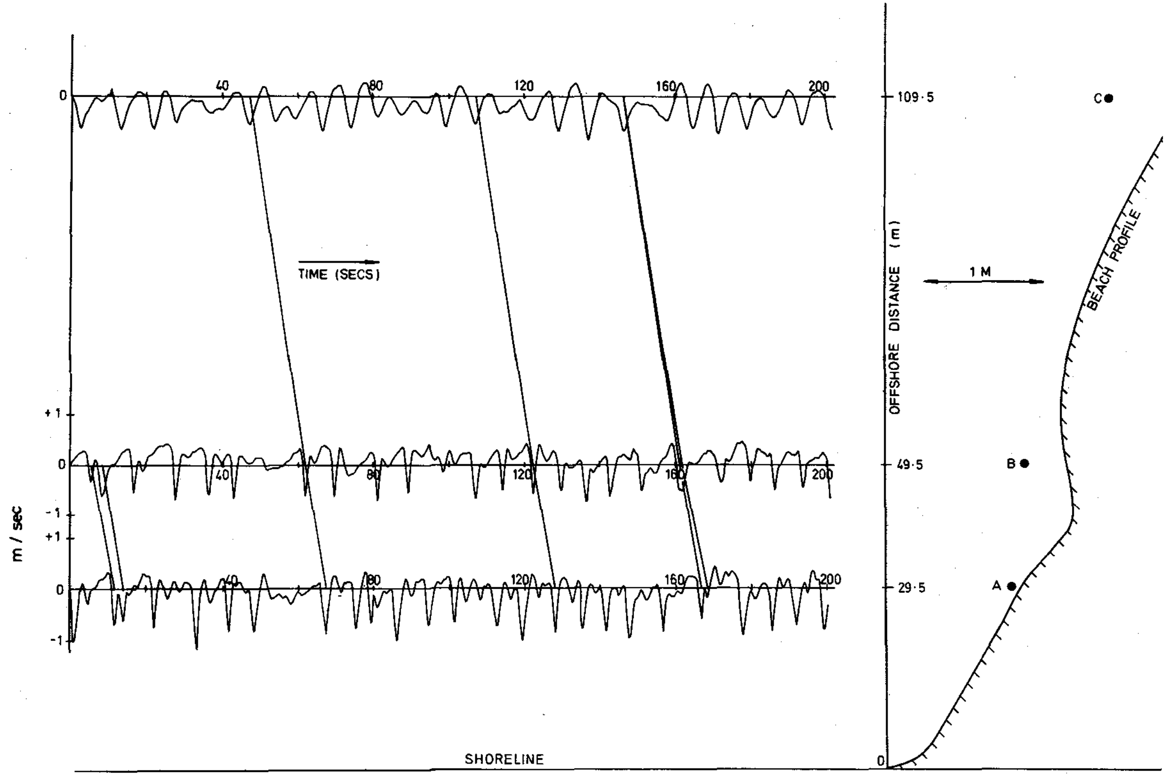

Figure 4. Simultaneous records of on/offshore velocities at three different points along a line perpendicular to the shoreline. The beach profile and positions of the flowmeters are shown on the right-hand side of the diagram.

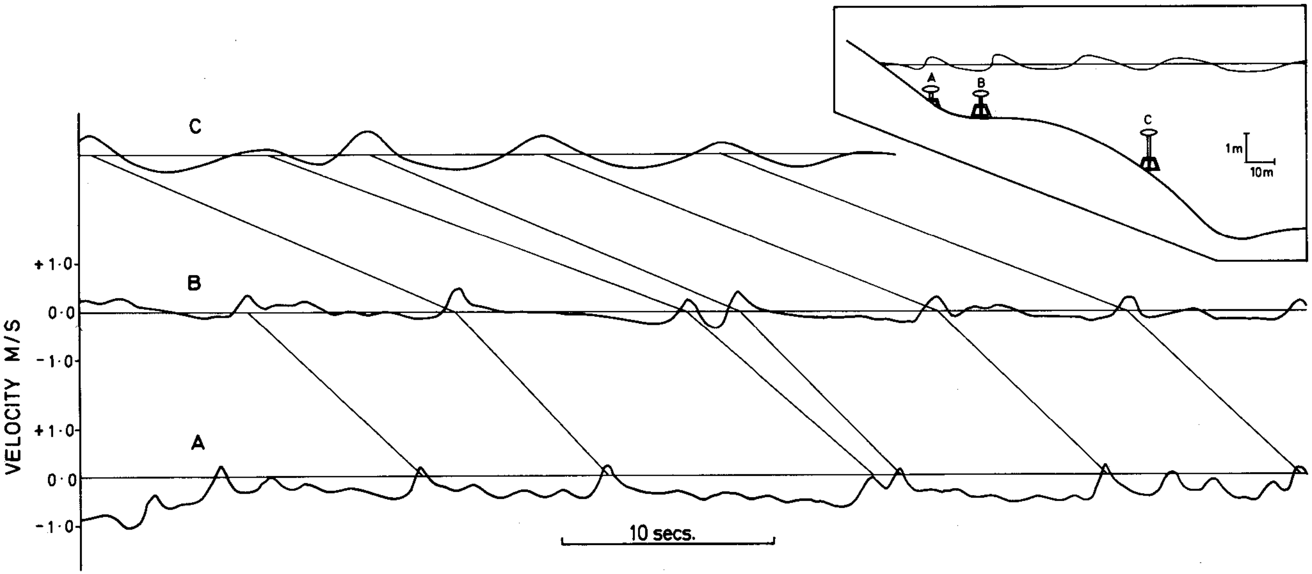

Figure 5. Onshore currents at different distances from the shoreline. The inset shows the positions of the flowmeters. The sketched flowmeters and their mounts are not to scale. The record for flowmeter C is uncalibrated.

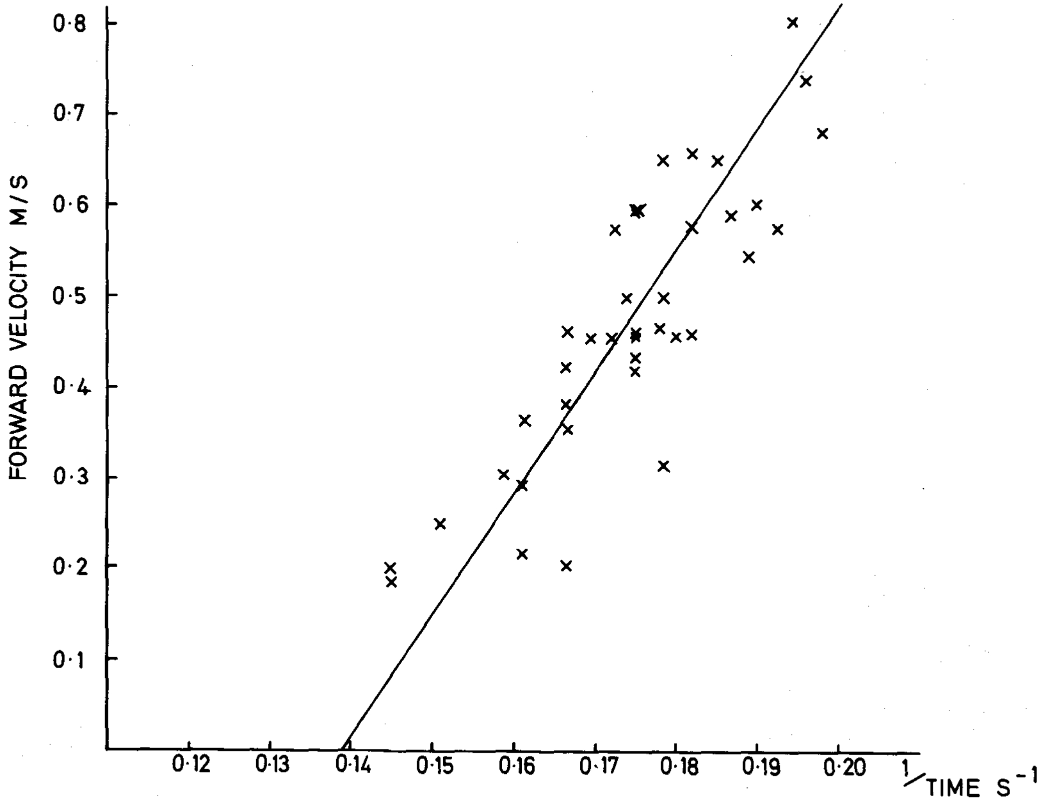

Figure 6. The reciprocal of the time for a wave to travel between flowmeters B and A, plotted against the forward velocity under the wave. The solid line through the data points is the theoretical variation based on the characteristic equation.

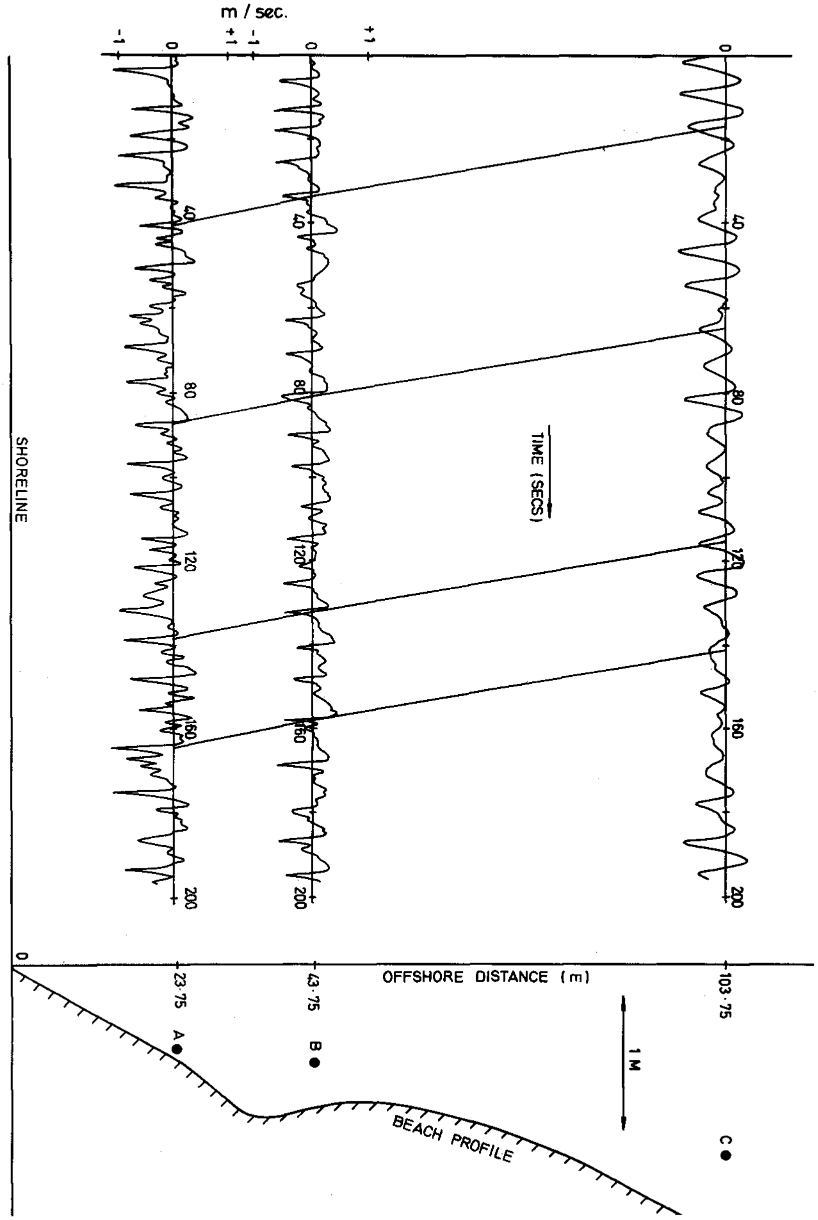

Figure 7. As figure 4, but with each flowmeter closer to the shoreline.

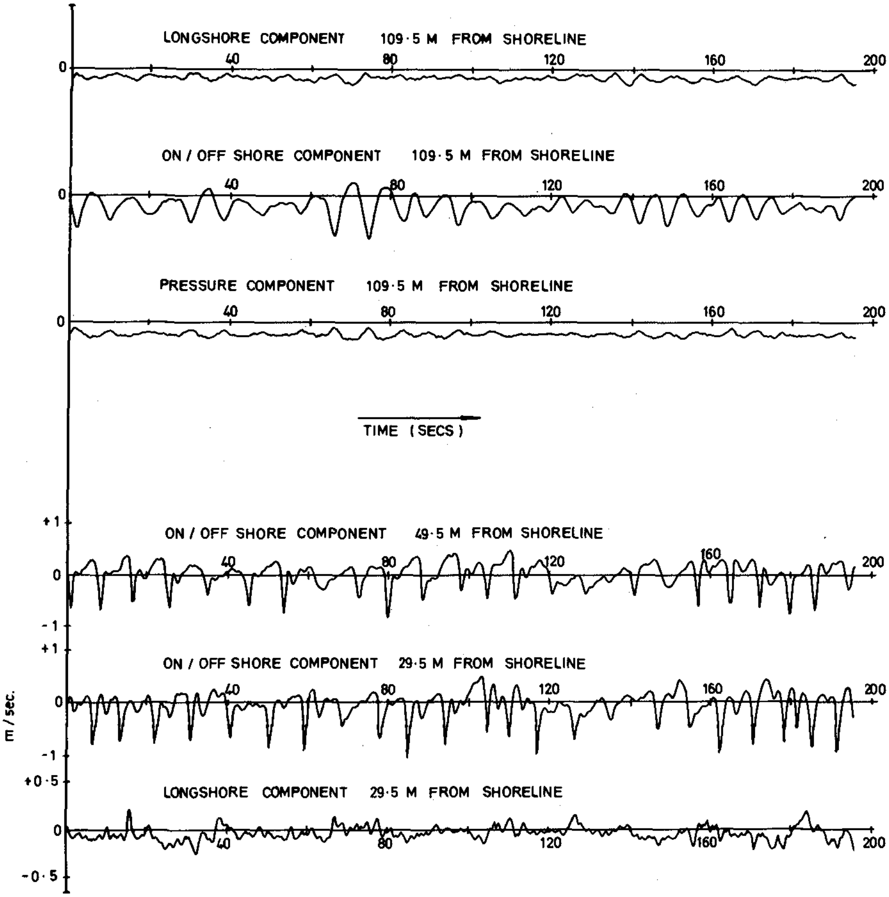

Figure 8. Simultaneous measurements made using three flowmeters and a pressure sensor along a line perpendicular to the shoreline. The longshore component of the flowmeter at 49.5 m. from the shoreline was not operating.

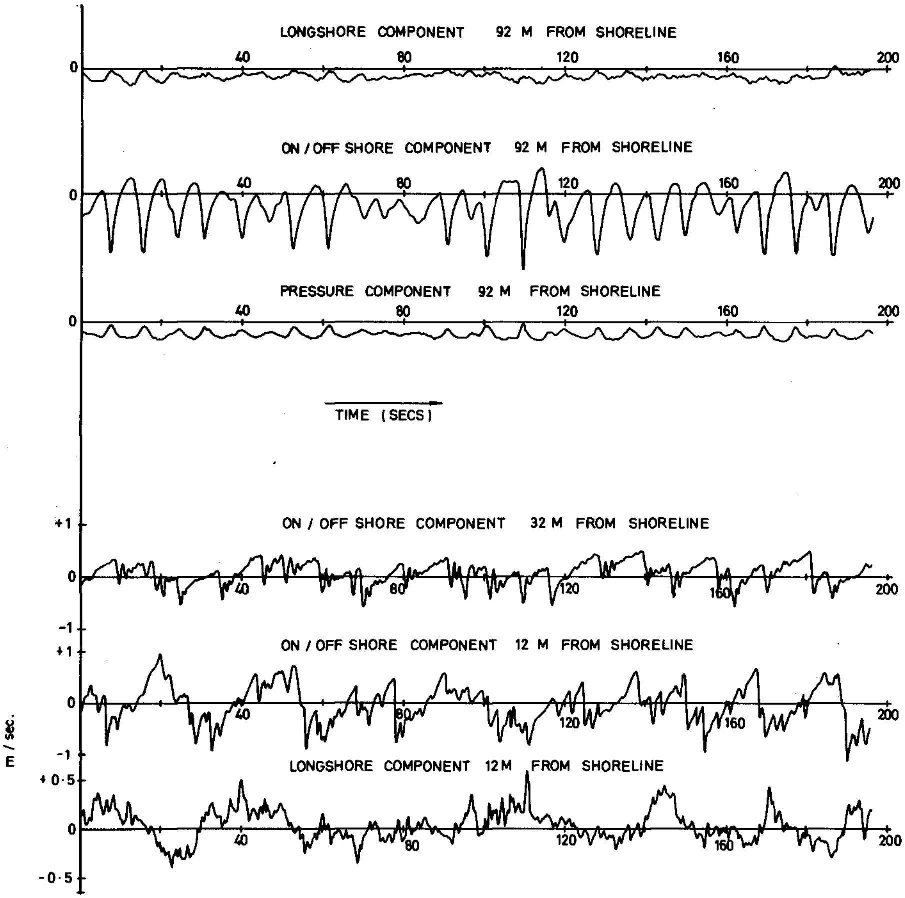

Figure 9. As figure 8, but with each instrument closer to the shoreline.