# CHAPTER 37

## LATERAL AND BOTTOM FORCES ON LONGSHORE CURRENTS

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ABSTRACT

A two-component electromagnetic flowmeter has been used on a natural beach of slope 0.01 to measure mean longshore currents and the horizontal fluctuating velocities in the frequency range 0-1 Hz. The measurements extend up to 120 m offshore and span about one third of a wide surf-zone. The cross product of the fluctuating horizontal velocities, assumed to contain the combined effects of radiation and Reynold's stresses, is plotted as a function of distance from the shoreline. The on/offshore gradient of the cross-product is then equated with a bottom friction term either in the form used by Bowen (1969a) or in a form similar to that used by Longuet-Higgins (1970). The apparent values of bottom friction coefficient obtained in this way are at least a factor of two smaller than expected for Reynolds numbers and bottom roughness appropriate to the beach. Attempts to separate the radiation stress and the Reynold's stress contributions to the total stress term using cospectra fail to show distinguishable Reynold's stress contributions. Although this may be construed as being consistent with Battjes' (1975) beach slope dependent form for horizontal eddy viscosity rather than Longuet-Higgins' (1970) form, it is argued that, in fact, the significant horizontal turbulence was not measured at all but was confined to a surface layer above the flowmeter. This leads to the hypothesis that lateral friction, as a surface boundary layer, and the bottom friction act on a less turbulent central layer, and that the small measured friction coefficient in the present experiment is the result of the combined effects of these layers.

## INTRODUCTION

Wave-induced longshore currents, confined mainly to the surf-zone, are assumed to be the result of a balance between a gradient of incident wave radiation stress, a gradient of horizontal turbulent Reynold's stress and bottom friction acting on the longshore current (for a recent review see Longuet-Higgins 1972). Recent theories have parametrised these three balancing forces in terms of easily measured macroscopic properties of the flow. Radiation stress is generally calculated from incident wave height and angle of approach; the Reynold's stress acting in the longshore direction is assumed to be the product of the on/offshore gradient of the longshore current and a coefficient of eddy viscosity dependent in some way on distance from the shoreline and beach slope; bottom friction has been parametrised in a number of ways

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involving a coefficient of friction, the value of the mean longshore current and possibly the wave orbital velocity (calculated in turn from the mean water depth).

Despite the success of these theories in predicting at least the order of magnitude of longshore currents there are a number of uncertainties, particularly in choosing the appropriate parametrisation of Reynold's stress and bottom friction. These uncertainties arise primarily because the nature of turbulence within the surf zone is not well understood. Is the appropriate scaling length for the horizontal eddy viscosity coefficient a horizontal distance from the shoreline or a local water depth (Longuet-Higgins 1970; Battjes 1975)? Is a depth mean turbulence picture in fact appropriate or is the wave-breaking turbulence confined to a relatively thin surface layer? What are appropriate values of bottom friction coefficient if much of the turbulence is generated not by bottom roughness but by wave breaking?

The fast response and ruggedness of electromagnetic flowmeters provide an opportunity to begin answering these questions by direct measurement of the fluctuating components of the velocity field, both waves and turbulence, simultaneously with measurement of the mean longshore flow.

This paper discusses an experiment on a shallow beach (beach slope $\beta = 0.01$) in which a two-component flowmeter was used to measure on/offshore and longshore currents in a frequency range 0 - 1 Hz along a line normal to the shoreline. The data provided a direct measurement of the combined local radiation and Reynold's stress forces as well as an on/offshore profile of longshore current. The first part of the paper discusses the friction coefficient obtained from these data, and there follows some discussion of attempts to separate the radiation stress and Reynold's stress components in the data.

## THEORY

We assume a co-ordinate system with the x - axis increasing seawards from zero at the shoreline, the y - axis alongshore and the z - axis increasing vertically upwards from the mean still water surface.

The longshore equation of motion for steady currents, assuming hydrostatic pressure and neglecting wave-current interaction, is the shallow water equation

$$\frac{u\partial v}{\partial x} + \frac{v\partial v}{\partial y} = - \frac{g\partial\bar{\eta}}{\partial y} + R_y + \tau_y \tag{1}$$

where u, v are the on/offshore and longshore depth mean currents (including wave-induced mass transport) respectively, $\bar{\eta}$ is the wave induced mean set-up of the water level, $R_y$ is the bottom friction term and $\tau_y$ is usually written as the sum of radiation stress and Reynold's stress gradients in the on/offshore directions. If conditions are uniform in the longshore direction then terms in $\partial/\partial y$ disappear and the first term also becomes zero as a consequence of continuity, leaving only

$$R_y + \tau_y = 0 \qquad (2)$$

The term $\tau_y$ is the on/offshore gradient of the flux towards the shoreline of parallel-to-the-shoreline momentum (Phillips 1969), and can be written

$$\tau_y = \frac{1}{\rho(\bar{\eta}+h)} \frac{\partial}{\partial x} S_{xy} \qquad (3)$$

where $$S_{xy} = \overline{\int_{-h}^{\eta} \rho\, u'v' dz} \qquad (4)$$

Here h is the still water depth and u', v' are the fluctuating velocity components, including both have orbital velocities and turbulence. $S_{xy}$ should also contain a term in the cross-product of the horizontal components of mass flux, but this term is proportional to the mean on/offshore flow. Its size can therefore be estimated from the measured mean on/offshore velocities. For the experiment under discussion it was much less than 10% of the term in eqn. 4 and has therefore been ignored.

If the assumption is made that wave and turbulent velocities are uncorrelated it is possible to separate the term on the right of eqn. 4 into a radiation stress part and a Reynold's stress part, and this is the usual way of proceeding. For the data from an electromagnetic flowmeter, however, it is not necessary to make this separation since the components u' and v' are measured directly. Nevertheless it is necessary to make two further simplifications of equation 4 before it relates directly to the measured quantities. These are

$$\overline{\int_{-h}^{\eta} \rho u'v' dz} \approx \int_{-h}^{\bar{\eta}} \overline{\rho u'v'} dz$$

$$\approx \rho \overline{u'v'} (\bar{\eta}+h) \qquad (5)$$

The first of these approximations is valid to the same order as our neglect of the mass flux term in $S_{xy}$. The second approximation implies that $\overline{u'v'}$ is independent of depth. This assumption must be made a priori since measurements were only made at a single position in the water column. However, the consistency of the results so obtained is later used to assess the validity of the assumption.

Although in principle the vertical and horizontal components of turbulent motion could be measured near the sea bed using the electromagnetic flowmeter, and these could be used to provide a direct measurement of bottom stress, in the present experiment only horizontal velocities were measured and hence the bottom friction must be approximated by empirical expressions involving horizontal components and bottom friction coefficients.

Three different forms of bottom friction have been considered, each involving a bottom friction coefficient. With these bottom friction terms, the equations of motion, eqn. 2, become

$$\frac{\partial}{\partial x}\left[\rho\overline{u'v'}\,(\bar{\eta}+h)\right] = \rho(\bar{\eta}+h)\,R_y$$

$$= \rho c_b V \quad \text{(Bowen 1969a)} \qquad (6)$$

$$= \rho c_f^1 |U_{orb}| V \quad \text{(Longuet-Higgins 1970)} \qquad (7)$$

$$= \rho c_f^2 |\underline{U}| V \qquad (8)$$

$c_b$ is a linear friction coefficient, with units m/s while $c_f^1$ and $c_f^2$ are dimensionless coefficients. In the Longuet-Higgins form $U_{orb}$ is the maximum orbital velocity of the incident waves. In the third formulation $|\underline{U}|$ is the modulus of the total current vector and differs from $|U_{orb}|$ mainly in including the steady longshore current V, which Longuet-Higgins assumed was much smaller than $U_{orb}$.

## THE EXPERIMENT

The field experiment was carried out on Saunton Beach, N. Devon, England. This is an essentially straight beach approximately 4 km. long and a survey out to 300 m from the high water mark showed an approximately linear slope of 0.014; this slope is modified to 0.010 relative to the mean water level inside the surf-zone when set-up is taken into account. On the day of the experiments the surf-zone was 300-400 m wide with long-crested spilling breakers.

A single two-component electromagnetic flowmeter was mounted about 20 cms off the sea bed, oriented so as to measure the on/offshore and the longshore components of flow. The effective shoreline distance from this instrument varied as a result of tidal motion and allowed estimates of $S_{xy}$ to be made in the region 0 - 120 m from the shoreline. The experimental technique was discussed in detail at the last Coastal Engineering Conference (Huntley and Bowen 1975a).

FRICTION COEFFICIENTS

Figure 1 shows the measured values of longshore current against distance offshore. The values shown are 8½ minute averages of digital current measurements recorded every ½ second. The measured currents compare well with independent measurements made using drifting floats at different distances offshore and the validity of the tidal excursion technique for measuring on/offshore variation of the velocity field is supported by the similarity of currents at the same offshore distance measured first on the rising and then on the falling tide (Huntley and Bowen 1975a). The current increases almost linearly with distance from the shoreline, as expected since the measurements were made within about 1/3 of the surf-zone width from the shoreline.

Figure 2 shows the corresponding values of $\overline{u'v'}$ plotted against offshore distance. Here the fluctuating components are taken to be the velocities after removal of the 8½ minute means only. High-pass filtering to remove energy at frequencies below the incident wave band would result in a reduction of about 20% in the values of $\overline{u'v'}$; the cause of this is discussed later. Apart from a single wild point at about 70 m offshore the values are encouragingly stable, the spread of points around 120 m suggesting that the estimates are stable to better than $\pm$ 40%.

Also shown on figure 2 are straight lines corresponding to different values of $c_b$, the linear friction coefficient. The fit of these straight lines is unconvincing and the values of $c_b$ are lower than might have been expected. Bowen (1969a) estimates values of 0.002m/s for some laboratory data.

The values of $c_f^1$ and $c_f^2$ were estimated separately for each 8½ minute section of record. A plot of $(\eta+h)\ \overline{u'v'}$ vs offshore distance was made and the data approximated by a smooth line increasing monotonically with distance from the shoreline. At the offshore distance corresponding to each 8½ minute record the gradient of this line was measured and equated to the bottom friction terms (eqns. 7 & 8) to obtain values of $c_f^1$ and $c_f^2$. Table 1 shows the results. It is seen that the estimates of $c_f^1$ and $c_f^2$ are generally stable, the standard deviations representing approximately $\pm$ 30%, and there is no obvious trend in the values with shoreline distance.

With the exception of the values nearest the shoreline, $c_f^1$ is consistently larger than $c_f^2$. Thus the assumption that $U_{orb}$ is much larger than V is invalid for this data. The ratio of mean values $c_f^1/c_f^2$ is about 1.4, implying that $U_{orb}$ and V are of the same size. In fact it can be shown using the theory of Longuet-Higgins (1970) that, except for very small angles of approach of the incident waves (of order $1^o$ at the breakpoint), V is generally of the same order as $U_{orb}$, and the Longuet-Higgins approximation, equation 7, is therefore usually invalid.

The coefficient $c_f^1$ deduced from longshore current data by various authors (Thornton 1970; Komar 1975) is therefore not a true bottom friction coefficient. The value of $c_f^1$ will generally be larger than the correct bottom friction coefficient, $c_f^2$ , but the amount by which it is larger will vary across the surf zone and will be strongly dependent on the angle of approach of the incident waves. This may explain the wide range of values of $c_f^1$ which have been deduced. [It is worth noting also that estimates of $c_f^1$ have often been made using the longshore current data of Galvin and Eagleson (1965), but the accuracy of these data is now questioned by Komar (1975) on the grounds of incompatibility with other data. Since the longshore currents of Galvin and Eagleson are larger than expected the estimates of $c_f^1$ will be low.]

The magnitude of the bottom friction coefficient $c_f^2$ is less than one half the magnitude expected on the basis of laboratory experiments of flow over rough plates. The experiments of Nikuradse (Prandtl 1952, Longuet-Higgins 1970) suggest that, for the bottom roughness appropriate to the beach and a Reynold's number determined by the incident waves, and friction coefficient should be around $5 \times 10^{-3}$ (Note that the friction coefficient defined in equation 38 of Longuet-Higgins (1970) and equations 7 and 8 of the present paper is one half the value of $c_f$ given by Prandtl (Longuet-Higgins - private communication)). Other direct estimates of wave friction coefficient have been made by Jonsson (1967) and Teleki and Anderson (1970), and estimates of a combined wave and longshore current friction factor have been made by Jonsson et al (1974), but in each case the values give a bottom friction term at least as large as Prandtl's estimate.

It seems probable that the apparently low value of friction coefficient $c_f^2$ is the result of the omission of a driving term in the equation of motion, equation 8. The two groups of terms which may have been omitted are the longshore variation terms included in equation 1, or the turbulent Reynold's stress term, which we assumed to be included in equation 5.

If the assumption of uniform conditions in the longshore direction were invalid, then the additional terms in equation 1 would have to be included and could result in a stronger (or weaker) longshore current than would be driven by $\tau_y$ alone. If it were nevertheless still assumed that the motion could be described by equations 2, and 6-8, this stronger (weaker) current could only be reconciled with these equations by an apparently smaller (larger) value of friction coefficient. Two mechanisms could be responsible for a longshore variability, edge wave generated circulation cells and refraction of incident waves. Edge wave generated circulation cells (Bowen 1969b, Bowen and Inman 1969) seem very unlikely to be generated on a beach as shallow as 0.01. Theory and experimental evidence suggest that circulation cells have an alongshore wavelength of the same order as the surf-zone width and edge waves of low mode number are most strongly generated; on Saunton beach synchronous edge waves giving circulation cells of the same size as the surf-zone would be of mode number greater than 200. The effect of wave refraction is less easy to dismiss since no measurements were made alongshore. However offshore topography was relatively smooth and there were no indications of refraction on this long smooth beach. Additional evidence that wave refraction is not responsible for low values of friction coefficient comes from field measurements of longshore currents made by Ramkema (Battjes - private communication). He also found consistently low values of friction coefficient, although his measurements were made for a variety of directions of approach of the waves, and thus for a variety of wave refraction conditions.

The second possible explanation for the low values of bottom friction is that we are just not measuring the Reynold's stress at all. Since the data comes from the 1/3 of the surf-zone closest to the shoreline, a region where the effect of lateral mixing is to *increase* the longshore current above the unmixed value, we are again ignoring a driving term in the force balance and hence underestimating the friction coefficient.

This hypothesis clearly leads to an attempt to find Reynold's stress contributions to the measured stress term, and this is discussed in the following section.

## SEPARATION OF REYNOLD'S AND RADIATION STRESSES

If we could separate the turbulent and wave contributions to the mean $u$, $v$ product we could examine the hypothesis that turbulence is perhaps not being measured, or possibly test the various parametrisations of horizontal turbulent stresses which have been used in longshore current theories. There are three possible ways in which such a separation might be made. Most obviously we might try to measure elevation at the same time as the horizontal velocities and then remove the calculated elevation-related contributions to the velocities. Alternatively we might measure the variation of the $\overline{u'v'}$ product across and beyond a surf-zone and attempt to distinguish the two stress components by their different dependences on offshore distance: the Reynold's stress should fall to zero some distance outside the surf-zone and pass through zero at the position within the surf-zone where the longshore current is maximum; these two points and the shoreline limit should allow a reasonable estimate to be made of the radiation stress contribution throughout the nearshore zone. Finally it might be possible to separate the two stresses if they occur predominantly in separate frequency bands.

Unfortunately the data from the present experiment includes neither elevation measurements nor sufficient spread of measurements across the surf-zone to test the first two of these techniques. In fact the first technique would require a rather accurate *directional* spectrum of elevations, and this would be difficult to measure in the nearshore zone. However frequency separation is in principle possible with the current measurements alone.

The co-spectrum $\overline{u'v'}(f)$ separates the real part of the $u'v'$ product into contributions in separate frequency bands. Since the effect of the Reynold's stress gradient is to increase the longshore current within the first one third of the surf-zone we expect the Reynold's stress to contribute to $\overline{u'v'}$ with the same sign as the radiation stress, but hopefully within a well defined band at a higher frequency than the incident wave band.

Figure 3 shows a typical example of the co-spectra calculated from the 8½ minute records. The peak just below 0.2 Hz represents the predominant incident wave frequency. The lower frequency contributions may be due to breaker interaction in the wide surf-zone (Huntley and Bowen 1975b) but in any case contribute only about 20% of the total area under the curve. There is no clear frequency band above 0.3 Hz containing a significant peak which may be attributed to Reynold's stress.

It is possible that the level of turbulence was too small to be significant in this co-spectrum. Longuet-Higgins (1970) estimates the total turbulent stress as

$$\overline{u'v'} = \frac{1}{\rho} N\rho x(gh)^{\frac{1}{2}} \frac{\partial V}{\partial x} \tag{9}$$

where h is local water depth
x is distance offshore

He assumes that the parameter N is a constant with a value ≈ 0.005; Bowen and Inman (1972) analyse surf-zone dye diffusion experiments and suggest that N should lie approximately in the range 0.01-0.06. In contrast Battjes (1975) suggests that N should not be constant but beach slope dependent in the form

$$N = \left(\frac{5}{16}\gamma^2\right)^{1/3} (\tan\beta)^{4/3} M \tag{10}$$

where $\gamma$ is the ratio of wave height to water depth.

M is a dimensionless parameter deduced by assuming that the N given by equation 10 for $\tan\beta = 0.1$ is similar to the constant N deduced by Bowen and Inman (1972); most experimental determinations of N were made on beaches of slope 0.1. The value of M calculated thus lies in the range 0.3-2.0. The effect of the beach slope dependence of equation 10 is then to give a considerably smaller estimate of turbulent Reynold's stress on a beach of the present slope of 0.01 than would be calculated using a constant N. We have calculated the Reynold's stress, equation 9, using both constant N ≈ 0.01-0.06, and the beach slope dependent N, equation 10, which for our slope of 0.01 gives $N \approx (3.5 - 21) \times 10^{-4}$. (we assume also that $\gamma \approx 1.2$ for $\tan\beta = 0.1$ and $\gamma = 0.78$ for $\tan\beta = 0.01$, following Bowen et al (1968), but the choice of $\gamma$ does not significantly effect the result). Comparison of these predicted Reynold's stresses with the observed contribution to $\overline{u'v'}$ for frequencies greater than 0.3 Hz shows that the observed values are of a similar magnitude to predictions made using equation 10 but are at least an order of magnitude smaller than predictions made using a constant (independent of beach slope) N. Thus the observed cospectra are not inconsistent with Battjes model for horizontal turbulence but are definitely inconsistent with Longuet-Higgins' model.

It seems more likely however that the flowmeter was not in fact measuring the wave-induced turbulence at all. The mean values of $u'$ and $v'$ integrated over the complete frequency range can be completely accounted for by the expected values for surface wave breakers propagating in the observed water depths. The coherence between u and v is also around 0.3 in the frequency range 0 - 1Hz as might be expected for short-crested incident waves (Battjes 1975).

## DISCUSSION

The conclusion from the present data is therefore that the turbulence is probably not being measured by our single flowmeter and that this omission is likely to be the cause of the low value of friction coefficient obtained.

The probable reason for the absence of turbulence in the flowmeter records is that the flowmeter was too far down in the water column. Laboratory experiments and field experience suggest that the turbulence of breaking is not distributed throughout the water column but is limited to the upper part, especially for spilling breakers. Thus the second approximation of equation 5 is invalid. Turbulence energy would also not be measured if it occurred predominantly at frequencies greater than the approximately 10Hz response frequency of the flowmeter, but this seems unlikely.

Thus the present results suggest a rather different model for longshore currents than has been used before. Rather than a turbulent intensity distributed throughout the water column, wave breaking turbulence is confined to an upper boundary layer which, with the bottom boundary layer, acts on a less turbulent central layer. If indeed the driving force of this upper layer is responsible for the low apparent value of $c_f$, then an upper limit of about one third the water depth can be put on the thickness of this upper layer, based on the fact that $c_f$ remains small down to as little as 40 m. from the shoreline (table 1).

The hypothesis, then, is that the value of $c_f$ measured here is not a bottom friction coefficient alone but is strongly modified by the existence of a surface turbulent boundary layer formed by wave breaking. The formulation of the effect of lateral mixing as some kind of boundary layer rather than a depth independent eddy viscosity may explain why Jonsson et al (1974) and Komar (1975) find so little effect on the match of predicted and measured longshore currents when the parameter N (equation 9) is varied over a wide range.

The suggested three layer model may also provide the means to explain Komar's observation (Komar and Inman 1970, Komar 1975, 1976) that for a wide variety of field and laboratory measurements of longshore currents, the ratio of beach slope to the coefficient $c_f^1$

$$\frac{\tan\beta}{c_f^1} \approx \text{constant} \tag{11}$$

The constant in equation 11 is variously found to be 6.05 $\pm$ 0.65 for beach slopes in the range 0.05 - 0.15 (Komar 1975), $\approx$ 6.7 (Longuet-Higgins 1972) and $\approx$ 7 for a beach slope of around 0.05 (Keeley 1975). The beach slope for the present experiment is considerably smaller than for these data, at 0.01, but, as a consequence of the smaller value of $c_f^1$, the ratio is found to be $3.9\,^{+1.1}_{-0.7}$, in reasonable agreement with the other estimates. In fact, using the correct friction coefficient, $c_f^2$, instead of $c_f^1$ also gives reasonable agreement, with the constant $\approx 5.2\,^{+2.4}_{-1.2}$.

Komar (1971) assumes that $c_f^1$ is a friction coefficient and he has attempted to provide a physical explanation for the empirical result of equation 11 by assuming that bottom stress exerted on the beach is proportional to the radiation stress in the incident wave direction at the breakpoint. However, this and other unproven assumptions which he needs to make have been criticized by Longuet-Higgins (1972), also on physical grounds. More recently Komar (1976) has pointed out that, for the field data, a constant ratio $\tan\beta/c_f^1$ suggests an increase in $c_f^1$ with sand size, as we might expect for flow over a rough bed. However, this argument cannot explain the laboratory results, where most beaches are solid, with a constant, generally small, bottom roughness independent of beach slope.

The three layer model, however, suggests that the measured $c_f$ parameters are strongly influenced by the intensity of breaking turbulence. Increased beach slope will result in a narrower surf-zone over which turbulent breaking occurs, and hence a greater level of turbulence in unit surface area. This increased horizontal mixing will result in a decreased longshore current and hence a greater apparent $c_f$ parameter in our three layer model. This explanation is consistent with Longuet-Higgins' (1972) comments on equation 11.

Clearly what is needed is a new model for longshore currents, involving the correct parametrisation of the bottom friction term in terms of equation 8 rather than equation 7, and involving a new parametrisation of horizontal turbulent mixing as an upper boundary layer. Such a model may provide an explanation for equation 11.

There are several ways that the present three layer hypothesis may be tested experimentally. Direct estimation of bottom friction is possible through use of the electromagnetic flowmeter to measure vertical and horizontal velocities near the bed. Measurements of the distribution of horizontal turbulence in the vertical may also be possible, though measurement in the turbulent surface layer may only be possible by dye diffusion (see Inman et al 1971). Finally the value of $c_f^2$ deduced from horizontal velocities, as described in this paper, should be measured across and beyond the surf-zone. Since the effect of a surface turbulent layer should be to reduce the longshore current gradient, the maximum longshore current will be <u>less</u> than predicted in the absence of horizontal mixing, the horizontal mixing term will be a <u>retarding</u> force, and the value of $c_f^2$ should be <u>larger</u> than expected for bottom friction alone. Thus $c_f^2$ should be smaller near the shoreline increase beyond bottom friction values as the surf-zone is traversed seawards, and then drop again, possibly even becoming negative beyond the surf-zone.

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TABLE 1

| Run I. D. | Distance from shoreline m. | Longshore current m/s | $c_f^{①}$ x $10^{-3}$ | $c_f^{②}$ x $10^{-3}$ |
|---|---|---|---|---|
| FFC 81 | 120 | 0.37 | 3.25 | 2.01 |
| FFC 82 | 117 | 0.41 | 2.60 | 1.46 |
| FFC 83 | 111 | 0.38 | 2.53 | 1.38 |
| FFC 5 | 90.5 | 0.25 | 3.25 | 2.03 |
| FFO 1 | 77 | 0.26 | 2.29 | 1.39 |
| FFO 21 | 60 | 0.17 | 2.27 | 1.80 |
| FFO 22 | 50 | 0.10 | 3.17 | 3.13 |
| FFO 23 | 42 | 0.10 | 1.74 | 2.29 |

Mean and standard deviation = 2.6 ± 0.6    1.9 ± 0.6

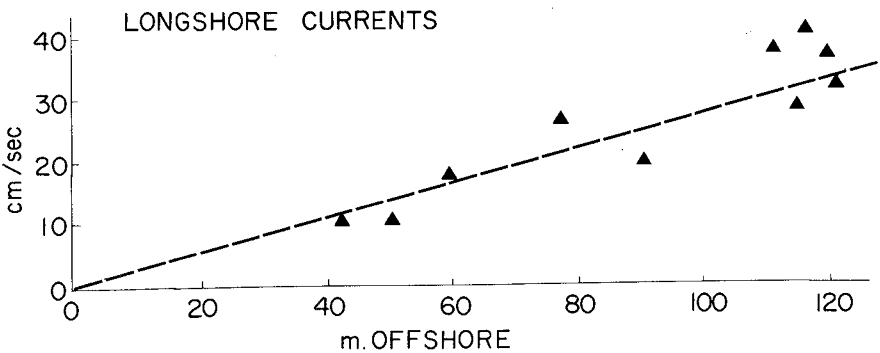


Figure 1.

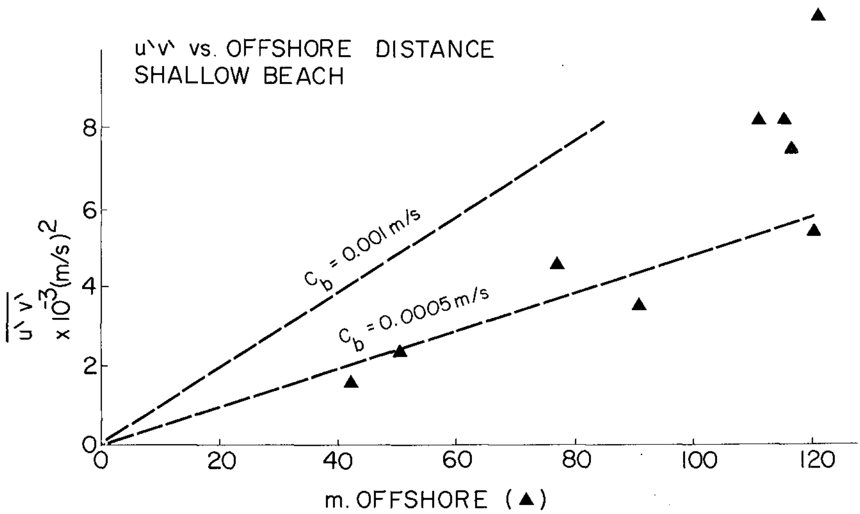


Figure 2.

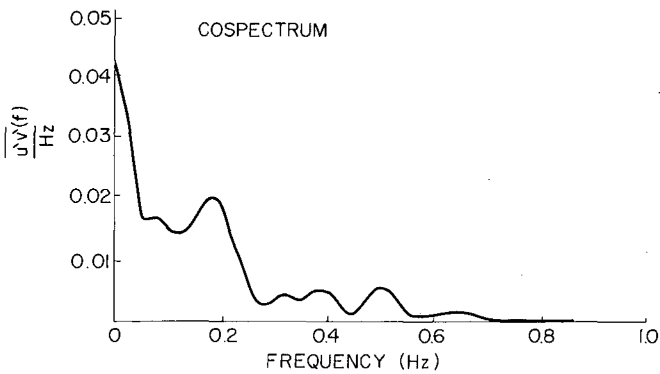


Figure 3.