DEVELOPMENT AND APPLICATION OF A FIELD INSTRUMENTATION SYSTEM
FOR THE INVESTIGATION OF SURF ZONE HYDRODYNAMICS

by

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(1975)

Submitted in partial fulfillment of the
requirements for the Degree of

OCEANOGRAPHIC ENGINEER

at the

WOODS HOLE OCEANOGRAPHIC INSTITUTION

and the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

and for the Degree of

MASTER OF SCIENCE IN OCEAN ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

(February 1979)

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Submitted to the Department of Ocean Engineering on
February 15, 1979 in partial fulfillment of the requirements
for the Degree of Oceanographic Engineer and the
Degree of Master of Science in Ocean Engineering

ABSTRACT

The development and application of an autonomous field instrumentation system consisting of four current meters and four wave gauges, along with a field monitor and digital recorder, is documented.

The flow sensors are electromagnetic current meters, which employ the principle of electromagnetic induction to sense an induced electrical potential from the flow of water through an imposed magnetic field. The 10 cm diameter, disc-shaped sensor was tested in the laboratory under a wide variety of conditions, including both steady and oscillatory flow tests. The results of these tests indicate an excellent response in terms of linearity and horizontal cosine. The vertical cosine response is close to ideal in the region of $\pm 30^\circ$, but beyond a negative angle of attack of approximately -30° the response is compromised by the onset of separation under dominantly steady flow conditions. The wave gauges are surface-piercing digital sensors, relying on the presence or absence of water at 128 individual sensing electrodes spaced 1.5 cm apart along the front surface of the wave gauge. On command, the instantaneous water surface elevation is measured, then telemetered digitally to the shore-based monitor and recorder.

Field measurements of waves and currents at four stations across the width of the surf zone were made, using this system at a beach along the southern coast of Maine. Spilling breakers (approximately 1.0 m in height with an angle at breaking of about 8°), translated across the 30 m surf zone, generated an observed net longshore current during the four hour measurement period. The subsequently analyzed data from this experiment showed a strong longshore current which varied across the width of the surf zone, having a maximum of about 15 cm/sec just inside the breaker line. A net offshore current was observed at all four stations, and averaged approximately 10 cm/sec to 15 cm/sec. Using a simplified force balance model for the generation of longshore currents on a plane, uniform beach, the data was further analyzed to investigate the validity and parameterization of the momentum flux forces and bottom

friction forces within the surf zone. There was an observed shoreward loss in momentum flux across the width of the surf zone, from about -150,000 dynes/cm outside the breakers to near zero close to the shoreward extent of the surf zone. The computed friction coefficient from the balancing longshore current-induced bottom friction was found to be relatively unstable during periods of changing wave and current conditions, but was observed to be between 0.10 and 0.15 during more stable conditions.

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ACKNOWLEDGEMENTS

Professor Ole S. Madsen helped me throughout the course of this thesis, from the initial stages of the design and experimentation to the final analysis and write-up. I am very grateful for this guidance and for his friendship.

Dr. William D. Grant was also very helpful during the developmental stages, as well as during the field experiments and the subsequent analysis. His excellent field capabilities are also noted.

Additional help from Dave Ostendorf, Tom Stefanick, York Warden, Carroll Beek, and Susan Smith during the field experiments is greatly appreciated. The cooperation of Ray Cronkhite in providing living quarters during one of the initial field experiments is also acknowledged.

Dr. Robert Spindel generously provided the use of his project's computer for the data analysis.

Susan Smith prepared the early drafts of the text, and was assisted in typing the final manuscript by Carole Solomon. Their swift and accurate typing is greatly appreciated.

The support of the NOAA Sea Grant Program through the MIT Sea Grant Program, along with the MIT/WHOI Joint Research Seed Funds is acknowledged. The support of the Woods Hole Oceanographic Institution Education Program is also acknowledged.

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NOTATION

Symbols from the English Alphabet:

a	wave amplitude
A_b	near bottom horizontal excursion amplitude due to wave motion
B	magnetic field intensity
c	phase velocity of a wave
c_g	group velocity of a wave
C_f	friction coefficient
d	diameter
D	energy dissipation per unit surface area
E_F	energy flux of waves, equal to E_{c_g}
F	time averaged driving force
F_B	time averaged bottom drag force per unit surface area of bottom
F_L	time averaged lateral shear force in the longshore direction per unit surface area
g	acceleration of gravity
h	time averaged water depth
H	wave height
I	electric current
k	wave number, equal to $2\pi/L$
l	length
L	wave length
M_{xy}	momentum flux in the y-direction applied across a plane perpendicular to the x-axis
Q	mass flow rate

NOTATION (cont.)

r	radius
S_{xy}	radiation stress in the y-direction applied across a plane perpendicular to the x-axis
t	time
T	wave period
u	on/offshore current velocity
$\vec{U}$	total flow velocity
v	alongshore current velocity
x	offshore distance
y	alongshore distance
z	vertical distance

Symbols from the Greek Alphabet:

α	angle between the wave crests and the shoreline
ϵ_v	turbulent eddy viscosity
η	water surface elevation as measured from still water
ρ	density of water
τ_b	bottom shear stress exerted by flow on bottom
τ_{xy}	lateral shear force per unit surface area in the longshore direction
θ	angle between wave crest and bottom contour
ϕ	velocity potential for waves
ϕ_x	velocity field in waves
ω	wave radian frequency, equal to $2\pi/T$

NOTATION (cont.)

Subscripts and Superscripts:

$()_b$	at the bottom
$()_w$	wave component
$()'$	fluctuating component
$\overline{()}$	time averaged quantity
$\langle () \rangle$	average
$()^{(1)}$	result of first order wave theory
$()^{(2)}$	result of second order wave theory

1. INTRODUCTION

An understanding of the natural processes acting in the near-shore region is clearly an important prerequisite for the successful management of the coastal zone. The ability to predict the dispersion and convection of pollutants, the stability of beaches and shore protection projects, along with the maintenance of inlets and waterways all require a detailed knowledge of the complex flow field of the nearshore region, and especially the surf zone.

Previous attempts to quantitatively model these transport processes have been generally unsuccessful, largely due to the poorly understood characteristics of breaking waves in the surf zone, and the complex fluid-sediment interactions responsible for the transport of sand and beach materials. In the case of longshore transport of sand due to wave action, for example, numerous field studies have attempted to relate the general characteristics of the breaking waves to the observed volume rate of longshore sediment transport. Having little relation to the actual hydrodynamics of the surf zone, the processes of sediment transport, and the advection by longshore currents, these models are highly empirical and very unreliable (Greer and Madsen, 1978).

Thus, as a starting point for the accurate prediction of sediment transport in the surf zone as well as for an understanding of the flow conditions responsible for pollution dispersion and convection, a more detailed understanding of the hydrodynamics of the surf zone is called for.

Recent analytical work in this area has led to the development of a more realistic model for the generation of longshore currents due to wave action. Although this model deals with only the simplest of conditions, those being of two-dimensional, monochromatic waves breaking at a slight angle on a plane, laterally uniform beach, it serves as a basis for the analysis of more complex topographies and wave conditions and represents an important step in quantifying the important forces present in the surf zone.

Although this model predicts the approximate magnitude and qualitative characteristics of longshore currents as commonly observed, it has yet to be quantitatively evaluated in terms of actual field measurements. To remedy this, a field investigation of the various hydrodynamic forces and longshore currents in the surf zone was undertaken in an attempt to evaluate the appropriateness and general applicability of this general model.

To ensure an efficient approach to the specification and design of the measurement system and field program, the general model was first analyzed in terms of the actual measurements required for a complete analysis of the forces and longshore current characteristics. Then, a complete, autonomous instrumentation system, capable of providing this detailed information under varying surf zone environments, was developed and tested under laboratory and field conditions. Finally, field measurements of waves and currents in the surf zone were used to investigate the various hydrodynamic forces and assumptions involved in the basic longshore current model.

2. SURF ZONE HYDRODYNAMICS AND LONGSHORE CURRENT GENERATION

The quantitative description of the flow field within the surf zone is rather difficult for many reasons. The complex velocity field in breaking waves, the influence of non-uniform wave conditions, complex bottom topographies and circulation patterns, for example, are all poorly understood themselves and, when put together as they commonly are in the surf zone, the combined effect is extremely nonlinear and poorly suited to straightforward analysis. As a result, studies and models of longshore currents have dealt almost exclusively with the simplest case, that of two-dimensional, monochromatic waves breaking at a small angle of a plane, gently sloping, laterally uniform beach.

Even so, prior to the 1960's, the available longshore current models were considered largely empirical, relating wave energy in some way to observed longshore currents. Then, following the work of Longuett-Higgins (1970), a more analytical approach involving the equilibrium of forces in the surf zone and based on a consideration of energy and momentum conservation led to the development of more realistic models (Madsen et al., 1978).

2.1 WAVE INDUCED LONGSHORE CURRENTS

The theoretical analysis which serves as the basis for the surf zone measurements undertaken in this study is based on a consideration of energy dissipation and conservation of momentum in the surf zone.

Starting with the region outside the surf zone, where the dissipation of wave energy is negligible, conservation of energy leads to

FIGURE 2.1: Definition Sketch Used in the Discussion of Wave Induced Longshore Currents

the general relationship:

$$E_F \cos\theta = \text{constant} \quad (2.1)$$

where θ is the angle of incidence (refer to Figure 2.1), and E_F is the energy flux per unit length of crest, given, for example, by linear theory as

$$E_F = \frac{1}{2} \rho g a^2 \left[\frac{\omega}{k} \frac{1}{2} \left(1 + \frac{2kh}{\sinh 2kh} \right) \right] \quad (2.2)$$

in which ρ is density, g is gravity, a is wave amplitude, ω is radian frequency, k is the wave number, and h is the water depth. From a consideration of energy conservation, it is clear that, as this wave energy flux into the surf zone is dissipated, a gradient in shore normal energy flux results. Denoting the average rate of energy dissipation per unit area of the bottom by D , conservation of energy leads to

$$\frac{\partial(E_F \cos\theta)}{\partial x} = + D \quad (2.3)$$

where the sign is positive since x is positive in the seaward direction, i.e., the gradient of shore-normal energy flux is positive.

The energy flux into the surf zone can also be expressed in terms of the equivalent rate of work done on an imaginary boundary parallel to the beach. The apparent stress on this boundary in the alongshore direction due to the transport of momentum past this boundary is:

$$\tau_{xy} = -\rho u_w v_w \quad (2.4)$$

where u_w and v_w are the on/offshore and longshore wave velocities (see Figure 2.1). This equivalent shear stress does work on this boundary at the rate of the wave propagation in the alongshore direction, $c/\sin\theta$, so the depth-integrated, time-averaged rate of work done is

$$\left\{ -\frac{1}{T} \int_0^T dt \int_{-h}^{\eta(t)} \rho u_w v_w dz \right\} \frac{c}{\sin\theta} \quad (2.5)$$

Since this is equivalent to the amount of energy being propagated past the boundary, then:

$$E_F \cos\theta = \left\{ -\frac{1}{T} \int_0^T dt \int_{-h}^{\eta(t)} \rho u_w v_w dz \right\} \frac{c}{\sin\theta} \quad (2.6)$$

The term in brackets is termed the momentum flux or, more precisely after Longuet-Higgins (1970), the radiation stress, S_{xy} , acting in the alongshore direction. Using this notation, the energy flux equation can be rewritten as a balance between the rate at which energy flows shoreward, and the average rate at which work is done on the fluid:

$$E_F \cos\theta = S_{xy} \frac{c}{\sin\theta} \quad (2.7)$$

Thus, the energy conservation principle, Eq. (2.3), can be restated in terms of a force balance

$$\frac{\partial(E_F \cos\theta)}{\partial x} = \frac{c}{\sin\theta} \frac{\partial S_{xy}}{\partial x} = D \quad (2.8)$$

where $c/\sin\theta$ is constant by virtue of Snell's Law. Thus, it is seen that the radiation stress gradient is positive.

Now, by looking at the equilibrium of alongshore forces acting on a slice of fluid inside the surf zone (see Figure 2.1), it can be seen that this shoreward variation in radiation stress has to be balanced by some force, say F_y ,

$$\frac{\partial S_{xy}}{\partial x} \delta x = F_y \delta x \quad (2.9)$$

This longshore force can only be balanced by a longshore current producing a net force on the fluid slice through bottom friction, and across the surf zone by lateral friction which acts to smooth out the longshore current profile.

This results in a balanced equation,

$$\frac{\partial S_{xy}}{\partial x} + F_B + \frac{\partial F_L}{\partial x} = 0 \quad (2.10)$$

where F_B is interpreted as the time average bottom friction force expressed in terms of the bottom shear stress in the alongshore direction,

$$F_B = -\frac{1}{2} C_f \rho \langle (u^2 + v^2)^{1/2} v \rangle \quad (2.11)$$

in which C_f is the bottom friction factor and $\langle (u^2 + v^2)^{1/2} v \rangle$ is the time averaged bottom velocity producing the y-component of bottom shear, and F_L is the lateral friction associated with the turbulent Reynolds stress,

$$F_L = - \frac{1}{T} \int_0^T dt \int_{-h}^{\eta} \rho u'v' dz \quad (2.12)$$

u' and v' are the fluctuating velocity components of the surf zone field.

This last term expresses the lateral friction between adjacent fluid slices, without which there would be a sharp discontinuity in the longshore current profile at the breaker line, since there is no driving force from the constant radiation stress outside the breakers. This shear is often expressed by introduction of a horizontal eddy viscosity. Longuett-Higgins (1970), for example, expresses this force as

$$F_L = \rho \epsilon_v h \frac{\partial \bar{v}}{\partial x} \quad (2.13)$$

where ϵ_v is this eddy viscosity. The use of mixing length arguments then allows for a parameterization of ϵ_v in terms of known parameters leaving a constant to be determined empirically. The appropriateness of this lateral friction term is somewhat suspect outside the surf zone since the mechanism for a continued strong horizontal mixing is unclear in the absence of wave breaking.

In summary then, the shoreward loss in radiation stress is balanced by lateral friction and bottom friction from an induced longshore current:

$$\frac{\partial S_{xy}}{\partial x} + F_B + \frac{\partial F_L}{\partial x} = 0 \quad (2.14)$$

Using various wave theories and assumptions as to the behavior of S_{xy} , this equation can be solved analytically to provide a predictive model of longshore currents in the surf zone (see, for example, Madsen et al., 1978).

The successful verification and application of this model is dependent on laboratory and field experiments that can verify the various contributing forces, S_{xy} , F_B , and F_L , as well as parameterize the two coefficients, C_f and ϵ_v . In terms of laboratory data, few experiments provide sufficient information to parameterize even C_f or ϵ_v , much less the gradient in radiation stress. Even then, uncertainties due to the problems of inadequately scaled turbulence from longshore currents and breaking waves necessitate the field confirmation of these laboratory results.

In terms of the most realistic and complete laboratory experiments, the data from Galvin and Eagleson (1965) probably provide the best estimates for the bottom friction factor (≈ 0.02), along with information for parameterizing the horizontal eddy viscosity (Ostendorf, 1978). A forcing analogous to the longshore forcing due to waves exist in the shore normal direction. This shore normal forcing is, however, balanced by a set-up and does not give rise to a current.

2.2 SIMPLIFIED MOMENTUM FLUX MODEL

To evaluate the validity and appropriateness of this model and the various coefficients, field measurements designed specifically to measure the different forces are ultimately required. By considering

the complete surf zone velocity field, including the influence of the waves, mean currents, and turbulent fluctuations, a simplified measurement and analysis scheme was developed to evaluate these forces and their balance in the surf zone.

First, considering the velocity field in the surf zone as being the combined influence of both wave and turbulent fluctuations, the horizontal velocities can be separated as

$$u = u_w + u' \quad (2.15)$$

$$v = v_w + v' \quad (2.16)$$

where the subscript w denotes the wave component and the superscript ' indicates the fluctuating component.

The local shear stress, τ_{xy} , associated with the total flow is given by

$$\tau_{xy} = -\rho u v \quad (2.17)$$

In terms of momentum, which is given in general by $\rho \vec{U}$ (a vector quantity), this term can be thought of as an equivalent onshore flux of alongshore momentum and thus the total, time averaged, depth integrated rate of momentum flux across an imaginary shore parallel boundary is

$$M_{xy} = \frac{1}{T} \int_0^T dt \int_{-h}^n \rho u v dz \quad (2.18)$$

using the coordinate system of Figure 2.1). Separating the total velocity components, this becomes:

$$M_{xy} = -\rho \frac{1}{T} \int_0^T dt \int_{-h}^{\eta} \{u_w v_w + u_w v' + u' v_w + u' v'\} dz \quad (2.19)$$

The first term is recognized as the radiation stress, S_{xy} , while the last is the turbulent Reynolds stress. Using the assumption that the time scale of the turbulent fluctuations is either much smaller or much larger than that of the waves, the two inner terms time average to zero, leaving

$$M_{xy} = -\rho \frac{1}{T} \int_0^T dt \int_{-h}^{\eta} u_w v_w dz - \rho \frac{1}{T} \int_0^T dt \int_{-h}^{\eta} u' v' dz \quad (2.20)$$

which is simply

$$M_{xy} = S_{xy} + F_L \quad (2.21)$$

In principle, these two terms could be evaluated by separating the measured velocities into the wave and fluctuating components, then evaluating the gradient in radiation stress and lateral friction. In view of the actual surf zone flow field, however, this separation is somewhat artificial since, in principle, there is no real reason for this separation except that it is analytically expedient in terms of establishing a model.

Since the momentum flux combines the influence of all these forces (wave, fluctuating, and steady) it is a more realistic quantity to evaluate in a field experiment. Then, just as was done with the radiation stress, the gradient in momentum flux in the shoreward direction drives a longshore current which in turn produces a bal-

ancing bottom friction force:

$$\frac{\partial M_{xy}}{\partial x} + F_B = 0 \quad (2.22)$$

or writing the friction force as before the following relationship emerges

$$\frac{\partial M_{xy}}{\partial x} = \frac{1}{2} \rho C_f \langle (u^2 + v^2)^{1/2} \rangle \quad (2.23)$$

This equation shows that the friction coefficient can be evaluated in terms of measured horizontal velocity components along with the surface elevation at locations separated in the shoreward direction by a distance ∂x by:

$$C_f = \frac{\partial M_{xy}}{\partial x} / \frac{\rho}{2} \{ \langle (u^2 + v^2)^{1/2} \rangle \} \quad (2.24)$$

2.3 PROPOSED SURF ZONE MEASUREMENTS

By evaluating the magnitude and behavior of the momentum flux across the surf zone, it should be possible to assess the validity of this momentum and radiation stress model, and by computing the friction coefficient, the appropriateness of the balancing of forces by bottom friction will be more clear.

To accomplish this, measurements of the instantaneous horizontal velocity components and surface elevation at at least two points across the surf zone are needed.. In addition, to get a more general view of the longshore current structure, several additional measurements extending across and beyond the surf zone are desirable.

Lastly, to provide information about the flux of energy into the surf zone, some measure of directional wave energy outside the surf zone is needed.

3. SURF ZONE INSTRUMENTATION SYSTEM

This section summarizes the design and development of the instrumentation system used for the measurement of waves, currents, and momentum fluxes in the surf zone. It includes a description of the electromagnetic current meter and digital wave gauge sensors, and outlines the complete field power and monitor system developed specifically for these surf zone measurements.

3.1 ELECTROMAGNETIC CURRENT METER

To provide the quantitative information needed to characterize the flow field of the surf zone, an electromagnetic current meter was designed and integrated into the measurement system. The final design was rigorously tested in various flow conditions to determine the overall hydrodynamic and electronic response.

3.1.1 Sensor Requirements

Ideally, a flow sensor provides an accurate measure of the flow, and introduces no errors of its own. Unfortunately, no one sensor accomplishes this perfectly. Technical and practical considerations necessitate trade-offs in the design of all flow sensors and, as a result, the selection of a flow sensor involves compromises in order to optimize certain important characteristics at the expense of others of less importance. Thus, to obtain the most valuable set of measurements, the choice of a flow sensor for use in the surf zone should be based on a consideration of the basic flow characteristics and the flow

scales of interest in the surf zone.

The most obvious general characteristic of the flow in the surf zone is that it is extremely variable in direction and magnitude due to the complex pattern of breaking waves and longshore currents. This means that the sensor has to provide accurate Eulerian vector information about the three-dimensional flow, and be capable of resolving both the mean and fluctuating components. In many oceanographic applications, these requirements can be more easily realized since the fluctuating component is often small compared with the mean flow, or the fluctuations are of secondary importance and can be averaged out in some way. Unfortunately, the accurate measurement of both the small means in the presence of larger fluctuating velocities and the fluctuations themselves are necessary for the determination of longshore currents and momentum fluxes in the surf zone. This requirement necessitates the use of a flow sensor having an accurate, linear response over a wide dynamic range, coupled with an adequate frequency response in order to eliminate the possibility of aliasing the higher frequency fluctuations.

In terms of the directional response of the sensor, the measured quantity should be a unique representation of the actual velocity vector. The techniques commonly employed in sensor design to provide this directional and scalar information lead to two distinct classes of sensors: Polar and Cartesian.

Polar sensors are actually two independent sensors, one measuring the scalar flow and another measuring the vector direction, combined into a single packaged current meter. Accordingly, the resolving

ability of polar current meters is separated into the scalar and directional response under varying conditions of flow. An example of this class of sensors is the Vector Averaging Current Meter (VACM) which combines an S-shaped Savonius rotor for the measurement of the flow velocity with a pivoting vane to determine flow direction.

Cartesian sensors, which are more commonly used in unsteady flows, measure the total flow in terms of the flow components along defined, independent axes. For such a sensor, the ideal response for each axis is simply:

$$V_{\text{measured}} = V_{\text{actual}} \cdot \cos \theta_1 \cdot \cos \theta_2 \quad (3.1)$$

where θ_1 and θ_2 are the angles in a Cartesian coordinate system between the flow vector and the sensor measurement axis. In the most commonly employed configuration, the axes are orthogonal to one another, enabling the straightforward calculation of the resultant vector magnitude and direction.

For these sensors, the ability to accurately resolve direction and magnitude is evaluated in terms of the sensor's observed response and the ideal response as given by the preceding equation. If the main component of flow lies in the horizontal plane (as is often the case), then the ability to resolve directional components in that plane is referred to as the "horizontal cosine response", while the response to flows out of the horizontal plane is referred to as the "vertical cosine response". In terms of the required directional sensitivity for surf zone measurements, where the velocities of primary interest

are in the horizontal plane, the flow sensor clearly must have an accurate horizontal and a satisfactory vertical cosine response.

In addition to considering the requirements called for by the characteristics of the surf zone flow field, environmental factors and practical operational considerations influence the choice of a flow sensor. Certainly, the high energy levels of the surf zone necessitate the use of a durable and easily deployable current meter, while the requirement for dense, fine scale measurements requires a small sensor which can be easily integrated into a larger measurement system.

3.1.2 Alternative Sensors

Previous field experiments in the surf zone have involved the use of a wide variety of flow sensors. As mentioned previously, there is no one "best" sensor, but it is possible to optimize the choice of a sensor by considering the relative merits and drawbacks of various sensors in terms of the required sensing characteristics outlined in the previous section.

Somewhat arbitrarily, these sensors can be classified as momentum, scattering, or volume averaging sensors, depending on the primary physical characteristic or mechanism employed in sensing the flow velocity.

Momentum sensors are most commonly mechanical, relying on rotors, propellers, or fans to sense the flow. Characteristically, these sensors are relatively simple, reliable, and require little interfacing. By definition, however, they all interfere with the flow to some extent, resulting in varying degrees of nonlinear response as

well as poor frequency and directional sensitivity. Savonius rotor current meters like the VACM, for example, are very susceptible to these response problems. Widely used by the oceanographic community in deep as well as shallow water applications, they have a good steady flow response, but in unsteady or oscillatory flow (like that found in the nearshore and surf zone regions), the rotor and vane sensors exhibit a complex response that is very difficult to interpret accurately (Fofonoff, 1967).

Other mechanical sensors, more responsive and accurate than the Savonius rotor, have been successfully used. For example, small ducted propeller sensors have been used by J.D. Smith (1974) in nearshore, unsteady flow environments to study fine scale turbulent structure. These sensors have a relatively linear response and an excellent frequency response, but still perform less than optimally in reversing flows due to the finite response thresholds on the order of 1-2 cm/sec (Smith, 1974). Interestingly, even though these sensors have less than ideal cosine responses, by carefully applying a nonlinear calibration transfer function, the directional response can be corrected for in the data analysis.

Recent mechanical sensors, like the Davis-Weller fan vector measuring current meter (VMCM) (Weller, 1978), have been experimentally optimized to have near-perfect cosine responses. To date, most of these sensors have been used in mean flow measurement experiments, but by using small, well-calibrated sensors, accurate high frequency measurements can be made. Commercially available VACM and VMCM sensors are not well suited for surf zone measurements, however, since it is

difficult to obtain accurate wave orbital velocity information, and their large size precludes their use in shallow water.

Hot wire anemometer flow sensors rely on the cooling properties of the dense fluid passing over the probe surface. Potentially, these sensors can provide very small scale, high frequency measurements in the surf zone. Unfortunately, poor directional sensitivity along with mechanical and fouling problems have plagued oceanographic measurements using these sensors (Frey and McNally, 1973).

The second group of flow sensors, the scattering type, obtain velocity information from the frequency shift of reflected energy from small particles moving along with the fluid. Most commonly laser or acoustic Doppler-shift instruments, they sense a small, well-defined volume that can be positioned away from the instrument package to eliminate almost all flow disturbance problems. With careful design, these sensors have shown excellent linearity, as well as outstanding frequency, horizontal, and vertical cosine response characteristics.

At present, technical difficulties and practical problems have prevented their wide usage in the ocean. Most importantly in terms of surf zone measurements, scattering sensors rely on the presence of a limited range of particle size and density for consistent signal quality; the presence of too many particles or large particles can result in serious signal losses (Wiseman, 1968). Also, the processing of the frequency information into velocity information is rather complex, and not easily accomplished in real time. Present research into laser Doppler current meters does show promise however, especially for very fine scale, high frequency measurements (Terry and Williams, 1978).

The last group, averaging sensors, rely on sensing some secondary phenomenon which is affected in some way by the flow of water through a control volume. Typically, these sensors exhibit good linearity, acceptable horizontal and vertical cosine responses, and, depending on the size of the averaging volume, good frequency response. On the negative side, volume averaging sensors are often plagued by poor absolute measurements due to zero flow determination and low frequency drift problems. Also, depending on the physical design, the averaging volumes can be complex and subject to sensor-induced flow disturbances. Two of the more successful and commonly used volume averaging sensors are the acoustic travel time and electromagnetic sensors.

The acoustic travel time sensor measures the slight shift in the speed of sound caused by the velocity of water along the acoustic measurement path. Although a travel time sensor (Williams and Tochko, 1976) has been used successfully in making detailed shallow water wave and current measurements, these sensors are potentially susceptible to signal dropouts similar to those observed with scattering sensors due to acoustic scattering off bubbles and sediment particles which could be common in the surf zone,

Electromagnetic current meters (EMCM's), the other common volume sensing current meter group, sense the small potential voltage gradient induced by the flow of water through an imposed magnetic field. These sensors, in common use by the oceanographic community for more than 20 years (Guelke, 1947; Tucker, 1970, 1972), have proven to be durable and reasonably linear. In addition, since the induced voltage sensed by the current meter is unaffected by moderate levels of sediment or

bubble concentrations, they are well-suited to the turbid surf zone environment. Even with such a long history of designs and usage however, many electromagnetic current meters have poor zero point stability and directional response records. Also, and very importantly, these sensors require much more power to operate than mechanical or acoustic current meters, so much so that they have not proved practical in most long-term, self-contained, oceanographic measurement programs.

It should be emphasized that this summary is not a definitive critique of flow sensors in general, but rather a careful summary of commonly used current meters and their important characteristics in light of specific surf zone flow measurement requirements. Most of the flow sensors discussed have been, or could be, successfully used in surf zone experiments, and the drawbacks mentioned could be overcome by careful design or, as in the case of the ducted propellers, by careful data interpretation.

Thus, the choice of the electromagnetic current meter as the flow sensor used in this measurement program does not mean that it is the "perfect" sensor, but instead, as shown in this summary, that it represents a good combination of the different characteristics of primary interest. With careful design it is potentially very linear, with good directional and frequency response, and has proved durable and accurate even in the sediment- and bubble-filled surf zone environment.

3.1.3 Electromagnetic Current Meter Principles

The first application of the principle of electromagnetic induction

to the measurement of natural flows was made by Michael Faraday in 1832. Shortly after proposing his general theory of induction, he attempted to measure the return current in the bottom sediment of the Thames, produced by the flow of the overlying water through the earth's magnetic field. Unfortunately, the electrochemical reaction between his copper electrodes and the bottom sediment produced such a large voltage that it effectively masked the much smaller voltage induced by the return current (Faraday, 1832). Other attempts to measure natural flows have been successful (Von Arx, 1950), but in terms of present current meter design, the first real advances came in the medical field with the application of artificially supplied magnetic fields to the measurement of blood flow (Kolin, 1936).

The first successful application of artificial magnetic fields to flow measurements in oceanographic research came in 1947, with the development of an alternating field current meter for measuring small scale wave and tidal flows by Guelke and Schoute-Vannek (Guelke, 1947). Then, in the late 1950's and early 1960's, work at the National Institute of Oceanography led to the development of a series of electromagnetic current meters applied to turbulence and Reynolds stress measurements (Tucker, 1956, 1960, 1972). At the same time, Miller and Zeigler (1964) at the Woods Hole Oceanographic Institution appear to have been responsible for the first work with electromagnetic current meters in the surf zone. More recently, numerous commercial current meters have been developed and marketed with varying degrees of success (NOIC, 1974).

All electromagnetic measurements of flow, regardless of whether

they utilize the earth's magnetic field or rely on an artificially produced magnetic field, rely on the same physical principle, that a conductor moving through a magnetic field experiences an induced electric potential (electromotive force, EMF) orthogonal to the direction of motion. In terms of Maxwell's Laws, this electric potential is governed by the relationship:

$$EMF = \int_L \vec{V} \times \vec{B} \, dL \quad (3.2)$$

where $\vec{V}$ is the vector velocity of the conductor, $\vec{B}$ is the component of magnetic flux, and L is the path integral through the magnetic field.

Referring to Figure 3.1, which is a schematic view of the electromagnetic current used in the surf zone measurements, it can be seen that the magnetic field, $\vec{B}$, is created by a circular coil of wire carrying a controlled amount of current, I . For a given radius, r , and number of turns, N , the magnetic field intensity at the center of the coil is approximately:

$$\vec{B} = \frac{\mu IN}{2r} \quad (3.3)$$

where μ is the permeability constant for free space ($4\pi \cdot 10^{-7}$ weber/amp-meter). Approximating the magnetic field as being constant over the central region of the coil, then the induced potential from the flow of the conducting fluid is orthogonal to the flow, and has a magnitude:

FIGURE 3.1: Schematic Representation of the Application of Electromagnetic Induction to Flow Measurement

$$EMF = \int_L (\vec{V} \times \vec{B}) dL \quad (3.4)$$

$$= \vec{V} \times \vec{B} \cdot 2r \quad (3.5)$$

$$= \vec{V} \cdot \vec{u} \cdot I \cdot N \quad (3.6)$$

where the extent of the length integral is taken as the coil diameter.

For the specific case of the current meter designed in this study:

$$r = 3.3 \text{ cm}$$

$$I = 0.10 \text{ ampere}$$

$$N \approx 2000$$

So, the induced voltage per cm/sec flow is roughly 2.51 microvolts (μV).

In actuality, since the magnetic field outside the central region of the coil is not at all uniform, the presence of the conductive fluid surrounding the central region acts to short-circuit much of this induced EMF. This effect essentially modifies the governing equation to:

$$EMF = \int_L (\vec{V} \times \vec{B} - J/\sigma) dL \quad (3.7)$$

where J is the short-circuit current, and σ is the conductivity of the surrounding fluid. In the present design, this effect, along with the non-uniformity of the magnetic field within the coil, reduces the sensitivity by a factor of approximately 3, leaving a sensitivity of about 1.0 microvolt per cm/sec flow. Of course, this sensitivity could

be improved by increasing the number of turns or current, and thus the magnetic field strength, but practical Ohm's law considerations (for a given supply voltage, increasing the number of turns means a higher coil resistance, thus less current flow, and vice-versa) led to a convenient coil design as used in this current meter.

Note that, with the electrodes spaced at the coil diameter, the size of the coil has no influence on the sensitivity.

The small magnitude of the final sensitivity has two important effects on the practical design of electromagnetic current meters in general.

First, chemical instabilities on the electrode surfaces and broad-band noise in electronic components such as high gain operational amplifiers and power regulators can easily be of the order of microvolts, so to insure adequate signal-to-noise ratios, special attention is required in their design and specification.

Secondly, and more significantly, the electrochemical difference between any two physically realizable electrodes is unstable and on the order of 100 to 1000 times the expected electrical potential due to magnetic induction. Fortunately, these electrochemical effects are very low frequency in nature, so the underlying signal can be detected by modulating the magnetic field, and thus the EMF, at a frequency well above DC. This modulated signal can then be selectively demodulated after eliminating the contaminated low frequencies.

In practice, this modulated magnetic field is produced by driving the coil with some controlled voltage signal, such as a square, sinusoidal, triangular, or trapezoidal wave. The use of such a wide variety of wave forms arises from various techniques used to account

for the hysteresis effects caused by the inductance of the electromagnetic coil. In the present design, the current is switched through the coil in alternating directions by a simple current-controlled square wave drive. With each change in direction, there is an initial voltage spike which decays as the current in the coil stabilizes. By sampling only during these periods of constant current, the hysteresis problems can be eliminated with only a slight increase in circuit complexity.

In summary, the application of the principle of electromagnetic induction to the measurement of natural flows is based on a rather straightforward application of physical principles, but requires some very careful considerations in terms of the complicated flow of short-circuiting currents in non-uniform magnetic fields. Also, practical sensing and noise problems necessitate careful design considerations.

3.1.4 Electromagnetic Current Meter Sensor Shapes

The preceding discussion of the application of the principle of electromagnetic induction to the measurement of flow velocity relied on a rather schematic representation of the interaction between the electromagnetic field and the flow field. In practice, mechanical, manufacturing, and flow field considerations have led to the development of several different coil and sensing volume configurations. Of these different shapes, the most commonly used are the cylindrical, spherical, discus, and Helmholtz configurations (see Figure 3.2).

The cylindrical sensor takes advantage of the relatively uniform external field of a solenoid encased within a long probe. The induced voltage from the flow of the conductive fluid around the sensor is then

FIGURE 3.2: Common EMC Sensor Shapes

sensed by two sets of electrodes on the cylinder's surface. Since the path integral between each pair of electrodes is primarily confined to the region along the surface of the cylinder, and at low Reynolds numbers the average flow being sensed around the cylinder is roughly the free stream velocity, the induced voltage has relatively little dependency on the orientation. This results in a rather poor horizontal cosine response at low velocities (as observed, for example, in NOIC, 1974). At higher velocities, when separation occurs, the horizontal response is even more complicated. In contrast, the vertical cosine response is inherently much better since, at a given angle of attack, ϕ , the path integral between electrodes sees a relative velocity of $V_{\text{free stream}} \cdot \cos \phi$. In terms of the characteristic response in oscillatory flow, the presence of the cylinder causes a significant amount of flow disturbance within the sensing volume, especially when the oscillatory component is larger than the mean component, i.e., the cylinder's wake is continuously advected past it, or when the characteristic length of the oscillatory component is close to the sensor diameter.

The spherical sensor, like the cylindrical sensor, relies on sensing the induced voltage in an external field, but instead of a long solenoid, the coil is a simple ring. Although the spherical symmetry of the sensor provides for a more uniform overall response in both the vertical and horizontal planes, the directional response in the horizontal plane is still rather poor (Collar and Griffiths, 1977). In addition, the response in oscillatory flow is similar to the response of the cylindrical shape, being less than ideal in flows dominated

by short scale oscillations.

The discus shaped sensor, more precisely referred to as an oblate spheroid, represents a departure from the basic sensing scheme used in the cylindrical and spherical sensors. Instead of sensing an external field, the discus sensor relies on sensing the flow through the more uniform, well defined magnetic field extending beyond the "front" surface (see Figure 3.2). Although this configuration has been shown to have a poor response to flows at arbitrary angles due to a poor vertical cosine response beyond 30° or so (Tucker, 1972), it has an excellent response in flows confined primarily to one plane. Since the sensing volume is subject to much less flow disturbance and the sensing paths have inherent cosine relationships to the flow, both the oscillatory and directional responses are much improved over those of the cylindrical and spherical sensors.

The Helmholtz sensor measures the induced voltage in the open region between two coils of diameter d , separated by a distance $d/2$ (see Figure 3.2). Since there is little flow disturbance in the central region between the coils and the magnetic field is very uniform, the characteristic response in arbitrary flow fields is excellent. Although this design has been shown to be practical (Olsen, 1972), it has not been extensively utilized to date, probably due to the increased manufacturing complexity and possible durability problems.

In summary, it is clear that different coil and sensor configurations lead to different characteristic responses. In terms of the flow field of the surf zone, it would appear that the directional resolution and oscillatory flow response problems of both the cylindrical and

spherical sensors precludes their use in favor of the discus shape. At the same time, although the potential response characteristics are very promising, the development and manufacturing complexities involved in the use of the Helmholtz sensor were considered to outweigh the benefits. Thus, the discus shape was chosen as the basis for the current meter design.

3.1.5 Drive Electronics

As outlined in Section 3.1.3, an alternating magnetic field is set up by switching current in alternating directions through an electromagnet using a simple square wave drive. Referring to the schematic diagram of Figure 3.3, it can be seen that this drive circuit is straightforward in design, consisting of an oscillator, digital gating logic, and a current switching network.

The master clock for the current meter is a one-chip multivibrator/divider, tapped at 120, 60, and 30 hertz (see the timing diagram in Figure 3.4). These outputs drive the digital gating logic which provide the switching pulses for the coil drive (operating at 30 hertz), as well as the control logic used in the sample-and-hold circuits of the synchronous amplifiers. These pulses are only high for the last 4.17 milliseconds of alternating 1/60 second cycles of current through the coil, and thus represent the time interval during which there is a uniform magnetic field (E and F in Figure 3.4).

The switching circuit of the drive electronics sends a regulated amount of current (approximately 0.10 ampere) through the coil in opposite directions every 1/60 second, using a simple bridge circuit

FIGURE 3.3: Schematic Diagram of Electromagnetic Current Meter Electronics

(page #33 not present in original)

FIGURE 3.4: EMCM Timing Diagram

routing system, controlled by the 30 hertz clock pulses (C and D in Figure 3.4).

The coil itself is made from approximately 2000 turns of closely wound copper wire impregnated in epoxy, and encapsulated in the sensor head as shown in Figure 3.5.

3.1.6 Amplifier Electronics

As the first step in decoding the modulated EMF from the flow of water through the imposed magnetic field, the small potential gradients above the surface of the sensor are electrically sensed by two orthogonal pairs of electrodes.

To minimize the noise and galvanic potential differences between electrodes (allowing a simplified preamplifier design), silver-silver chloride electrodes patterned after those used by Von Arx in his Geomagnetic Electrokinetigraph (Von Arx, 1974) were used.

Each pair of electrodes, representing the two orthogonal flow channels, are coupled directly to a high gain preamplifier that has a high common mode rejection ratio (CMRR) in order to eliminate contaminating common mode signals present between the ground reference and the sensing electrodes. This preamplifier boosts the sensed voltage by a factor of 200, and provides a low impedance output capable of driving a long telemetry cable (refer to Figure 3.3).

The modulated preamplifier output feeds into a buffered differential amplifier that is referenced to the sensor ground via an isolated ground line. This not only provides a high impedance, high CMRR buffer so as not to load the sensor preamplifier, but, by virtue of the

FIGURE 3.5: Electromagnetic Current Meter Sensor

isolated ground reference, reduces ground sensing problems. Unfortunately, when using several sensors, or when working in electrically noisy environments, this differencing circuit is not adequate in dealing with the multiple grounds and heavy ground line noise. To handle this, an optional isolation circuit (see Figure 3.3) can be inserted between the telemetry cable and the differencing cable to provide the complete electrical isolation of all sensor power and signal lines. This optional isolation system is discussed further in Section 3.3.3.

After passing the differencing buffer, the signal branches to the demodulating sample-and-hold (S/H) amplifiers. Controlled by the logic from the drive circuit, these amplifiers are alternately switched to sample 12.5 milliseconds after each change in the magnetic field, thus allowing the magnetic field to stabilize. First, one branch is sampled, then when the current has reversed and stabilized, the other branch is sampled. The control for each sampling lasts only 4.2 milliseconds, after which the analog signal filtered with roughly a 1.0 millisecond time constant is stored.

At this point, one branch holds the value of the induced EMF from one direction of the magnetic field plus the electrode offset difference, while the other branch holds this same electrode offset difference as well as the EMF from the reversed magnetic field. By taking the difference between these two values in a precision difference amplifier, the low frequency electrode offset potential subtracts out, leaving only the desired EMF signal.

Although this electrochemical offset has been effectively filtered

out at this point, a long time constant negative feedback loop is coupled between one of the sample-and-hold outputs and an earlier high-gain amplifier to ensure that the total signal stays within bounds. Without this provision, the modulated signal would be out of range due to the simultaneous amplification of the larger electrode offset.

After the differencing circuit, the signal is amplified one last time, then filtered and buffered for output with a single-pole R-C filter having a 3 dB roll-off point at 4.0 hertz.

3.1.7 Hydrodynamic Response

The design of an instrument such as the electromagnetic current meter to meet a set of general requirements like those outlined in Section 3.1.1 is difficult to optimize, since the overall performance, both operationally and in terms of its sensing abilities, represents the combined effect of interrelating physical, electrical, and hydrodynamic characteristics (see Note). During the development of the current meter, these interrelationships had to be considered, since changes in one area often resulted in modifying the characteristics of another. For example, the general shape of the sensor was modified several times in order to ensure an acceptable vertical cosine response.

In terms of the quality of the actual measurements however, the

Note: For example, the cosine response of the current meter is a function of the shape of the sensor and the shape of the sensing volume, which is itself a function of the position of the electrodes, the coil size and shape, as well as the number of turns, etc.

bottom line is the actual hydrodynamic response of the complete sensor. To evaluate this, the final current meter design was rigorously tested in a wide variety of flow conditions using the tow tank and flume facility of the Woods Hole Oceanographic Institution. In all, over 200 towing and flume tests were run in order to establish the general response characteristics in terms of linearity and horizontal and vertical cosine response in steady, oscillatory, and combined steady and oscillatory flow conditions.

Steady Flow Response

As a first step in determining the general response characteristics of the current meter, tests at various speeds and orientations were performed under steady flow conditions.

The results of the tests for the on-axis response versus flow velocity are presented in Figure 3.6. From the figure, it appears that the sensor's response is linear, all the way from the minimum tow speed of about 7.5 cm/sec to the maximum of about 120 cm/sec. Since the accuracy of the tow speed and sensor output was approximately 0.5%, it is possible to look at this linearity in more detail by plotting the gain (i.e., output voltage/tow speed) versus velocity as shown in Figure 3.7. From this plot, it is clear that some nonlinearity exists in the response, especially at low velocities ($\approx 10\%$). This nonlinearity in response appears to be caused by changing boundary layer conditions within the averaging volume above the sensor surface. As the tow velocity increases, the surface boundary layer not only becomes thinner, but the velocity within this layer increases relative to the mean flow.

BLUE SENSOR LINEARITY 0-120 cm/sec

$\theta = 0$

$\phi = 0$

FIGURE 3.6

FIGURE 3.7: Normalized Sensor Gain

Since the mean velocity sensed within the fixed averaging volume has increased, this leads to an apparent increase in gain. Although the plot of Figure 3.7 shows a 10% nonlinearity over the test velocity range, it should be emphasized that by using the more constant gain found at higher velocities, the absolute error, even at the low velocities, is only 1 to 2 cm/sec at most.

The horizontal cosine response was determined by rotating the sensor in the horizontal plane through 180° in 15° steps. The results of these tests, performed at three different tow velocities, are presented in Figure 3.8, and show a rather impressive response when compared with the superimposed ideal horizontal cosine response.

The vertical cosine response was investigated by towing the sensor with one axis aligned with the flow at changing vertical angles of attack. From the plot of Figure 3.9 it appears that, for the range of angles from about -30° to $+30^\circ$, the response is approximately cosine. At increased negative angles of attack, however, the response becomes unstable due to the onset of separation, causing random eddies and fluctuations within the sampling volume on the front face of the sensor.

This instability at large negative angles of attack is potentially a serious shortcoming in the general applicability of the sensor to the measurement of large orbital or vertical flows. However, since the flows in the surf zone of primary interest are in the horizontal plane, and since there is a confining bottom boundary, vertical velocity components are small and can be dealt with by placing the sensor near the bottom, with the averaging volume facing upward.

FIGURE 3.8

FIGURE 3.9

Oscillatory Flow Response

To investigate the response in oscillatory flow conditions, the sensor was rocked back and forth in the tow tank with a sinusoidal motion.

The plot of Figure 3.10 summarizes the results of these tests, which covered oscillatory motions of amplitudes, a , ranging from 5 centimeters to 40 centimeters, and periods from 1 second to about 7 seconds. In the figure, the gain is defined as the ratio of the peak-to-peak sensor output, V_{p-p} , to twice the maximum angular velocity, $2a\omega$, while the measurement accuracy is indicated by the error bars. Most significantly, there is no evidence of a lower response at higher frequencies due to possible flow instabilities or disturbances caused by the sensor itself. It does appear, however, that there may actually be an increase in gain with frequency. By replotting the data in terms of the angular velocity as shown in Figure 3.11, it appears that this nonlinearity has the same general characteristics as those found in the steady flow tests. Furthermore, this nonlinearity is inversely proportional to the ratio of the excursion amplitude of the flow (A_p) to the diameter of the sensor (d). For higher ratios of A_p/d , the nonlinearity approaches that of the steady flow case, while for lower ratios the nonlinearity is more pronounced. (Unfortunately, it is not possible to compare absolute gains between the steady and oscillatory tests, as different sensors, having different electronic gains, were used.) Thus, it appears that the nonlinearity associated with Figure 3.10 is really caused by a nonlinear response to velocity, as shown in Figure 3.11, rather than a nonlinear frequency response due to flow disturbances or electronic

OSCILLATORY FLOW - GAIN VS FREQUENCY

FIGURE 3.10

OSCILLATORY FLOW - GAIN VS RADIAL VELOCITY

FIGURE 3.11

□ - $a = 40$ cm Δ - $a = 20$ cm $\bigcirc$ - $a = 10$ cm $\bigcirc$ - $a = 5$ cm

problems. This increase in nonlinearity, associated with the lower $A_b/2aw$ ratios, is consistent with the boundary layer model hypothesis put forward in the discussion of the steady flow response. In this case, the short-excursion, higher frequency oscillatory flow velocities cause a thinner, less developed boundary layer, resulting in an even higher apparent gain.

It should be pointed out here that, even though the sensing electronics has the ability to provide a reasonable frequency response well past 4 hertz and the oscillatory flow tests show no loss of hydrodynamic response at frequencies up to the maximum test frequency of 1 hertz, the actual frequency response realizable in practice is limited by the size of the averaging volume and the mean advection velocity. Assuming that the higher frequencies are characterized by smaller length scales, at some point these fluctuations have characteristic lengths which no longer dominate the sensing volume ($A_b/d < 1$), so they must be advected through the averaging volume in order to be adequately sampled, and not "spatially aliased". For example, mean longshore currents are often on the order of 20 cm/sec, so when coupled with a sensor diameter of 10 centimeters, the maximum frequency that can be resolved without aliasing is 2.0 hertz. An important point that should be mentioned is that, although the current meter is aliased at frequencies beyond 2 or 4 hertz, for example, the sensor still responds to higher frequency fluctuations, so care must be taken to ensure that this information does not contaminate the lower frequency signal. In the case of the current meter, the 30 hertz sampling rate, coupled with the 4 hertz output filter, provides an efficient sampling and filtering

scheme for eliminating this higher frequency information.

Response in Combined Steady and Oscillatory Flow

Since the field application of the current meter calls for the ability to resolve means and oscillatory components from the combined flow field, a final series of tests was run to make sure that the sensor's response is simply a linear superposition of its characteristic responses in the two flows.

In these tests, the current meter was towed at a constant velocity of 25 cm/sec, and was given an additional sinusoidal motion of varying frequency. To investigate the effect of the vertical cosine response, these tests were also carried out at varying positive and negative angles of attack.

The plots of Figures 3.12 and 3.13 show the results of these tests in terms of the resolution of the correct mean velocity (taking into account the ideal vertical cosine response) and oscillatory component as a function of the relative dominance of the mean to the oscillatory component. From these plots it can be seen that, for vertical angles of attack between $\phi = 30^\circ$ and $\phi = -15^\circ$, the response is simply a superposition of the mean flow and oscillatory flow response. But, as was found in the case of pure oscillatory flow, beyond a negative angle of attack of approximately -30° the response becomes unstable. Interestingly, however, as long as the oscillatory component is equal to or greater than the mean flow ($V_{\text{mean}}/a\omega < 1.0$), it appears that separation does not take place, as the response remains stable and the correct components can still be resolved.

RESOLUTION OF MEAN COMPONENT

$$V_{\text{MEAN}} = 25 \text{ cm/sec } a = 25 \text{ cm}$$

FIGURE 3.12

RESOLUTION OF OSCILLATORY COMPONENT

$$V_{MEAN} = 25 \text{ cm/sec } a = 25 \text{ cm}$$

FIGURE 3.13

In summary, the tow tank tests show that the overall response is more than acceptable in terms of the desired sensing characteristics for surf zone measurements of the horizontal velocity components near the bottom. In addition, the tests have shown that, in general, the size and shape of the sensor head is the most important factor in the overall response. In terms of the steady flow response, the ratio of the major to minor axis governs the instability of the vertical cosine response and the general linearity of the horizontal gain. In unsteady flow, the relative length of the sensor to the wave particle excursion length governs the frequency response, while the relative magnitude of the mean and oscillatory velocity components governs the instability of the vertical cosine response.

3.2 DIGITAL WAVE GAUGE

In addition to the electromagnetic current meter, a digital wave gauge (DWG), designed to provide complimentary information about the instantaneous surface elevation, was developed and integrated into the field measurement system.

3.2.1 Response Requirements

The measurement of the instantaneous water surface elevation is necessary both inside and outside the surf zone for the determination of mean water level, wave height, and momentum flux. "Since anything that responds to a change in the level of a water surface is potentially an instrument for measuring waves, one might suppose that instruments for measuring waves would be well developed and readily available.

Such is not the case. Available wave instruments are all unsatisfactory in one respect or another." (Kinsman, 1965). So, just as in the case of the choice of a current sensor, the response requirements in terms of temporal and spatial accuracy have to be defined.

In terms of the expected dynamic range of the surface elevation, the New England beaches that have been considered of interest exhibit moderate wave climates during most of the year, with significant wave heights on the order of 1.0 meter. Tidal ranges vary from less than 1.0 meter in some areas to over 3.0 meters in others, but the expected elevation changes due to tides over the two to three hours of each short term experiment are only on the order of 0.5 meters. Based on these two estimates, the required dynamic range to ensure continuous coverage without loss of signal due to wave overtopping is roughly 2.0 meters.

In terms of a required temporal resolution, a good DC response as well as an adequate sampling of the nonlinear wave characteristics is required. This upper limit is difficult to estimate without a prior knowledge of the frequency composition of the surf zone waves, but a reasonable criterion is to match the response of the wave sensor to the frequency response of the current meter.

In addition to the response measurements, there are several important operational considerations. First, since the surf zone is an energetic region, any sensor has to be durable and relatively easy to deploy. Secondly, since it is to be used near other sensors, it should not interfere with their operation, and it should be easily integrated into a larger system. More generally, for ease in analysis, any sensor should exhibit a linear, stable response, and have a high

signal-to-noise ratio.

3.2.2 Alternative Sensors

Surface elevation sensors can be roughly categorized into three groups: those relying on direct, indirect, or remote methods for sensing the surface.

"Direct" methods, such as surface piercing resistance or capacitance wave gauges, rely on sensing the actual presence of water along a vertical line. Such sensors are widely used, since they are relatively simple and economical, and they provide the most direct measure of the surface. The main disadvantage of this class of sensors is that they often disturb the flow, so the measured elevation is somewhat altered by the presence of the sensor itself. Depending on the physical design, there is often a significant run-up on the front surface of the sensor with each passing crest and a hysteresis associated with the influence of a surface tension film left following each crest. One type of direct measuring sensor that does not have this run-up or hysteresis problem is the acoustic travel time wave gauge, since it senses the free surface without disturbing it (see Note). Unfortunately, field experiments at the Woods Hole Oceanographic Institution with this type of sensor have shown it to be susceptible to signal drop-outs in breaking or near-breaking waves, due to the poor acoustic reflection from the rough surface and the presence of scattering bubbles and sediment

Note: The acoustic wave gauge is sometimes considered an indirect sensor, since it relies on the speed of sound in water.

in the water column (Cornuelle, 1977).

"Indirect" methods rely on sensing some secondary characteristic of the water column which can be related back to the surface elevation using some transfer function. Pressure sensors, which are simple and easily deployed, are the most commonly used indirect surface elevation sensors. Unfortunately, since the transfer function used to go back up to the surface elevation relies on the validity of linear wave theory, i.e., small amplitude waves, and is a function of frequency and depth, the accurate interpretation of pressure records in or near the surf zone is rather complex.

Motion recording surface floats belong to the class of indirect surface measuring sensors. Most commonly, these floats are instrumented with accelerometers which are used to compute the vertical displacement of the float. Since the combined response of the float and the mooring system used to position the float is amplitude and frequency dependent, the interpretation of the acceleration information in terms of the actual surface elevation is, once again, rather complicated.

"Remote" sensing of the free surface is the most technologically sophisticated and expensive of the three sensor groups. Using photographic, radar, or laser imaging techniques, for example, these sensors can provide valuable large scale, two-dimensional information about the water surface. These remote sensors also have the desirable characteristic of not interfering with the free surface.

In view of the response requirements outlined in Section 3.2.1, which called for continuous point measurements in and near the surf zone, it seems clear that the best choice is a direct measuring sensor.

Certainly, the nonlinear and high velocity characteristics of the surf zone eliminate the possibility of using indirect sensors such as pressure or float gauges, while the expense and complexity of remote sensing is prohibitive.

Within the direct measuring category of surface elevation sensors, there are still numerous possible sensors. Due to the lack of interference and low power requirements, it was decided that a surface piercing, discrete element, digitally controlled wave gauge would be developed. Such a sensor could be rigidly mounted inside or outside the surf zone to provide an easily telemetered, accurate measure of the sea surface elevation. The principles of operation, development, and integration of this digital wave gauge (DWG) into the field measurement system is outlined in the next four sections.

3.2.3 Principle of Operation

The digital wave gauge is made up of 128 independent, controllable conductivity sensors arranged in a vertical array. Each of these sensors relies on the high input impedance characteristics of the Complimentary Metal Oxide Silicon (CMOS) family of digital integrated circuits. In essence, each of these sensors acts as a digital switch, normally in the "high" logic level due to a slight positive biasing applied to each input. When sea water completes a path between each sensor electrode and ground, the output level switches to "low" as the input potential swings to ground.

The output levels of all these digital buffers combine to produce an indication of the changing surface elevation; i.e., digital logic

levels of high or low correspond to elements either out of the water or in the water, respectively. These outputs are, in turn, monitored by a 128 element parallel to serial shift register. On command, this register stores the instantaneous logic state of each buffer, then proceeds to shift that parallel information in a serial manner out of the register and into the receiver. There, the serial logic levels are counted, stored, and converted into an analog voltage representing the level of the water surface on the sensor.

To maximize the signal-to-noise ratio during telemetry, the DWG electronics are divided into two parts: the sensor transmitter, which controls and includes the 128 element shift register, and the receiver counter and converter.

The wave gauge electronics also include a provision on the receiver end of the cabling for the electrical isolation of signal and power between the transmitter and receiver. This provision, which arises from noise and ground loop considerations, is covered in Section 3.3.3 and, for completeness, is discussed there.

A detailed schematic diagram of the digital wave gauge electronics is shown in Figure 3.14.

3.2.4 Transmitter Electronics

The transmitter electronics can be broken down into three functional blocks: the signal conditioner for the strobe command, the parallel/serial control logic, and the 128 element shift register (see Figure 3.14).

The strobe signal conditioner accepts a sloppy trigger pulse from

the outside world, and produces a 32 ms clean strobe command to the sensor. This is accomplished with a 4047 multivibrator configured as a monostable oscillator, the input to which is protected by a capacitor and clipping circuit that only passes pulses within the power supply limits.

At the sensor, this strobe pulse triggers a "one-and-only-one" circuit configured with two 4013 flip-flops. The output is a single clock pulse of about 012 ms duration, which is applied to the parallel/serial control line of all 16 of the 8 bit shift registers in the 128 element array. At the trailing edge of this clock pulse, the logic state of each register is stored internally.

The actual logic state is determined by the amount of conductivity between each individual input and the ground reference electrode. If no water is present, the input is forced high due to the presence of a small positive bias current. But, when a sea water path exists between the input and ground, this bias current is shorted to ground and, as a result, the input swings low. In the final design, the amount of biasing (i.e., the resistor values) was optimized experimentally to provide a change in logic level to low only when the electrode actually touches the water surface, and a change back to high when the water surface falls just below the electrode, even though a thin film might still remain.

After storing these logic states, the data is serially shifted by the transmitter clock up the wave gauge, through a NOR circuit, and onto the serial data output line.

The NOR circuit is necessary in order to obtain individual data

pulses, since the 4020 shift register outputs only change state when necessary. In other words, as long as high logic levels are being shifted, the serial output remains high, and only when a low comes along does the output change. By combining this serial output with the clock, separate pulses corresponding to the input state of individual registers appear on the output line. For convenience in decoding the serial data, a NOR circuit was used instead of an AND circuit in order to have positive pulses represent elements under water, rather than elements out of the water.

An important design element of the transmitter is a transistor switch that only sends current through the bias resistors when the parallel/serial clock pulse is present. This has two significant effects. First, since the electrodes are biased for only 0.2 ms during each measurement, the electric field radiated into the surrounding water has little influence on other instruments like the electromagnetic current meter, which is very sensitive to electric fields. Also, since the timing of this biasing signal is controllable, the wave gauge can be made virtually "invisible" to the current meters by strobing during the settling period of the EMCM's magnetic field, when no measurement of the electric field is being made.

The other main advantage to controlling the biasing current is a reduction in current consumption by a factor of nearly 100, resulting in a maximum current requirement of only 3 ma.

3.2.5 Receiver Electronics

The wave gauge receiver totalizes the number of serial data pulses from the transmitter shift register, then converts this total into an analog voltage representing the level of water present along the wave gauge surface.

The serial data is totalized by a 4040 binary counter, which is reset at the start of each measurement cycle by a simple RC filter tied to the strobe output line. Since the counter has not totalized all the possible data pulses from the transmitter until there have been 128 clock pulses, the receiver includes a data storage register that is only updated after the counter has had enough time to receive all the data. The update command for this 8 bit digital latch is derived from the compliment of the 32 ms monostable output. Since it only takes the transmitter about 25.6 ms to clock the 128 possible data pulses, this 32 ms waiting period between the initial strobe command and the latching of the binary data allows more than enough time for all the data to be counted.

The output of this digital latch, which now represents a stable measure of the total number of elements under water, is then converted into an analog voltage by a two chip digital to analog (D/A) converter. As a final step, the output from this D/A converter, which is trimmed to produce 30 mv for each binary bit, is buffered from the outside world by an operational amplifier configured as a simple voltage follower.

3.2.6 Sensor Characteristics

The digital wave gauge sensor, consisting of the sensing electrodes and the transmitter electronics, is constructed from a 1.25 inch diameter polyvinyl chloride (PVC) tube (see Figure 3.15).

The 128 electrodes are small stainless steel screws, spaced 1.5 centimeters apart along the front surface of the sensor. Inside the sensor, these electrodes are wired directly to the transmitter electronics, which are mounted on thin printed circuit boards. The power and signal connections needed to control and telemeter the wave gauge data are made through a waterproof connector mounted on the bottom of the sensor. For waterproofing and strength, the PVC tube is filled with a flexible, nonconducting epoxy, then backed with an aluminum channel. The cabling to the wave gauge is ordinary four conductor, unshielded, neoprene cable, which has proved more than adequate in handling the almost continuous 5 kHz data rate from the sensor.

As discussed in Section 3.2.2, the finite diameter of the sensor results in a certain amount of run-up on the front surface with each passing crest. To minimize this as much as possible, the smallest diameter tubing that could still accommodate the transmitter electronics was used in the final design. Even so, under near-breaking wave conditions, when surface velocities were very high, run-up was observed right at the crest of the wave. Although this run-up occurs over a very short portion of each wave period, under certain conditions it can result in a significant overestimation ($\approx 10\%$ observed) in wave height. To remedy this, future sensors could be made with electrodes spaced away from the sensor surface on thin insulators.

FIGURE 3.15: Digital Wave Gauge

3.3 FIELD SYSTEM DESIGN

For the proposed surf zone field experiments outlined in Section 2, calling for detailed measurements of the spatial variation in waves and currents, it was decided that a field system capable of supporting up to four wave gauges and four current meters was needed. In integrating these sensors into one complete, flexible measurement system, such things as power requirements, sensor compatibilities, and interferences, as well as noise and ground loop problems had to be considered.

The final field system, incorporating the eight sensors, the field power/monitor unit, and the data logger are briefly discussed in the next sections.

3.3.1 Field Power/Monitor Unit

The field power/monitor unit, pictured in Figures 3.16 and 3.17, houses the power supply and switching network, as well as the wave gauge receivers and current meter electronics.

The power to operate the field system is derived from a 10 ampere-hour, sealed lead acid battery pack, which ensures more than enough power to operate all the sensors over each high tide cycle. In addition to being easily and quickly recharged, this battery pack can be paralleled with an external power source to extend the system's operational life indefinitely. To ensure maximum flexibility and to minimize current consumption, the battery power is switched to each current meter individually, while the wave gauges, which consume only a fraction of the power needed for each current meter, are switched on together.

FIGURE 3.16: Front Panel - Field Power/Monitor Unit

FIGURE 3.17: Inside View - Field Power/Monitor Unit

The power and signal connections for the wave gauge and current meter sensors are made via connectors mounted on the front panel. The lines from the waterproof sensor cables are routed through these connectors to the appropriate receiver electronics, mounted on replaceable printed circuit boards (see Figure 3.17). For completeness, the component layouts and pin assignments for the different printed circuit boards are presented in Appendix A.

To provide a means of checking the operation of each sensor, three channels of analog monitoring are incorporated in the field power/monitor unit. To protect the internal signals from noise or heavy loading, these monitor outputs are buffered with simple voltage followers. One of these monitor channels is dedicated to an analog meter located on the front panel, while the other two are available for display on an external chart recorder via front panel connectors.

3.3.2 Timing Considerations

In integrating the eight sensors into one system, the measurement timing cycles of each instrument had to be considered in order to eliminate cross-talk and interference.

As discussed in Section 3.2.4, the most significant source of interference exists between wave gauges and current meters located close to each other. Since they both rely on precise measurements of the electric field in the water, design provisions to synchronize the measurement cycles of the two instruments were included in the basic design of the two sensors (see Section 3.2.4 for a complete discussion).

Another source of interference between sensors was found during preliminary lab and field experiments using several current meters at once. Since the individual current meters are controlled by their own clocks, small differences in frequency led to occasional cross-talk between current meters, due to ground line instabilities when the sampling time of one current meter passed through the switching time of another. To eliminate this problem, all the clocks were synchronized through the use of a common feedback line between the individual clocks (see Figure 3.3).

3.3.3 Noise and Ground Loop Considerations

Following the first preliminary field experiments using several sensors with long cables, it was found that the output signals were often contaminated with high frequency noise and low frequency ground loop instabilities. The main source for these problems was the presence of several virtual grounds spread over wide areas in regions of high electrical activity. In addition, electromagnetic induction in the long cables contributed to large common-mode voltages being present on the signal and ground lines.

To eliminate these problems, the power and signal lines from all the sensors were individually isolated from the field power/monitor unit. By doing this, the ground reference for the shore electronics never sees more than one virtual ground, and is much less susceptible to the effects of electromagnetic induction.

The isolation of the electromagnetic current meters was accomplished through the use of analog differential isolation

amplifiers. These amplifiers not only ensure a complete electrical isolation between input and output, but they also provide an isolated ± 15 volt power supply that is used to power the sensor preamplifiers. The circuit diagram for this isolation system is shown in the schematic diagram of Figure 3.3 and resulted in a noise level below 1 cm/sec.

To isolate the wave gauges, a DC to DC power supply that produces an isolated 12 volt output was used in conjunction with optical isolators on the serial data lines. The circuit connections for this scheme are shown in Figure 3.14.

3.3.4 Data Recording

To provide an accurate record for later analysis, the twelve channels of analog data are permanently recorded on digital cassettes by a 12 channel Sea Data data logger.

This logger is a self-contained, high-density recorder, which provides 12-bit accuracy on all channels, and can be programmed to scan at rates of up to 4 hertz. Each 450-foot cassette tape has a capacity of 15 million bits, which translates into a continuous tape record of roughly five hours when sampling every 250 ms. By simply inserting a new cassette into the logger when one has been filled, this data capacity can be extended indefinitely.

4. MAINE FIELD EXPERIMENT

After several field tests of the instrumentation system and its components, a comprehensive field experiment designed to measure wave induced longshore currents took place on a beach along the south coast of Maine in late October of 1978. During this experiment, which included four of the current meters and wave gauges described in Section 3, a period of rather large, uniform wave and longshore currents existed at the site. In addition to providing an experimental data base for momentum fluxes and longshore current analyses, this experiment provided the most extensive test of the instrumentation system to date.

4.1 LOCATION AND BEACH CHARACTERISTICS

The site of the experiment, along the south coast of Maine, near the community of Biddeford, is shown in relation to the New England coast in Figure 4.1. The beach itself faces south-southeast, and is about 1 km long, ending in curved rocky headlands at both ends. The beach face is gently sloping (about 1 on 30), with a characteristic berm and steep foreslope. The beach profiles near the transect site, as determined from a series of transit surveys before and after the experiment, are shown in plan view in Figure 4.2, and in contour view in Figure 4.3. From these figures, it can be seen that the beach is fairly uniform laterally, with a slight shift in beach contour direction at the foot of the foreslope. The beach face itself consists of a well-sorted sand, having a mean diameter of approximately 0.3 mm.

FIGURE 4.1: Location of the Maine Surf Zone Hydrodynamics Experiment

FIGURE 4.2: Maine 2 Experiment Beach Profiles

FIGURE 4.3: Maine 2 Experiment 30.0 cm Beach Contours

4.2 DEPLOYMENT AND MEASUREMENTS

The large tidal range along the Maine coast (~ 3.0 m) made it possible to install all the sensors and measurement stations during low tide, take measurements during high tide, then remove all the equipment with the next low tide.

During the field experiment in October of 1978, four measurement stations were installed along a shore-normal transect at the locations shown in Figures 4.2 and 4.3. Each station, supporting a wave gauge and current meter, as shown in Figure 4.4, consisted of a simple guyed-pole structure, tensioned by three cables attached to pipe anchors. After installing the stations and sensors, the telemetry cables were run to the shore field monitor power unit, while the current meter alignments were being determined with the aid of the survey transit. These orientations, along with the station heights relative to the lower baseline (which was approximately 0.7 m below the mean high water line) are presented in Table 4.1.

As the tide came in, all the sensors were slowly covered, and when all the current meters were operational (i.e., they were totally submerged), recording began. Unfortunately, the wave gauge at Station 1 did not prove operational, due to a connector failure that occurred during installation. After the proper operation of the other sensors was confirmed qualitatively by the monitor output on the portable strip chart recorder, zero flow measurements were made on each of the current meters to determine the actual offset on each velocity channel. These measurements were made by covering each of the sensors

FIGURE 4.4

Mounting Configuration for the Wave Gauge and Current Meter

MAINE SZH EXPERIMENT: M2

STATION 4:

Distance from baseline:	65.5 m
Elevation:	- 1.85m
EMCM sensor:	RED
Height of EMCM:	43.0cm
Orientation of EMCM	
CHA:	on/offshore
CHB:	alongshore
DWG sensor:	#2
Height of DWG:	87.0cm

STATION 3:

Distance from baseline:	43.7 m
Elevation:	- 1.06m
EMCM sensor:	GREEN
Height of EMCM:	23.5cm
Orientation of EMCM	
CHA:	alongshore
CHB:	on/offshore
DWG sensor:	#4
Height of DWG:	46.5cm

STATION 2:

Distance from baseline:	32.8 m
Elevation:	- 0.69m
EMCM sensor:	ORANGE
Height of EMCM:	17.5cm
Orientation of EMCM	
CHA:	alongshore
CHB:	on/offshore
DWG sensor:	#3
Height of DWG:	38.5cm

STATION 1:

Distance from baseline:	21.9 m
Elevation:	- 0.34m
EMCM sensor:	YELLOW
Height of EMCM:	9.0cm
Orientation of EMCM	
CHA:	on/offshore
CHB:	alongshore
DWG sensor:	#1
Height of DWG:	33.5cm

TABLE 4,1

with PVC caps for several minutes while continuing to record on the data logger.

When this process had been completed, the system was allowed to operate for the next several hours, during which time visual observations of wave height, breaker point and angle, as well as longshore currents were made. After the passing of high tide, and just before the inner current meter began to be exposed, another set of zero flow measurements were made, then the system was shut down. As the tide continued out, the orientations of the current meters were measured again, then the four stations were disassembled.

In general, the waves and currents observed during the course of the experiment were rather stable; the wind was low, and there was a consistent and uniform offshore swell. Figure 4.5 shows a representative view of these wave conditions, being taken shortly after high tide.

Throughout the experiment, numerous visual estimates of the waves and currents were made. These observations were used in the field to confirm the operation of the instruments, and later as a check of the results obtained in processing the recorded data.

4.2.1 Observed Wave Conditions

During the period corresponding to that analyzed in Section 4.5, the waves were observed to have a significant height of approximately 1.0 meter, and a period of 10 to 11 seconds. The waves broke in the vicinity of Station 3, and were characterized as spilling breakers,

FIGURE 4.5

General Wave Conditions Observed During the Field Experiment

although the largest ones were often plunging. The width of the surf zone was estimated at 30 meters on the basis of the distance from Station 3 to the end of the swash zone, which extended just past the step in the foreslope. The angle of the waves to the shoreline at breaking was roughly estimated at 5° to 10° from the southwest.

4.2.2 Longshore Current

Lagrangian estimates of the longshore current were made using buoyant floats timed over varying distances. Although significant variability in the instantaneous speed and direction of the floats was observed, a net flow of 15 to 20 cm/sec to the northeast was always observed in the vicinity of Stations 2 and 3. Rip currents were not observed within the transect area during the experiment, but they were noticed occasionally at widely spaced intervals to the east and west.

4.3 PRE-PROCESSING SUMMARY

The analog signals from the wave gauges and current meters are permanently recorded on the Sea Data digital cassette data logger. Then, prior to the analysis of the data in terms of the measured waves and currents, the data has to be reformatted in order to make it compatible with the Hewlett-Packard computer system, calibrated, and qualified. Figure 4.6 presents a block diagram of this processing sequence.

SURF ZONE HYDRODYNAMICS DATA PATH

* indicates plotting programs

FIGURE 4.6

4.3.1 Data Reformatting

Reformatting the data is the single most time consuming step in the analysis of the digital recordings. First, the digital cassette, which contains four track serial data at a density of 800 bits per inch, is read on a high-speed tape transport. The serial bit stream is intercepted and processed by a standard cassette reading program called CARP, developed at Woods Hole for processing Sea Data cassette tapes (Hunt, 1974). The processed data, still in a multiplexed serial format, is stored on a 9 track magnetic tape, then unpacked onto fifteen parallel disc files, which include the notation headers, the sampling speed, the binary clock, as well as the twelve data channels, by a program written specifically for the Model 1250 data logger.

4.3.2 Editing of Wild Points

The next step in the pre-processing of the wave gauge and current meter records is the editing of "wild points" or "outliers". The introduction of these wild points is characteristic of digital recording schemes, and is caused by a severe loss of sensitivity in a short length of tape. This loss of sensitivity is usually due to surface flaws, mechanical damage, or geometric distortion during reading or writing.

The number of wild points in a time series is usually low ($\ll 1\%$), but they can have a significant influence over short intervals when numerous wild points occur. Since the values of the wild points are characteristically large, but of random sign, the computed mean value

is little affected. The main source of error due to wild points is in the computation of frequency and power spectra, as the large spikes introduce high frequency components that can severely contaminate the spectrum. An example of this is shown for the time series in Figure 4.7 which is taken from an unusually poor record made during an early field test. Here, before editing, there are eighteen wild points in 2048 points (0.8%). The power spectrum for both the unedited and the edited series is presented in Figure 4.8. From Figure 4.8 it is clear that the wild points significantly influence both the amount of power in the spectrum and its frequency distribution.

There are several methods commonly used to edit wild points; the simplest is the use of a level detector set outside the range of expected data values but within the range of wild points. This technique is simple, but is data specific and not entirely reliable.

Another method which is more general and reliable is the use of a standard deviation criterion on the difference series of the data. The basic algorithm for this method is straightforward. The forward difference series for the data,

$$X_{\text{dif},i} = X_i - X_{i-1} \quad (4.1)$$

is computed for the unedited data. Then, a multiple of the standard deviation of this series is used as a limit criterion for passing each point. If a given point is less than this standard deviation criterion,

FIGURE 4.7: 2048 Point Time Series -
Before and After Editing

FIGURE 4.8: Power Spectrum Comparison - Before and After Editing - 2048 Points, 50 DOF

it passes the filter, and if not, it is replaced by one-half the sum of that point and the subsequent point. The process is repeated until there are no points outside the standard deviation limit, then the time series is recomputed by the backward difference series:

$$X_i = X_{i-1} - X_{\text{dif},i-1} \quad (4.2)$$

The successful application of this method relies on the assumptions that the wild points are few in number, with no more than a few adjacent to one another, and that the data is relatively stationary. If there are numerous wild points in a series, the standard deviation of the difference series will significantly overestimate the true variability of the underlying data, and as a result, a lower apparent limit criterion must be applied to the series in order to eliminate the wild points. This can be a serious problem in editing numerous blocks of data, since regions with numerous wild points may not be edited with a given criterion, while regions with no wild points may be edited using a "low" criterion, set for regions with wild points. This problem can be minimized by using the standard deviation from a previous, edited series. Assuming the data is relatively stationary, this estimate represents only the variability of the underlying data, and is not influenced by the wild points. The only remaining problem is to establish an estimate for the first series. This can be done by selecting a series that has no wild points, or, as in the program

used on this data set, a survey is made of the number of points edited for the first block, given different standard deviation criterions based on the unedited variance. This survey is then presented to the operator, and a decision is made as to the criterion to be used on the first block, and all subsequent blocks. Once the first block is edited, then the edited variance is used for the next block, and the algorithm begins repeating for each block.

4.3.3 Calibration of Wave Gauge and Current Meter Records

The calibration of the wave gauge records is relatively straightforward, since they are calibrated in the lab to give a 30 millivolt per 1.5 cm step. Taking into account the 2.44 millivolt per bit analog to digital conversion by the data logger, the final calibration factor is 0.122 cm water per binary bit. Then, the height of the bottom element above the bottom, as recorded in the field, is added to the entire data set.

The calibration of the current meter records is more involved, since each channel must be calibrated for gain, adjusted for offset, then the orientation must be defined.

The gain for each channel is set by the laboratory towing tank calibrations, using the same sensor, cabling, and amplifier channels as used in the field.

The offset applied to each channel in order to reference the signal to zero flow conditions was determined from the recorded signal from each of the current meters when PVC caps were placed over each sensor, as previously described in Section 4.2. This determination

was necessary due to the lack of experience with the system; not knowing the effects of ground loops given the actual physical layout of the sensors, the influence of environmental electrical noise, and a desire to measure changing offset, or "drift" in the sensors.

The zero flow offsets were measured at the beginning of the experiment, then again at the end. The results of these measurements are presented in Table 4.2.

The data in Table 4.2 show an average drift of 0.9 cm/sec, with the maximum observed drift being 1.9 cm/sec. The actual source of this drift is unknown, but may be due to a breakdown in sensor insulation material, or due to the tide acting on the wave gauges, which, when located very close to the current meters, do exhibit a slight influence on the current meter offsets (1 - 2 cm/sec observed in the lab tow tank when separated by about 10 cm). Also, after the three hours of the experiment, the change in battery level may have a contributing influence. Since the combined electronic and hydrodynamic accuracy is approximately 1.0 cm/sec, the drifts observed are considered to be within this uncertainty range, and therefore acceptable for this experiment. However, more work should be done to determine the magnitude and sources of the offset changes. The offsets determined at the beginning of the experiment were used to set the zero points of the current meter data. A computer plot of 4.26 minutes of data for all 11 channels after calibration is shown in Figure 4.9.

Sensor	Channel	Beginning Offset		Ending Offset		Drift cm/sec
		mv	cm/sec	mv	cm/sec	
Red	A	1056.0	52.8	1039.4	52.0	- 0.8
	B	92.9	4.6	54.4	2.7	- 1.9
Green	A	56.4	2.8	84.2	4.2	+ 1.4
	B	12.2	0.6	30.5	1.5	+ 0.9
Orange	A	-429.4	- 21.5	-439.2	- 21.9	- 0.4
	B	534.4	26.7	551.4	27.6	+ 0.9
Yellow	A	- 0.4	0.0	14.6	0.7	+ 0.8
	B	7.4	0.4	- 0.4	0.0	- 0.4

TABLE 4.2

Summary of Current Meter Offsets

HEADER 6

CLOCK 16262

DISC SECTOR 128

FIGURE 4.9: 4.26 Minute Time Series Plot of Calibrated Data

4.3.4 Alignment of Current Meter Axes

In addition to setting the gains and the offsets, the orientation of each current meter must be defined, and for ease in analysis, the current meter data can be rotated in space to bring all the current meter axes into similar alignments.

At the beginning of the experiment, the current meters were aligned, with the aid of a transit, to have one channel aligned parallel with the upper baseline (63° east of north). These alignments are shown in Figure 4.10, where flow in the direction of the arrow gives a positive value of current flow. After analyzing the beach profile data (see Figure 4.3), the actual beach contours were found to have an orientation of 67° east of north. To account for this, the reference directions for the four current meters were rotated 4° clockwise, so as to keep the axes aligned with the local bottom contours.

During the course of the experiment, surprisingly large waves (≈ 1.5 meter) exerted large moment forces on the current meters and wave gauges which were mounted on the guyed pole stations as shown in Figure 4.4. Although these mounting structures had proven durable and stable in smaller wave conditions, they were not able to withstand this extreme forcing, and as a result, the sensors rotated from their original alignments. The measured apparent change in orientation of the four current meters from that measured at the beginning to that measured at the end was:

STATION 4 - RED SENSOR

STATION 3 - GREEN SENSOR

STATION 2 - ORANGE SENSOR

STATION 1 - YELLOW SENSOR

FIGURE 4.10: Current Meter Alignments at the Beginning of the Experiment

Station 4	62° counter-clockwise
Station 3	88° counter-clockwise
Station 2	7° clockwise
Station 1	6° clockwise

Unfortunately, from a visual inspection of the time series, it is not possible to quantitatively determine when and how much each sensor moved during the course of the experiment. Thus, a more elaborate scheme had to be devised in order to resolve the change in orientation of the sensors.

Current Meter Variance Ratio vs. Time

In order to assess the actual orientation of the sensors during the experiment, the data were analyzed statistically to determine the relative alignment of each axis to the incident waves and longshore current. More specifically, the variance of the axis believed to be more closely aligned with the longshore current was computed for a two-minute time series. Then, the variance of the other axis, under more influence from the waves, was computed for the same time series. The ratio between these two:

$$\text{Ratio} = \frac{\sigma_v^2}{\sigma_u^2} = \frac{\frac{1}{N} \sum_{i=1}^N (v - \bar{v})^2}{\frac{1}{N} \sum_{i=1}^N (u - \bar{u})^2} \quad (4.3)$$

(where v is the alongshore velocity, u is the on/offshore velocity, " $\bar{}$ " denotes the average velocity, and σ^2 is the variance)

is a good measure of the relative alignment of the sensor to the waves. For ratios less than one, the sensor alignment is correctly assumed, while for ratios greater than one, the sensor channels have been assumed incorrectly, as the longshore current channel (numerator) is being influenced more by the waves than the on/offshore channel (denominator). More importantly, the stability of this ratio during the course of the experiment is a measure of the changing orientation of the sensor. Since the wave direction varied little over the duration of the experiment, abrupt changes in the variance ratio suggest a change in sensor alignment, while a constant ratio suggests a stable alignment. The results of this analysis for the four stations are presented in Figure 4.11.

From the plot of Figure 4.11, it can be seen that for Stations 1 and 2, there is no significant change in the variance ratio. And, since the alignment difference between the before and after measurements are of the order of the estimated measurement error, and would correspond to a rotation into the waves, it appears that these stations did not move. The plots for Stations 3 and 4 show a significant shift in the variance ratio in the region of Sector 66 to 74, then a slight shift near Sector 120. Most importantly, the stability in the variance ratio following Sector 124 suggests that the sensors did not move during this time.

It should be noted that the measurements of orientation were made much earlier and later than the time shown on the plots, since it was only possible to measure orientation at low tide. This means that,

FIGURE 4.11: Variance Ratio vs. Time

although the sensor may appear to remain stable during a significant amount of the data record, the absolute orientation is still unknown, since the current meters may have moved either prior to or after the plot record.

Current Meter Variance Ratio vs. Angle

Since the current meter provides vector information about the horizontal water velocity, it is possible to steer the current meter, much as one would steer an acoustic array, to look at processes from any angle. So, by steering the current meter data through angles from +90 to -90 degrees, while computing the previously mentioned variance ratio, the relative alignment of the current meter to the incident waves can be determined. The algorithm used to rotate the data and compute the variance ratio is outlined below:

(1) The vector angle (θ) for each measurement is computed based on the coordinate system in Figure 4.12, using the relationship:

$$\theta = \tan^{-1}\left(\frac{v}{u}\right) \quad (4.4)$$

(where u and v are the on/offshore and alongshore velocities respectively, before rotation)

(2) The coordinate system is shifted by ϕ degrees (positive clockwise), as shown in Figure 4.13. The new vector angle θ' is then given by:

$$\theta' = \theta - \phi \quad (4.5)$$

FIGURE 4.12: Coordinate System Before Rotation

FIGURE 4.13: Coordinate System After Rotation

(3) The two orthogonal vector components are recomputed in the new coordinate system.

(4) The variance ratio is computed for the rotated data.

(5) This process is repeated until all desired angles have been swept.

An example of this process of steering the current meter data through angles of -90 to $+90$ is presented for Station 4, using the data corresponding to the plot of Figure 4.9 in Figure 4.14. Note that the positive correlations between the velocity data on channels 10 and 11 (Station 4) indicate that waves are originating in the first quadrant. This agrees with the results of Figure 4.14, which shows an angle of incidence of $+34$. (See Note.)

The results of this computation for Stations 2 and 1 show peak variance ratios of 12° and 10° , respectively. Since this corresponds well to observed conditions when taking into account the error in transect alignment, and considering the results of the variance ratio through time analysis, the original alignment measurements for these two stations are considered more reliable than those taken after the experiment.

As expected, however, the angles corresponding to the maximum on/

Note: The peak variance ratio angle represents an approximation to the direction of the lumped wave radiation stress, or, in other words the angle found by this technique conserves radiation stress. A discussion of this in terms of the variance from a given number of wave components is presented in Appendix B.

512 SECOND AVERAGE -STARTING AT SECTOR 128
MINIMUM AT - 56 MAXIMUM AT 34

STATION 4

FIGURE 4.14: Station 4 Variance Ratio vs. Angle Plot

offshore vs. alongshore variance for Stations 3 and 4 do not correspond well to the observed wave conditions, even when taking into account the effect of the 4° correction in the transect alignment. From the discussion of the variance ratio for Stations 3 and 4, it appears that the sensors at both these stations rotated under the influence of the waves sometime after the plots of Figure 4.11, since the observed wave angles do not correspond to the alignments before or after the experiment. Since it is necessary to estimate the longshore currents and momentum flux, the data for Stations 3 and 4 have to be rotated. The information available is not sufficient to determine the exact angle of rotation during the experiment, so it can only be estimated on the basis of observed conditions, and the information from Stations 1 and 2. For the estimation of longshore currents, the angle of rotation is not so critical, as the error factor is $(\cos \theta_{\text{error}})$. However, as will be discussed, the momentum flux is more sensitive, and an error of even 5° may significantly alter the subsequent friction factor estimates.

The rotation estimates for Stations 4 and 3 were determined by refracting the waves observed at both Stations 3 and 4. Using shallow water wave theory, the average of the refracted angle of incidence from both Stations 1 and 2 were calculated first for Station 3, then for Station 4. For a straight beach with parallel contours, Snell's Law holds:

$$\frac{\sin \theta_a}{c_a} = \frac{\sin \theta_b}{c_b} \quad (4.6)$$

where the subscripts a and b refer to the appropriate stations.

Using the expression for the wave phase speed:

$$c^2 = \frac{g}{k} \tanh kh \quad (4.7)$$

and taking advantage of the shallow water relationship:

$$\tanh kh \rightarrow kh \quad (4.8)$$

Snell's Law may be rewritten as:

$$\frac{\sin \theta_a}{\sqrt{h_a}} = \frac{\sin \theta_b}{\sqrt{h_b}} \quad (4.9)$$

or:

$$\theta_b = \sin^{-1} \left(\sin \theta_a \frac{\sqrt{h_b}}{\sqrt{h_a}} \right) \quad (4.10)$$

where h_a and h_b are the corresponding mean water depths.

After the data for Stations 1 and 2 were rotated $+4^\circ$ to account for the transect alignment, this equation was used to obtain the following estimates of the rotation angle to apply at Stations 3 and 4:

TABLE 4.3

<u>Station</u>	<u>Expected Angle Based on Station 1</u>	<u>Expected Angle Based on Station 2</u>	<u>Average</u>	<u>Rotation Angle</u>
3	7.8	8.8	8.3	-20.3
4	9.5	10.8	10.1	+23.9

A summary of the angles of maximum variance ratio before and after the rotation procedure is presented in Table 4.4, and for comparison with Figure 4.9, the 12 channel plot of data following the rotations is presented in Figure 4.15.

4.4 DATA ANALYSIS

Following the preprocessing described in Section 4.3, the data from the Maine field experiment were analyzed to determine the wave environment, longshore and net on/offshore currents, momentum fluxes, and bottom friction. This section outlines the computational procedures and the results of these different analyses.

4.4.1 Wave Environment

The wave environment was analyzed in terms of the wave height, frequency, and directional distribution, both in space and in time.

Height Distribution

The wave height distribution was determined by computing the wave height histogram for 1024 second blocks of the surface elevation time series at each station. Individual waves were located by successive zero upcrossings from a 64 second sliding mean average of the surface elevation (a sliding average was used instead of a block average in order to eliminate the influence of set-up and set-down as well as that of the changing tide). After locating each wave, the wave height was then found from the difference between the maximum and minimum. As a check, the maximum was compared with the maximum possible surface elevation for that station, and if these were found to be equal, that

	ANGLE Before Rotation	AXIS Rotation Angle	ANGLE After Rotation	Estimated Error
STATION 4	+34	+23.9	+10.1	8°
* STATION 3	-12	-20.3	+ 8.3	8°
** STATION 2	+12	+ 4.0°	+ 8.5	5°
STATION 1	+10	+4.0°	+ 6.0	5°

* The assumed axis orientation for convenience is:

since, from the plot of Figure 4 it can be seen that the sensor has shifted close to 90° prior to Sector 128.

** The data for Channel A has been multiplied by -1 to give the axis orientation:

TABLE 4.4

Variance Ratio vs. Angle Data - Before and After Rotation

FIGURE 4.15: 4.26 Minute Time Series Plot of
 Rotated and Calibrated Data

wave was considered to have overtopped the wave gauge. The wave heights were then sorted into height bins, normalized, and plotted. An example of this histogram plot is shown in Figure 4.16.

From the histograms of the analysis period from 1:15 p.m. to 2:25 p.m. the significant wave heights at Stations 3 and 2 were approximately 70 cm and 100 cm, respectively. This shoreward increase in wave height was due to the dramatic shoaling of the waves just prior to breaking, which was observed to be between the two stations during this portion of the experiment. This shoaling of the waves is also evident in the shape of the histogram plots shown in Figures 4.17 and 4.18. In contrast, during the second analysis period, from 3:00 p.m. to 3:35 p.m., when the breaking point was between Stations 4 and 3 due to the lower tide, the waves were decaying in height between Stations 3 and 2 (the significant wave height at Station 3 was 120 cm, while the significant wave height at Station 2 was only 90 cm). The histograms for Station 4 show numerous overtoppings which contaminate the shape of the histogram since the large overtopping waves are misinterpreted as smaller waves. These overtoppings are present during much of the experiment and, as a result, the wave height information from Station 4 is of limited value.

Frequency Distribution

The frequency distribution of the waves was determined by the computation of the power spectrum for the surface elevation time series. More specifically, the Fourier transform of 4096 data points

STATION 4

1024 SECOND RECORD

STARTING SECTOR : 128

WAVES IN RECORD : 121

NUMBER OF OVERTOPPINGS : 19

SIGNIFICANT WAVE HEIGHT : 75.0 CM

WAVE HEIGHT HISTOGRAM

FIGURE 4.16: Station 4 Wave Height Histogram

STATION 3

1024 SECOND RECORD

STARTING SECTOR : 128

WAVES IN RECORD : 94

NUMBER OF OVERTOPPINGS : 0

SIGNIFICANT WAVE HEIGHT : 70.0 CM

WAVE HEIGHT HISTOGRAM

FIGURE 4.17: Station 3 Wave Height Histogram

STATION 2

1024 SECOND RECORD

STARTING SECTOR : 128

WAVES IN RECORD : 113

NUMBER OF OVERTOPPINGS : 0

SIGNIFICANT WAVE HEIGHT : 107.0 CM

WAVE HEIGHT HISTOGRAM

FIGURE 4.18: Station 2 Wave Height Histogram

was taken, then the conjugate of the transform was multiplied by itself to obtain the auto power spectral density function, $G_s(f)$.

The accuracy of this unaveraged spectral density function is related to the statistics of the Fourier transform estimates. In taking the Fourier transform, each frequency value is a complex Gaussian estimate, whose real and imaginary parts

$$X(f_i, T) = X_r(f_i, T) + j X_i(f_i, T) \quad (4.11)$$

are random and uncorrelated. When the complex conjugate of this transform is multiplied by itself, the resultant

$$|X(f_i, T)|^2 = X_r^2(f_i, T) + X_i^2(f_i, T) \quad (4.12)$$

is a chi-squared distributed variable, with $n = 2$ degrees of freedom (DOF). The random error for each of these estimates is substantial, as the normalized standard error is,

$$\epsilon = \frac{\sigma[G_x(f)]}{G_x(f)} = \frac{\sqrt{2n}}{n} \quad (4.13)$$

for a chi-squared variable with mean n and variance $2n$ (Bendat and Piersol, 1971). Since $n = 2$ for a 2 DOF variable, the standard deviation is as large as the quantity being measured. Consequently, the random error of the spectral density function has to be reduced by smoothing the estimate to increase the degrees of freedom. In this analysis, the smoothing is accomplished by averaging over frequency,

which leads to a distribution having approximately

$$\text{DOF} = \frac{2N}{m} \quad (4.14)$$

degrees of freedom (N is the number of frequency bands, and m is the number of smoothed bands or lags). It is important to note that the unaveraged estimates are independent of record length, so that longer time series do not change the standard deviation of each estimate. But, when averaging over a given number of estimates, a longer time series helps to maintain resolution, since there are more estimates in a given frequency band.

In analyzing the wave records, a time series of 4096 points was used, and the spectral density function was averaged in order to end up with 60 degrees of freedom. In doing this, the reliability of the estimates increases, but at the expense of a loss in frequency resolution corresponding to the 30 millihertz averaging window. A plot of the averaged power spectrum for Station 3, along with the 90% confidence interval and the 30 millihertz averaging window corresponding to 60 DOF is shown in Figure 4.19.

Figure 4.19, which is a representative spectrum for all three stations in terms of frequency distribution, shows several important characteristics of the waves. First, the large peak indicates that the wave climate is rather narrow band, and has its main component at about 0.085 hertz, which corresponds to a 12 second wave. The secondary peak at 0.168 hertz is the second harmonic of the 0.085 hertz peak, and is due to the pronounced nonlinearity of the near breaking waves.

STATION 3 WAVE SPECTRUM

FIGURE 4.19: Station 3 Wave Spectrum -
2048 Points, 60 DOF

Also, the spectrum shows very little energy above 500 millihertz, which is somewhat surprising, but is a good indication that there is no aliasing present.

Directional Distribution

The directional properties of the incident waves were analyzed using the variance ratio technique described in Section 4.3.4 and Appendix B. This technique uses the vector information from two orthogonal current meter channels to determine the direction of maximum variance. For a single wave train, this leads to the actual angle of incidence relative to the current meter, while for multiple wave trains with small angles of incidence, it conserves radiation stress, leading to an angle corresponding to that of an equivalent single wave, having the same average energy and radiation stress.

This technique was used to align the current meter data of Stations 3 and 4, due to the unknown orientations of these stations during the experiment. A summary of this aligning procedure was presented in Section 4.3.4 and the resulting angles of maximum variance ratio were presented in Table 4.4.

To better interpret the angles in Table 4.4, the spectra for the current meter channels were analyzed to obtain an estimate of the number of sources, and thus determine the reliability of these angles in terms of their conserving the actual radiation stress. From Figures 4.20 and 4.21, which are typical on/offshore and longshore power spectra, it can be seen that the on/offshore velocities represent a narrow band process, correlated with the surface elevation, while the

STATION 3 ON/OFFSHORE

FIGURE 4.20: Station 3 On/Offshore Velocity Spectrum -
2048 Points, 60 DOF

STATION 3 LONGSHORE

FIGURE 4.21: Station 3 Longshore Velocity Spectrum -
2048 Points, 60 DOF

longshore velocities are much wider band, with less energy. This implies that there is only one major wave component and, consequently, the variance ratio analysis yields a reliable direction for the radiation stress, and it can also be loosely interpreted as the actual breaker angle.

It is also noted that the spectral peaks of the velocity spectra coincide with the peaks of the spectrum of surface elevation presented in Figure 4.19.

4.4.2 Longshore and On/Offshore Currents

To estimate the net longshore and on/offshore currents, the current meter records were averaged with sliding windows sufficiently wide to eliminate the variability associated with each individual wave. Since the main wave component had a period of about 12 seconds, a 512 second window was used in order to have a sufficient number of waves to average over, yet retain the variability associated with wave sets, set-up, and set-down. Plots of the 512 second averages for all 8 channels of current meter data are presented in Figures 4.22 and 4.23.

Longshore Currents

The data for all four longshore current meter channels show an average net flow to the north, which is the expected direction due to wave forcing. Also, as can be seen from the plots of Figures 4.22 and 4.23, the variability in longshore current over about five minutes increases in the shoreward direction, and is of the same order magnitude as the net longshore current.

FIGURE 4.22: Average Longshore and On/Offshore Velocities - Plot A

FIGURE 4.23: Average Longshore and On/Offshore Velocities - Plot B

To reduce the variability in the average longshore current, and to get an idea of the profile of longshore current across the surf zone, longer block averages of 8.5 minutes were computed (see Table 4.5). The results of these longer averages are plotted in the lower portions of Figures 4.28 and 4.29, and not surprisingly, they show a non-uniform distribution, with a maximum just shoreward of the breaker line. What is surprising though, is the steady current at Station 4, which was well outside the breaker zone.

Based on several observations, this current at Station 4 appears to be a tidal current rather than a wave-induced longshore current. First, according to the local tide charts a north-flowing tidal current was present offshore during the early afternoon. Secondly, the plots of longshore current for Station 4 show a very strong current during the early afternoon, yet at the end of the experiment, when there are still strong longshore currents evident at Stations 3, 2, and 1, the current at Station 4 is noticeably less, implying that there is little coupling between the wave-induced current within the surf zone and the observed current at Station 4. Finally, if the current at Station 4 was a result of wave forcing from inside the surf zone, one would expect that the observed longshore current outside the surf zone would be somewhat less in magnitude than that observed inside, yet would show a variability similar to that found inside the surf zone. The fact that it appears much more steady, and larger than the currents observed at the inner stations indicates that the driving mechanisms are different.

TABLE 4.5

512 Second Longshore Current Averages

Time	Station 1	Station 2	Station 3	Station 4
1:20	-12.	-13.	- 4.8	-12.
1:29	- 5.2	-17.	- 4.8	-12.
1:37	-15.	-18.	- 5.1	-12.
1:46	-14.	-20.	-12.	-11.
1:54	3.4	- 7.2	- 6.1	-13.
2:03	- 9.8	-14.	- 6.2	-12.
2:11	1.9	- 9.1	- 3.8	-11.
2:20	.2	-13.	- 9.5	-16.
3:06	-15.	-24.	- 4.6	- 4.5
3:14	-12.	-31.	- 9.7	- 6.5
3:23	4.8	-13.	10.7	- 9.6
3:31	- .0	-20.	5.9	- 7.1

Note: Values are in cm/sec.

On/Offshore Currents

The plots of net on/offshore currents in Figures 4.22 and 4.23 show a significant net offshore flow, which is rather surprising at first, since a simple consideration of conservation of mass would suggest that there could be no net onshore or offshore mass flow. There are several mechanisms which could account for this observed net offshore flow, one being a return current caused by the onshore mass transport associated with the waves, and another due to a non-uniform vertical velocity distribution.

First order linear wave theory does not predict a mass flow in shallow water, but if second order terms are considered, a simple relationship for shallow water can be found.

Starting with the mass flux across a plane normal to the direction of wave propagation,

$$\langle Q \rangle = \frac{1}{T} \int_0^T dt \int_{-h}^{\eta} \phi_x dz \quad (4.15)$$

where ϕ_x is the velocity potential describing the wave motion. Including second order terms, this becomes

$$\langle Q \rangle = \frac{1}{T} \int_0^T dt \int_{-h}^{\eta} \phi_x^{(1)} dz + \frac{1}{T} \int_0^T dt \int_{-h}^{\eta} \phi_x^{(2)} dz \quad (4.16)$$

where

$$\phi_x^{(1)} = -A_1 \cosh k(h+z) \sin kx \quad (4.17)$$

$$\phi_x^{(2)} = -A_2 \cosh 2k(h+z) \sin 2kx \quad (4.18)$$

Each of these terms can be expanded into two components, one being an integral from $-h$ to 0 , and the other from 0 to η . Keeping only the second order terms, the mass flux becomes

$$\langle Q \rangle = \frac{1}{T} \int_0^T dt \left[\int_{-h}^0 \phi_x^{(1)} dz + \int_0^\eta \phi_x^{(1)} dz \right] + \frac{1}{T} \int_0^T dt \int_{-h}^0 \phi_x^{(2)} dz \quad (4.19)$$

Integrating the last term, and recalling that

$$\langle Q_x^{(1)} \rangle = 0 \quad (4.20)$$

then

$$\langle Q \rangle = \frac{1}{T} \int_0^T dt \int_0^\eta \phi_x^{(1)} dz + k_1 h \quad (4.21)$$

where k_1 represents a steady current that balances this mass flux shoreward associated with conditions near the surface only. Since only second order terms are retained, this simplifies to

$$\langle Q \rangle = \frac{1}{T} \int_0^T dt [\eta^{(1)} \phi_x^{(1)}]_{z=0} + k_1 h \quad (4.22)$$

Substituting the shallow water approximations

$$\eta^{(1)} = a \sin \omega t \quad (4.23)$$

$$\phi_x^{(1)} = a \left(\frac{g}{h} \right)^{1/2} \sin \omega t \quad (4.24)$$

then

$$\langle Q \rangle = \frac{1}{T} \int_0^T [a^2 \left(\frac{g}{h} \right)^{1/2} \sin^2(\omega t)] dt + k_1 h = \frac{a^2}{2} g^{1/2} h^{-1/2} + k_1 h \quad (4.25)$$

Since conservation of mass requires that

$$\langle Q \rangle \equiv 0 \quad (4.26)$$

then

$$k_1 = \frac{a^2}{2} g^{1/2} h^{-3/2} \quad (4.27)$$

which shows that near the bottom, there is a steady offshore flow to balance the shoreward mass flux near the surface.

Not surprisingly, this relationship shows that this velocity is a function of the ratio of wave height to water depth, and for a given wave height, as the water depth decreases, the return flow increases exponentially until the wave breaks at a wave height to water depth ratio of about 0.78. Using the observed wave conditions at the different stations to predict the return flow, it appears that although the flows are of similar magnitude, the mass flow consideration does not adequately account for all the net offshore flow.

As mentioned before, another way to account for this observed net offshore flow is through the effect of a non-uniform vertical velocity profile, where the offshore flow is concentrated in the bottom region where the current meters were located. Inside the surf zone, this seems very plausible since, during the experiment, it was observed that translating bores appeared to move on top of an underlying sluggishly responsive lower layer. Figure 4.24 which shows the Station 2 surface elevation and on/offshore record, shows several striking examples of this. The first two waves, identified as A and B, are large breaking waves, which, as they translate shoreward, exhibit

FIGURE 4.24: Station 2 Surface Elevation and Bottom On/Offshore Velocity

a significant lag (≈ 2 sec) between the passing of the crest of the wave and the corresponding peak in the near-bottom current meter record. This lag, corresponding to a phase difference of between 30° and 60° , is similar to that observed by Thornton (1976).

The third wave, identified in the time series as C, is also rather large, but the current meter registers only a very small near-bottom onshore velocity, which is quickly swamped by an offshore surge of current. This suggests that, even though the wave was translating shoreward on the surface, there was a very large return flow near the bottom. Both of these wave signatures point toward a multi-layer system similar to that discussed by Huntley (1976), having a non-uniform vertical velocity profile that could easily account for an observed near bottom net offshore flow.

Thus, it appears that a combination of a mass flow return current, along with a non-uniform vertical velocity distribution caused by a multi-layer system can adequately account for the measured net offshore currents in the surf zone, i.e., at stations 1 to 3. The large offshore current observed at station 4 outside the surf zone, does not, however, appear to be adequately explained by the above mechanisms.

4.4.3 Momentum Flux and Bottom Friction

Using the surface elevation and horizontal velocity information from the individual stations, momentum fluxes and bottom friction coefficients were computed.

Recalling from Section 2, the principal driving force for the longshore current within the surf zone is considered to be the shoreward gradient in momentum flux. Considering a simple control volume analysis (see Figure 2.1), the shoreward loss in momentum flux drives a longshore current, which in turn is balanced by bottom friction:

$$\frac{\partial M_{xy}}{\partial x} + F_B = 0 \quad (4.28)$$

where the momentum flux (M_{xy}) is given by:

$$-\rho < \int_{-h}^{\eta} (uv) dz > \quad (4.29)$$

and the bottom friction is interpreted in terms of the y-component of the bottom shear stress:

$$F_B = -\frac{1}{2} C_f \rho < (u^2 + v^2)^{1/2} v > \quad (4.30)$$

where C_f is the friction coefficient and the time averaged quantity is the average quadratic velocity in the longshore direction.

Momentum Flux

The general behavior and magnitude of the momentum flux can be seen from a simple decomposition based on a single wave train and a uniform vertical velocity profile. First, considering each of the components as having a mean denoted by an overbar and a wave component denoted by the subscript:

$$u(t) = \bar{u} + u_w \cos\theta \cos\omega t \quad (4.31)$$

$$v(t) = \bar{v} + v_w \sin\theta \cos\omega t \quad (4.32)$$

$$\eta(t) = \bar{h} + a_w \cos\omega t \quad (4.33)$$

where the wave has a frequency ω , and the angle of incidence θ .

Then, substituting,

$$M_{xy} = -\rho \langle (\bar{u} + u_w \cos\theta \cos\omega t) (\bar{v} + v_w \sin\theta \cos\omega t) (\bar{h} + a_w \cos\omega t) \rangle \quad (4.34)$$

After expanding and dropping terms that time average to zero, the momentum flux simplifies to four terms:

		Relative Magnitude
$-\frac{M_{xy}}{\rho} = \left\{ \frac{1}{2} u_w^2 \bar{h} \cos\theta \sin\theta \right.$	(1)	75% (4.35)
$+ \frac{1}{2} a_w \bar{v} u_w \cos\theta$	(2)	12%
$+ \frac{1}{2} a_w \bar{u} u_w \sin\theta$	(3)	1%
$+ \bar{u} \bar{v} \bar{h} \}$	(4)	12%

Using the observed estimates of the waves and currents during the field experiment at Station 3:

$$a_w = 25 \text{ cm}$$

$$\bar{h} = 150 \text{ cm}$$

$$u_w = 100 \text{ cm/sec}$$

$$\bar{u} = 10 \text{ cm/sec}$$

$$\bar{v} = 15 \text{ cm/sec}$$

$$\theta = 10^\circ$$

then the total momentum flux has an estimated value of -122,000 dynes/cm, with the relative contributions from each of the components listed above.

Clearly, the first term is the main contributor to the total momentum flux, while the second, representing the influence of the longshore current, is next, since the last term is a positive quantity. In fact, in view of the previous discussion of the net offshore flow, the third and fourth terms are most likely always small, since the observed offshore flow is probably confined to the bottom layer, and the actual depth-averaged mean on/offshore flow is much smaller.

Since the momentum flux analysis presented assumes that the velocities are uniform with depth, the observed average offshore flow was removed prior to computing the momentum flux.

In computing the momentum flux, the same time averaging window used to average the longshore and on/offshore currents was applied to the data. This 160 second sliding average was intended to preserve as much resolution as possible in terms of the wave sets and set-up and set-down, yet eliminate the variability due to individual waves. Figures 4.25 and 4.26 show the results of these computations for Stations 4 and 3, while Figures 4.27 and 4.28 show the same information for Station 2, along with the longshore current block averages mentioned in Section 4.4.2.

From the plots of these four figures, it can be seen that, as expected, there is a shoreward loss in the total momentum flux. In addition, however, there is significant variability in the momentum

FIGURE 4.25: Momentum Flux at Stations 4 and 3 - Plot A

FIGURE 4.26: Momentum Flux at Stations 4 and 3 - Plot B

FIGURE 4.27: 8.5 Minute Average Longshore Currents and Momentum Flux at Station 2 - Plot A

FIGURE 4.28: 8.5 Minute Average Longshore Currents and Momentum Flux at Station 2 - Plot B

flux at each station (up to 50% of the mean), and there does not appear to be any clear correlation at Stations 4 or 3 between the observed changes in the longshore current and changes in momentum flux, wave conditions, or mean water depth.

The plots of the momentum flux at Station 2 are interesting in that they show several periods of positive momentum flux (see Figure 4.27). The presence of this positive momentum flux is rather surprising, since the theory presented in Section 2 cannot explain the reversal of this force (the momentum flux is negative at Stations 4 and 3). A possible explanation for this positive quantity could be the influence of an error in the assumed alignment of the current meter at Station 2. However, since the longshore current at Station 2 appears to respond to this change by reversing direction (which is reasonable, if not explainable) this does not appear to be the case.

Bottom Friction

Since there is a general trend in the loss of momentum flux in the shoreward direction, and the longshore current is reasonably stable during much of the experiment, it does seem reasonable to compute the bottom friction and its corresponding friction coefficient in order to further investigate the validity of this momentum flux model.

Recalling the expression for the bottom friction in terms of the near-bottom flow conditions,

$$F_B = - \frac{1}{2} \rho C_f \langle (u^2 + v^2)^{1/2} v \rangle \quad (4.36)$$

then, by substituting into the force balance equation and solving for the friction coefficient:

$$C_f = \frac{\partial M_{xy}}{\partial x} / \frac{\rho}{2} (u^2 + v^2)^{1/2} v \quad (4.37)$$

In terms of the measurements inside the surf zone at Stations 3 and 2, this becomes:

$$C_f = \frac{(M_{xy})_3 - (M_{xy})_2}{x_3 - x_2} / \frac{\rho}{4} \{ \langle (u^2 + v^2)^{1/2} v \rangle_3 + \langle (u^2 + v^2)^{1/2} v \rangle_2 \} \quad (4.38)$$

where the velocity component is taken as the average between Stations 3 and 2, and the distance between the two stations is $x_3 - x_2$.

On the basis of the wave and current estimates used to evaluate the momentum flux in the vicinity of Station 3, the average friction velocity is approximately $800 \text{ cm}^2/\text{sec}^2$. By estimating the difference in momentum flux between Stations 3 and 2 from the plots of Figures 4.25 and 4.27, the friction coefficient can be roughly estimated by:

$$C_f = \frac{|-50,000 + 25,000|}{1090} / \frac{1.025}{4} (800) = 0.10 \quad (4.39)$$

where the separation between Stations 3 and 2 is 1090 cm, and the density of water is 1.025 gm-cm^3 .

The actual results of the computer calculations for the momentum flux, friction velocity, and resulting friction coefficient are presented in Table 4.6, and plotted in Figure 4.29.

From the previous rough estimate of the friction factor, and the

TABLE 4.6

8.5 Minute Momentum Flux, Friction Velocity,
and Friction Coefficient Averages

Time	STATION 3		STATION 2		Friction Coefficient
	M _{xy}	FVel	M _{xy}	FVel	
1:18	-44.25	-280.74	-41.44	-712.42	.0101
1:22	-59.46	-382.84	-32.87	-622.12	.0947
1:26	-62.77	-285.19	-23.82	-756.76	.1339
1:31	-49.58	-126.14	-15.67	-715.62	.1442
1:35	-49.47	-293.12	- 2.36	-855.15	.1469
1:39	-54.79	-274.25	- 3.88	-867.45	.1596
1:44	-39.95	-383.95	- 7.77	-960.23	.0857
1:48	-55.25	-592.02	- 3.30	-775.20	.1360
1:52	-65.67	-516.05	5.49	-147.31	.3840
1:56	-65.89	-317.33	6.47	-185.27	.5154
2:01	-53.27	-297.49	- 1.56	-493.61	.2340
2:05	-56.06	-244.94	8.96	-517.46	.3053
2:09	-79.74	-159.60	16.51	-317.74	.7219
2:13	-63.12	-374.47	14.13	-368.48	.3722
2:18	-67.81	-542.68	- 1.34	-560.72	.2157
2:22	-81.11	-482.23	- 7.55	-564.73	.2516
3:04	-89.00	-286.65	- 2.88	-1121.22	.2190
3:08	-81.54	-339.34	.78	-1496.12	.1606
3:12	-65.03	-555.16	3.07	-1560.45	.1152
3:16	-42.27	-115.36	- .49	-1041.56	.1293
3:21	-37.79	539.67	2.66	-536.62	47.4772
3:25	-44.07	516.62	10.40	-408.74	1.8075
3:29	-55.62	281.40	5.18	-809.97	.4118
3:33	-44.55	346.49	1.14	-837.66	.3330
3:38	-30.61	112.20	2.74	-761.59	.1839
3:42	-44.07	-760.23	- 3.08	-1684.84	.0600

Note: Momentum flux values are in thousands of dynes/cm.
Friction velocity values are in cm²/sec².

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FIGURE 4.29: Bottom Friction Coefficient

results of the actual computer analysis, it is clear that the friction coefficient is rather unstable and surprisingly large compared with those observed and estimated from other laboratory and field measurements (Huntley, 1976). Since these measurements represent one of the most complete sets of momentum flux and longshore current measurements to date, it is possible that these large friction coefficients are "correct", but more likely the lack of stable longshore current conditions accounts for much of the variability, while the questionable accuracy of the assumed orientation at Station 3 may account for the large magnitude.

In terms of the influence of longshore current variability on the friction coefficient, the model presented here does not include any consideration of the forces caused by the accelerating or decelerating fluid. For example, during an accelerating flow, there is an added resistive force that would supply much of the force previously accounted for by bottom friction, thus the calculated friction coefficient in the absence of unsteady effects is too large for accelerating flow. Similarly, in a decelerating flow, the friction coefficient would be too small. Thus, in light of the model being investigated here, only periods of relatively stable longshore currents should be used to get a clear picture of the magnitude and behavior of the friction coefficient. From the plot of Figure 4.27, it is seen that the first four 8.5-minute periods are relatively stable, while the last four are rather unstable. As expected, the friction coefficient is lower and more stable during this first period, averaging between 0.10 and 0.15.

Looking at the second analysis period of Figure 4.28, once again only the first half is relatively stable in terms of longshore currents, and encouragingly the C_f is relatively stable and averages between 0.10 and 0.15 again.

As discussed in Section 4.3.3, the absolute orientation of Station 3 is not well defined. Since the amount of rotation of the current meter during the experiment could not be precisely determined, it had to be estimated from the relative alignment of the current meter to the measured waves. As a result, the accuracy of alignment was estimated to be $+5^\circ$. Since the main component of momentum flux from the preceding discussion is of the form

$$\frac{1}{2} u_w^2 \bar{h} \cos\theta \sin\theta \quad (4.40)$$

and the angle θ is about 8° , it can be seen that this level of accuracy is very significant, as the absolute momentum flux could be overestimated by a factor of two. Coupled with the fact that the gradient in momentum flux is a small difference between two relatively large quantities, this accuracy renders the friction coefficient values very suspect. Fortunately, the general indication from the data (no negative values of C_f , the shoreward loss in M_{xy} , etc.) is that the momentum flux measurements are not completely unrealistic, so the friction coefficients are probably relatively reliable.

In summary, the force balance based on the momentum flux gradient seems physically plausible during periods of relatively stable conditions, but quantitative evaluation in terms of the relationship between

significant changes in the observed longshore current and momentum flux shows only moderately supportive evidence. In addition, the lack of confidence in the absolute orientation of the Station 3 current meter renders the friction coefficient values somewhat suspect. Taking this into account, along with a consideration of the influence of unstable longshore currents, the most reliable estimate of the friction coefficient is between 0.10 and 0.15.

5. SUMMARY AND CONCLUSIONS

5.1 INSTRUMENTATION

The development of the field instrumentation system, including the electromagnetic current meter and the digital wave gauge as described in Section 3, provided the basis for making successful field measurements of waves and currents in the surf zone.

The electromagnetic current meter proved to be well suited for making surf zone measurements in terms of response characteristics, as well as durability and reliability. The final sensor design, pictured in Figure 3.5, was well matched to the flow characteristics of the surf zone, as it took advantage of the generally horizontal flow field in order to optimize the linearity and horizontal cosine response at the expense of a somewhat compromising vertical cosine response. The sensor's frequency response, which is really limited by the finite size of the sensing volume rather than the electronic design, proved more than adequate in resolving the vast majority of the energy contained in the surf zone velocity field.

In terms of the current meter's reliability and durability two characteristics that have proved to be major problems in many studies utilizing electromagnetic flow sensors), the present design has fared very well. Laboratory and field tests have shown that, with reasonable care in handling and use, the current meters will provide consistent, stable measurements. In addition, from the experience gained in the development and manufacture of the many prototypes leading up to the final design used in the field experiments, it appears that, by taking

extreme care to isolate the coil current from the sensing electrodes and by ensuring the isolation between electrodes, zero drift and offset problems can be virtually eliminated. More effort in this area is still needed though, as the influence of ground differentials and the problems inherent in transmitting the sensor power over long distances necessitate the in situ measurement of the actual current meter offsets. Although this procedure is simple and direct, it does require that the sensors be accessible, so that deeper water deployments may present a problem if the offsets cannot be more efficiently predicted or determined.

Except for the one connector failure mentioned, the digital wave gauge proved to be both durable and reliable in all the field experiments. The wave gauge not only proved to be extremely low power and the data easily telemetered, but in addition, the wave gauge was able to make consistent and reliable surface elevation measurements very close to the current meters without noticeably affecting their performance. In terms of its hydrodynamic response, the wave gauge did exhibit a characteristic and noticeable amount of run-up on the front surface of the sensor during the passing of very peaked waves, but it was not considered to be a critical problem based on field observations, and could be significantly reduced by mounting the electrodes away from the front surface of the sensor on insulated spacers.

The field power/monitor unit was very versatile and efficient in processing and monitoring the twelve channels of sensor data telemetered to shore by the underwater cables. The noise, ground loop, and interference problems encountered during the early laboratory and field tests were successfully handled by the timing and isolation provisions

incorporated into the power/monitor unit.

The main problem with the field experiments proved not to be electronic or sensor related, but rather mechanical; the stability of the guyed-pole sensor stations proved to be inadequate to resist the turning moments from the large incident waves. Although it was possible to determine the relative orientations during the experiment, the absolute alignments are still somewhat suspect, and certainly, before more experiments are undertaken, modifications must be made to ensure a more adequate rotational stability.

5.2 SURF ZONE HYDRODYNAMICS

The twelve channels of data provided by the field instrumentation system served as a basis for a preliminary investigation into some of the important and characteristic forces in the surf zone: wave heights and directions, longshore and on/offshore currents, as well as momentum fluxes and bottom shear stresses. Coupled with a simplified force balance model based on the momentum flux into the surf zone, this data enabled an investigation into the validity and correct parameterization of the present model for the generation of longshore currents by breaking waves.

Unfortunately, the analysis of the waves and currents was significantly complicated by the rotation of the measurement stations, which led to an uncertainty in the absolute orientation of the current meters. The development of the variance ratio technique made it possible to align the data by relying on the observed wave conditions along with the measurements from Stations 2 and 1 which did not move, but the

absolute accuracy is still uncertain within a range of approximately $\pm 5^\circ$ to $\pm 8^\circ$.

In terms of longshore currents, the measurements show a gradient in longshore current across the width of the surf zone, with a peak somewhat inside of the breaker line as expected. Interestingly, the measured on/offshore currents at the four stations show a significant and consistent net offshore flow. When viewed in light of the mass transport due to waves in shallow water, along with the influence of an apparent vertically non-uniform velocity distribution, this net flow appears very reasonable.

This latter analysis led to an investigation into the appropriateness of the assumption of a vertically uniform velocity distribution used in the computation of momentum flux. In light of the field observations and the phase lag between the surface elevation and the bottom velocity, it appears less than realistic. In fact, it suggests that it might be more realistically modelled as a multilayer system, having a top layer subject to wave breaking and translation, overlying a more sluggishly reacting bottom layer.

The momentum flux measurements, utilizing the surface elevation and horizontal velocity information, showed a general loss in momentum flux across the surf zone as expected. In addition, although there is some correlation between the observed changes in longshore currents and the changes in momentum flux at the different stations, it is not as prominent as might be expected, and points out the inadequacy of the simple model in accounting for changes in wave and current conditions.

The evaluation of the bottom shear stress enabled the computation

of the bottom friction coefficient between Stations 3 and 2. The results of this computation again emphasize the inadequacy of the model in accounting for changes in conditions, as the coefficient is very unstable during changing conditions. During periods of more uniform waves and longshore currents, it does lead to a generally stable estimate for the friction coefficient, averaging between 0.10 and 0.15. The magnitude of this friction coefficient is somewhat large compared with those estimated from laboratory experiments and those observed by other investigators, and is somewhat suspect in light of the alignment uncertainty at Station 3. Since the main component of momentum flux is very sensitive to direction, having a factor of $\cos \theta \sin \theta$, this alignment problem is very significant, even beyond the rotation problem, since the combined alignment accuracy and the current meter's directional accuracy is on the order of 2° to 5° . Thus, even when making measurements on beaches subject to large angles of wave attack, the inherent measurement uncertainty in the current meters and alignment determination is potentially larger than the momentum flux itself. Clearly, more attention must be paid to the alignment and accuracy of the current meters.

As a next step in the investigation of surf zone hydrodynamics and the generation of longshore currents, several additional deployments of the complete instrumentation system incorporating the changes in the mounting structures to eliminate the rotation problem are needed to provide a more reliable data base. In addition to measuring the momentum fluxes and longshore currents, however, the vertical structure of the velocity field should be investigated by making detailed velocity

measurements at different elevations in order to get a more realistic picture of the multilayer structure. These future deployments will also serve to more completely evaluate the performance of the current meters, wave gauges, and field system, and will undoubtedly suggest additional refinements and modifications.

Finally, the successful deployment of the instrumentation system and the analysis of the field data has demonstrated the reliability and versatility of the current meters and wave gauges, and suggests the possibility for broadening the scope of applications to other coastal processes. Hopefully, by making these detailed, accurate field measurements, the processes responsible for shaping and modifying the coastal environment will become more completely understood. Then, with this knowledge in hand, it will be possible to more intelligently manage the valuable resources of the coastal zone.

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APPENDIX A

Wave Gauge and Current Meter Circuit Board Layouts and Connections

- Figure A.1 DWG Receiver Card
- Figure A.2 EMCM Driver Card
- Figure A.3 EMCM Amplifier Card
- Figure A.4 EMCM Isolation Amplifier Card
- Figure A.5 EMCM Isolation Amplifier and DWG Isolation Card

DWG RECEIVER CARD LAYOUT AND PIN ASSIGNMENTS

CONNECTOR PIN ASSIGNMENTS

- 7 CHANNEL B STROBE INPUT
- 9 CHANNEL B STROBE OUTPUT
- 11 CHANNEL B SERIAL INPUT
- 13 CHANNEL B ANALOG OUTPUT
- 21 CHANNEL A ANALOG OUTPUT
- 23 CHANNEL A SERIAL INPUT
- 25 CHANNEL A STROBE OUTPUT
- 27 CHANNEL A STROBE INPUT
- 29 -12V REGULATED INPUT
- 31 +12V REGULATED INPUT
- 33 GROUND

FIGURE A.1: DWG Receiver Card

EMCM DRIVER CARD LAYOUT AND PIN ASSIGNMENTS

CONNECTOR PIN ASSIGNMENTS

- 2 OSCILLATOR FEEDBACK LINE
- 5 COIL SENSE LINE (A)
- 9 COIL SENSE LINE (B)
- 10 COIL DRIVE A
- 12 COIL DRIVE B
- 18 S/H GROUND
- 20 S/H CONTROL A
- 22 S/H CONTROL B
- 24 +V UNREGULATED IN
- 26 - V UNREGULATED IN
- 30 + V REGULATED 12 V OUT
- 32 - V REGULATED 12 V OUT
- 33, 34, 35 GROUND

FIGURE A.2: EMCM Driver Card

EMCM AMPLIFIER CARD LAYOUT AND PIN ASSIGNMENTS

CONNECTOR PIN ASSIGNMENTS

- 4 CHANNEL A SIGNAL INPUT
- 6 CHANNEL B SIGNAL INPUT
- 8 INPUT GROUND SENSE
- 14 CHANNEL A SIGNAL OUTPUT
- 16 CHANNEL B SIGNAL OUTPUT
- 18 S/H GROUND
- 20 S/H CONTROL A
- 22 S/H CONTROL B
- 30 +12 V REGULATED INPUT
- 32 -12 V REGULATED INPUT
- 34 GROUND

FIGURE A.3: EMCM Amplifier Card

EMCM ISOLATION AMP CARD LAYOUT AND PIN ASSIGNMENTS

CONNECTOR PIN ASSIGNMENTS

	<u>EMCM 1</u>	<u>EMCM 2</u>	<u>EMCM 3</u>
+V UNREG	6	16	26
+V ISOLATED	7	17	27
-V ISOLATED	9	19	29
GND ISOLATED	8	18	28
CHA INPUT	10	20	30
CHB INPUT	12	22	32
CHA OUTPUT	11	21	31
CHB OUTPUT	13	23	33
GND SYSTEM	—	34	—
+V OSCILLATOR	—	2	—
ϕ	—	3	—
$\bar{\phi}$	—	4	—

FIGURE A.4: EMCM Isolation Amplifier Card

EMCM ISOLATION AMP AND DWG ISOLATION CARD LAYOUT

CONNECTOR PIN ASSIGNMENTS

	EMCM 4		DWG 1	DWG 2	DWG 3	DWG 4
+ V IN	33	STROBE IN	11	15	19	23
GND SYSTEM	35	STROBE OUT	12	16	20	24
+ V ISOLATED	2	SERIAL IN	13	17	21	25
- V ISOLATED	3	SERIAL OUT	14	18	22	26
GND ISOLATED	4	+12 V ISOLATED	_____	27	_____	_____
CHA INPUT	5	GND ISOLATED	_____	28	_____	_____
CHB INPUT	7	+V UNREG IN	_____	31	_____	_____
CHA OUTPUT	6	-V UNREG IN	_____	32	_____	_____
CHB OUTPUT	8	GND SYSTEM	_____	34	_____	_____
φ	9	+12 V REG	_____	30	_____	_____
φ	10	-12 V REG	_____	29	_____	_____

FIGURE A.5: EMCM Isolation Amplifier and DWG Isolation Card

APPENDIX B

Analysis of the Variance Ratio Technique in Terms of Conserved Radiation Stress

The relationship of the angle determined from the peak variance ratio of two orthogonal current meter records to the wave radiation stress can be shown through an analysis of the two variances and the derivative of the variance ratio. First, the transforming of the reference frame for the orthogonal current meter data is discussed. Then, the variance ratio for an arbitrary number of sources is presented, and the peak ratio is found.

I. In general, a sinusoidal wave of amplitude a and frequency ω will have velocity components in the respective x and y directions:

$$u_o = a \cos \omega t \cos \theta \quad (B.1)$$

$$v_o = a \cos \omega t \sin \theta \quad (B.2)$$

where θ is as shown in Figure B.1. Note that this coordinate system physically corresponds to the current meter stations discussed in Section 4. The velocity components can be generalized to any orthogonal reference frame by using the transformations:

$$u = u_o \cos \phi + v_o \sin \phi \quad (B.3)$$

FIGURE B.1: Coordinate System Before Rotation

FIGURE B.2: Coordinate System After Rotation

$$= a \cos \omega t \cos (\theta - \phi) \quad (\text{B.4})$$

$$v = -u_o \sin \phi + v_o \cos \phi \quad (\text{B.5})$$

$$= a \cos \omega t \sin (\theta - \phi) \quad (\text{B.6})$$

where ϕ is the angle of rotation from the old coordinate frame (see Figure B.2). These transformations can be easily generalized for an arbitrary number of sources

$$u_{\text{TOT}} = \sum_{i=1}^N a_i \cos \omega_i t \cos (\theta_i - \phi) \quad (\text{B.7})$$

$$v_{\text{TOT}} = \sum_{i=1}^N a_i \cos \omega_i t \sin (\theta_i - \phi) \quad (\text{B.8})$$

II. The variance for a periodic function is simply the time average of the function squared, so the two velocity variances are:

$$\sigma_u^2 = \overline{(u)^2} \quad (\text{B.9})$$

$$\sigma_v^2 = \overline{(v)^2} \quad (\text{B.10})$$

To evaluate these variances for the generalized case, first by expanding the first few terms:

$$\sigma_u^2 = \overline{\{ a_1 \cos \omega_1 t \cos (\theta_1 - \phi) + a_2 \cos \omega_2 t \cos (\theta_2 - \phi) + \dots \}^2} \quad (\text{B.11})$$

it can be seen that the expanded variance consists of two types of terms, one being of the form:

$$\overline{a_i^2 \cos^2 \omega_i t \cos^2 (\theta_i - \phi)} \quad (B.12)$$

and the other:

$$\overline{a_i a_k \cos \omega_i t \cos \omega_k t \cos(\theta_i - \phi) \cos(\theta_k - \phi)} \quad (B.13)$$

where $i \neq k$. Provided that all the components are of different frequency (if not, then phase must be considered, and the phase angles assumed random), and the averaging time sufficiently long, then all terms of the second form time average to zero, and the variance becomes:

$$\sigma_u^2 = 1/2 \sum_{i=1}^N a_i^2 \cos^2 (\theta_i - \phi) \quad (B.14)$$

$$\sigma_v^2 = 1/2 \sum_{i=1}^N a_i^2 \sin^2 (\theta_i - \phi) \quad (B.15)$$

The ratio of these two variances is then a reasonably sensitive measure of the relative alignment to the waves, since if the waves come from one predominant direction, the ratio of the on/offshore variance (σ_u^2) to the alongshore variance (σ_v^2) becomes a maximum at that angle,

$\phi_{\max}$.

III. To find this angle corresponding to the maximum ratio, the derivative of the ratio is set equal to zero and solved in terms of $\phi_{\max}$.

First though, since

$$\cos^2 \alpha = \sin^2 (\alpha + \pi/2) \quad (\text{B.16})$$

and

$$\cos^2 \alpha = 1 - \sin^2 \alpha \quad (\text{B.17})$$

the ratio can be written as:

$$\text{Ratio} = \frac{\sigma_u^2}{\sigma_v^2} = \frac{\sum a_i^2 (1 - \sin^2 (\theta_i - \phi))}{\sum a_i^2 \sin^2 (\theta_i - \phi)} \quad (\text{B.18})$$

$$= \frac{\sum a_i^2 - \sum a_i^2 \sin^2 (\theta_i - \phi)}{\sum a_i^2 \sin^2 (\theta_i - \phi)} \quad (\text{B.19})$$

Now, taking the derivative and setting it equal to zero,

$$\frac{\partial \text{Ratio}}{\partial \phi} = 0 = \sum a_i^2 \sin 2(\theta_i - \phi_{\max}) \quad (\text{B.20})$$

Solving in terms of $\phi_{\max}$,

$$\phi_{\max} = 1/2 \tan^{-1} \left\{ \frac{\sum a_i^2 \sin 2\theta_i}{\sum a_i^2 \cos 2\theta_i} \right\} \quad (\text{B.21})$$

In the case of small angles, this reduces to

$$\phi_{\max} = \frac{\sum a_i^2 \theta_i}{\sum a_i^2} \quad (\text{B.22})$$

IV. If there is only one wave present, this angle can be interpreted as the angle of the wave relative to the sensor's reference frame, but if there are numerous wave trains, this angle has little significance in terms of the wave angles or energy. In terms of radiation stress, however, this angle is significant, as it can be shown to be a close approximation to the angle which would represent an equivalent lumped radiation stress.

Considering the radiation stress contribution from individual waves to be of the form

$$S_{xy,i} \propto a_i^2 \sin \theta_i \cos \theta_i \quad (\text{B.23})$$

the total radiation stress is simply

$$S_{xy,\text{TOT}} \propto \sum a_i^2 \sin \theta_i \cos \theta_i \quad (\text{B.24})$$

Lumping this all together into an equivalent radiation stress having an angle of incidence, ϕ_S , which then conserves radiation stress, this relationship can be written as

$$S_{xy} = \sum a_i^2 \cos \theta_i \sin \theta_i = \cos \phi_S \sin \phi_S \sum a_i^2 \quad (\text{B.25})$$

Solving in terms of ϕ_S ,

$$\phi_S = 1/2 \sin^{-1} \left\{ \frac{\sum a_i^2 \sin 2\theta_i}{\sum a_i^2} \right\} \quad (\text{B.26})$$

Now, for small angles this simplifies to

$$\phi_S = \frac{\sum a_i^2 \theta_i}{\sum a_i^2} \quad (\text{B.27})$$

which is equivalent to the angle found using the maximum variance ratio technique (Equation B.22).

In the case of finite angles, no simple substitutions can be made, but the similarity between the maximum variance ratio angle and the equivalent lumped radiation stress can be demonstrated by an example. Figure B.3 shows the time series for two waves superimposed on each other. One wave is of unit amplitude, has a period of 9 units, and an angle of incidence of 0° . The other wave has a 0.5 unit amplitude, a period of 10 units, and an angle of incidence of 30° . Using Equation B.26, the equivalent radiation stress angle is 5° , which compares reasonably well with the result of 6° from the variance ratio vs. angle plot in Figure B.4.

FIGURE B.3: On/Offshore and Alongshore Velocity
Time Series for Two Waves

512 SECOND AVERAGE -STARTING AT SECTOR 1
MINIMUM AT - 84 MAXIMUM AT 6

FIGURE B.4: Variance Ratio vs. Angle Plot for Two Waves